

Thermal stability of glued wood joints measured by shear tests

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Abstract The thermal stability of glued wood joints is an important criterion to determine the suitability of adhesives in the field of engineered wood. During their product life, glued wood joints can be exposed to high temperatures in various ways (direct exposure to the sun, fire, etc.). Thereby the cohesiveness of the adhesive must not degrade. This raises the question of how the strength of bonding changes under thermal load. The current investigation covers the influence of temperature ($T = 20$ to 220°C) on the shear strength of glued wood joints. Different adhesive systems were investigated. With increasing temperature, the shear strength of solid wood and also of glued wood joints decreased. There were big differences in thermal stability and failure behaviour between the adhesive systems as well as within the polyurethane group. The thermal stability of one-component polyurethane systems can be greatly varied by modifying their chemical structure. Well adapted one-component polyurethane adhesives reach a strength similar to that of phenol resorcinol resin.

Temperaturbeständigkeit von Holz-Klebstoffverbindungen

Zusammenfassung Die Temperaturbeständigkeit von Klebstoffverbindungen ist ein wichtiges Kriterium um die Eignung eines Klebstoffes für den Holzleimbau zu beurteilen. Klebstoffe können hohen Temperaturen in vielfältiger Weise ausgesetzt sein (direkte Sonneneinstrahlung, Feuer, etc.), jedoch sollte sich die Festigkeit der Verbindungen dabei möglichst wenig verringern. Daraus resultiert die Frage,

inwiefern sich verschiedene Klebstoffsysteme unter thermischer Belastung bezüglich ihrer Festigkeit unterscheiden. In der vorliegenden Untersuchung wurden Klebstoffverbindungen im Temperaturbereich von 20 bis 220°C hinsichtlich ihrer Zugscherfestigkeit untersucht. Mit zunehmender Temperatur nahm die Festigkeit von Vollholz und auch von Holz-Klebstoffverbindungen ab. Dabei waren deutliche Unterschiede sowohl zwischen den Klebstoffsystemen als auch innerhalb der Polyurethane zu verzeichnen. Die Temperaturbeständigkeit von Polyurethanen kann durch Variation der chemischen Komponenten an den jeweiligen Temperaturbereich angepasst werden, sodass Festigkeiten wie bei Phenol-Resorcin-Formaldehyd-Klebstoff erreicht werden.

1 Introduction

In practical use, glued wood components can be exposed to thermal loading in various ways. Behind glass facades of buildings, temperatures of about 60°C can be reached under direct exposure to the sun. These conditions can lead to failure of the supporting structure (Falkner and Teutsch 2006). During fire, adhesives are exposed to even higher temperatures. In the outer regions of a timber beam, temperatures higher than 100°C can occur (Glos and Henrici 1991). In contrast, much lower temperatures are measured inside the beams due to the poor thermal conduction of wood. Furthermore the water contained in the timber evaporates, so the introduced energy is partly converted into evaporation heat and delays an increase of temperature.

In the field of timber construction, the investigation of temperature influence on the adhesive performance has gained in importance over several years. Frangi et al. (2004) investigated comparatively different types of adhesives. They found that a decrease in strength occurred over a wide

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range of temperatures. Some of the tested one-component polyurethane (1C PUR) adhesives significantly lost strength from 70°C, others reached a good thermal stability up to high temperatures. Phenol-resorcinol-formaldehyde (PRF) resins showed an initial decrease of strength at around 180–190°C.

Investigations on the creep behaviour of adhesive bonds were carried out by George et al. (2003) and Na et al. (2005), whereas a temperature dependant creep of PUR adhesives was found between 40 and 80°C. In the case of a higher initial strength (caused by a higher content of isocyanate), the creep in the low temperature range up to 50°C could be reduced. Richter et al. (2006) investigated the relationship between the chemical structure and temperature-dependent creep properties of different commercial polyurethanes. They reasoned, by comparison of mechanical performance with ¹³C-NMR spectroscopy, that the combination of a few chemical parameters had a big impact on the thermal stability of 1C PUR adhesives. These parameters were the relative proportion of remaining-NCO groups in the polyurethane, the degree of polymerisation of the prepolymer and also the rate of reaction.

Within the current investigation, different commercially available adhesives have been investigated with respect to their thermal stability. The chosen adhesives are used in the wood industry and, with the exception of PVAc and UF, also in the field of engineered wood. A special focus was made on 1C PUR adhesives due to their controversially discussed behaviour at high temperatures. A generalized conclusion for a type of adhesive by comparing different products without a variation of each type is not possible. The investigation rather gives an overview of currently used adhesives concerning their bonding strength in a wide range of temperatures.

2 Methods and materials

2.1 Wood

All bondings were carried out with beech wood (*Fagus sylvatica* L.). The raw density ρ at an EMC ω of $(13 \pm 1)\%$ amounted to $(756 \pm 54) \frac{\text{kg}}{\text{m}^3}$. The growth ring angle α (angle between growth rings and glued surface of the specimen) of the wood was between 30 and 90°.

2.2 Adhesives

For testing the thermal stability, commercially available adhesives (list below) from different producers were used. Table 1 lists the bonding parameters for each adhesive as they are recommended by the manufacturers and which were followed strictly. All used adhesives and hardeners were applied in liquid state.

- Urea-formaldehyde resin (UF)
- Melamine-formaldehyde resin (MF)
- Melamine-urea-formaldehyde resin (MUF)
- Phenol-resorcinol-formaldehyde resin (PRF)
- Polyvinyl acetate (PVAc)
- Emulsion-polymer-isocyanate (EPI)
- One-component polyurethane (1C PUR)

PVAc belongs to the group of thermoplastic polymers. These polymers are able to deform reversibly within a special temperature range. If this range is exceeded, a thermal degradation occurs. PVAc glues are, for example, used in the further processing of solid wood boards and veneers, and also in furniture manufacturing in general. The used adhesive was applied without hardener. For this reason, high thermal stability was not expected.

EPIs are reaction adhesives known for a relatively high thermal stability. By the cross linking of polyvinyl alcohol with diphenylmethan-4,4'-diisocyanate (MDI) in combination with hydrophobic dispersions, high bonding strengths are achieved.

UF resins are the most common adhesives in the wood-based materials industry. Fields of application are particle boards, MDF boards, solid wood boards, plywood, engineered wood and furniture production. Due to their sensitivity to moisture (especially in combination with higher temperatures), UF adhesives often are fortified by cocondensation with melamine or phenol.

The tested MF adhesive is commonly used for bonded wood components (such as glulam) for supporting constructions. It is certified in combination with an appropriate hardener according to EN 301 (2006).

MUF adhesives are produced either by separate production of UF and MF or by cocondensation of melamine, urea and formaldehyde in one and the same batch. The adhesives are characterized by a higher moisture stability compared to UF adhesives. They are used in the production of particle boards, MDF boards, solid wood boards, plywood and engineered wood.

PRF resins are generally used as cold curing adhesives for engineered wood products. Bondings with PRF are characterised by a good climatic stability and high bonding performance. From investigations on the temperature behaviour of phenolic resins (PF), it is known that they tend to post-cure at high temperatures. Ohlmeyer (2003) showed that hot stacking of particle boards bonded with PF and MDI partly led to higher tensile strength perpendicular to the surface.

One-component polyurethane adhesives are classed as reactive adhesives. They are produced by a reaction of polyether polyols with a stoichiometric excess of isocyanate. Thereby long-chain polymers with isocyanate end and side groups are developed, which cure by a reaction with water contained in the wood. The isocyanate also reacts with the

Table 1 Adhesives and their bonding properties
Tab. 1 Klebstoffe und Parameter der Verklebung

Adhesive	Adhesive-hardener ratio ^a	EN 301 certification	EMC ^b [%]	Pressure ^b [MPa]	Pressing time	Temperature [°C]	Application	Spread per side [$\frac{g}{m^2}$]
PUR 1	–	✓	≥ 8	0.6–1.0	3 h	20	One side	200
PUR 2	–	✓	≥ 8	0.6–1.0	6.5 h	20	One side	180
PUR 3	–	✓	≥ 9	0.8–1.2	2.25 h	20	One side	250
UF	100/20	–	6–13	0.3–1.6	7 min	70	Two sides	130
PVAc	–	–	n/a	0.8–1.2	15 min	20	Two sides	150
MUF	100/35	✓	≈12	0.8–1.2	4 h	20	Two sides	200
MF	100/10	✓	≈12	0.8–1.2	6 h	20	Two sides	200
PRF	100/20	✓	≈12	0.8–1.2	5 h	20	Two sides	180
EPI	100/15	✓	6–15	0.8–1.2	65 min	20	Two sides	250

^aApplied in liquid state^bAs recommended by adhesive producer

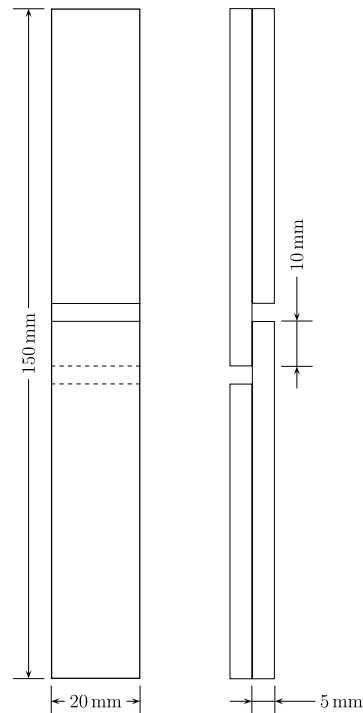
functional OH-groups of the adherend. The used adhesives are fabricated by different producers and vary in their chemical composition. All of them are certified according to EN 301/302 standards and are primarily used in the field of engineered wood.

2.3 Production of the specimens

According to EN 302-1, the prefabricated boards were stored under standard climatic conditions (20°C, 65% RH) until the equilibrium wood moisture was reached. Directly before the bonding process, the boards were planed to the necessary thickness of (5 ± 0.1) mm to exclude aging effects on the wood surface. The adherends were bonded with close contact bond lines (≈ 0.1 mm) at room temperature and 50% RH according to the producer's instructions in Table 1. The pressure for all adhesive bonds was 0.8 MPa. After one week storage under standard climatic conditions, the bonded adherends were cut into specimens according to EN 302-1 (Fig. 1).

2.4 Testing procedure

The shear strength was determined according to EN 302-1. To investigate the influence of the temperature on shear strength, 25 specimens of each group were tempered in a drying chamber for 1 h at 50, 70, 110, 150, 200 or 220°C, respectively. Subsequently, they were tested using an universal testing machine (Zwick Z100). The testing room of the machine was not tempered, thus the specimens' temperature could slightly decrease. Up to 70°C, the specimens were tempered in a plastic bag to ensure that the EMC remained constant. During the shear tests, the EMC corresponded to the wood moisture under standard climatic conditions.

**Fig. 1** Dimensions of test specimens according to EN 302-1
Abb. 1 Abmessungen der Prüfkörper gemäß EN 302-1

Above 110°C, the specimens reached oven-dry density. Reference specimens were stored under standard climatic conditions. The tests were performed position-controlled with a feed speed of $2 \frac{mm}{min}$. The strain up to the maximal load was evaluated with a video-extensometer. After measuring the shear strength and strain, the wood failure percentage was estimated visually in 10%-steps, as recommended in EN 302-1 (2004). Furthermore, the specimens were weighed

and the wood moisture content was determined according to ISO 3130 (1975).

3 Results and discussion

3.1 Solid wood specimens

To obtain a reference value for the strength of the glued specimens, non-glued solid wood specimens were tested in addition. In doing so, specimens were designed according to the geometry requirements of shear specimens in EN 302-1. The geometry of the specimens and the direction of loading therefore differed from the requirements of the German standard DIN 52187 (1979) for wood specimens. Under standard climatic conditions, the shear strength ($15,0 \pm 3,5$ MPa) corresponded to values determined by Horvath et al. (2007). EN 302-1 stipulates a growth ring angle of 30–90°; since this angle affects the shear strength of wood (Mihulja et al. 2008), a higher variance occurred as a consequence of the orientation.

The shear strength of the tested solid wood specimens decreased with increasing temperature. At 110°C the shear strength dropped disproportionately and contradicts the linear trend which was shown by Frangi et al. (2004) for the range between 20 and 170°C. For the bending strength Sonderegger and Niemz (2006) also showed a linear decrease with the temperature for different wooden materials in the range between –20 and 60°C. The same correlation is known from former investigations by Östman (1985) and Kudela (1996) for tensile and compressive strength, respectively.

The chemical components of wood undergo a thermal degradation which affects the strength properties if the material reaches elevated temperatures. From about 65°C, permanent reductions in strength are possible. Thereby the amount of degradation depends on moisture content, temperature, exposure time, pH of wood and species. Reasons for strength degradation are depolymerisation reactions without significant weight loss. The chemical bonds of wood start breaking at temperatures higher than 100°C. Thereby lignin and carbohydrate weight losses occur that increase with the temperature. A significant pyrolysis of hemicelluloses and lignin starts from about 200 and 225°C, respectively (White and Dietsberger 2001). Probably the pyrolysis is the reason for the rapid reduction in strength between 200 and 220°C (Fig. 2). As a consequence tensile fracture was frequently found within this temperature range.

It should be pointed out that a temperature exposure in principle is accompanied by a change in wood moisture. Above 150°C, the average wood moisture of the specimens was 0%. According to Horvath et al. (2007), the reduction of wood moisture to less than 6% leads likewise to a decrease in shear strength. The results therefore show an interaction of the effects.

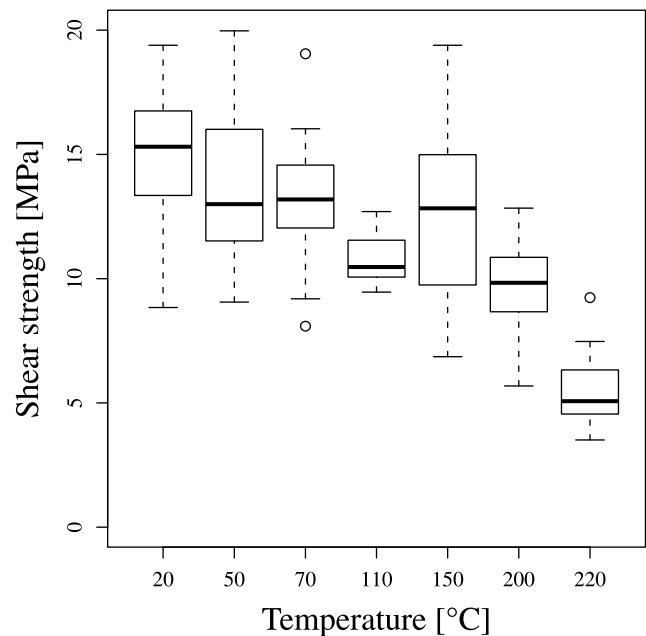


Fig. 2 Shear strength of beech against temperature (box: quartile of distribution, whiskers: at most $1.5 \times$ interquartile range, points: outliers)

Abb. 2 Zugscherfestigkeit von Buche in Abhängigkeit der Temperatur

3.2 Glued wood specimens

Table 2 shows the average shear strength of the tested adhesive bonds. Under standard climatic conditions, all adhesives passed the wood strength, which is shown by the high amount of wood failure. The polyurethanes PUR 1 and PUR 3 were also in the range of wood strength but the wood failure percentage was comparatively low (Table 3). With increasing temperature, PVAc proved itself the weakest adhesive. Around 50°C, the strength reached only 35% of beech wood. However, PVAc must be considered as a special case as it was applied without hardener and is not certified for engineered wood construction. Up to 150°C, MF, PRF, PUR 2, PUR 3 and UF reached values beyond 80% of the reference value. Around 220°C, only MF, PRF and PUR 2 exceeded the average of beech wood (with PUR 2 showing the highest shear strength). In this temperature range, EPI and UF also showed lower wood failure percentages.

Regarding the interpretation of these results, it should be considered that during the drying process a change in wood moisture content occurred. Up to 70°C, the wood moisture remained at about 12% whereas it dropped to 0% from temperatures of 150°C. Therefore, oven-dried specimens were tested. Figure 3 shows the influence of temperature on the shear strength of all tested adhesives and beech wood. Between 70 and 150°C, the strength slightly increased, due to the reduction in wood moisture, which has a bigger effect on the strength than the increase of temperature (Kudela 1996).

Table 2 Shear strength of adhesive bonds at variable temperatures**Tab. 2** Zugscherfestigkeit der Verklebungen bei der entsprechenden Prüftemperatur

T [°C]	τ [MPa]										
		Beech	EPI	MF	MUF	PRF	PUR 1	PUR 2	PUR 3	PVAc	UF
20	$\bar{\tau}$	14.96	12.72	12.50	12.25	14.65	12.15	13.17	13.35	12.07	14.86
	s_{τ}	3.54	1.72	1.54	2.44	1.92	1.02	1.05	1.98	1.38	3.15
50	$\bar{\tau}$	13.90	11.70	11.81	12.54	14.95	8.94	11.76	11.30	4.90	13.39
	s_{τ}	3.36	1.12	1.17	2.47	2.08	1.31	1.05	0.98	1.31	1.55
70	$\bar{\tau}$	13.17	10.28	11.03	11.36	13.33	8.34	11.45	9.38	3.93	11.27
	s_{τ}	2.73	1.10	1.27	1.52	1.84	0.98	0.94	1.77	0.87	2.42
110	$\bar{\tau}$	10.89	10.82	10.53	8.75	10.86	9.56	11.86	10.87	3.90	11.48
	s_{τ}	1.03	1.72	1.84	2.46	1.51	1.55	2.00	1.22	1.43	2.45
150	$\bar{\tau}$	12.71	9.31	10.72	9.01	12.55	9.31	11.33	11.12	2.23	10.77
	s_{τ}	3.77	1.79	1.65	3.32	2.53	1.06	1.40	1.28	1.00	1.75
200	$\bar{\tau}$	9.57	7.46	8.80	9.11	10.1	7.94	9.57	8.56	0.96	6.59
	s_{τ}	1.96	0.86	1.54	2.76	1.88	1.79	1.38	1.69	0.51	2.41
220	$\bar{\tau}$	5.56	4.21	5.85	5.38	5.70	2.19	6.87	4.22	0.89	0.89
	s_{τ}	1.46	0.59	0.92	1.23	1.07	0.78	0.89	1.53	0.31	0.64

τ shear strength, $\bar{\tau}$ mean, s_{τ} standard deviation, T temperature

Table 3 Wood failure percentage of adhesive bonds at variable temperatures**Tab. 3** Holzbruchanteil der Verklebungen bei der entsprechenden Prüftemperatur

T [°C]	Wood failure [%]									
	EPI	MF	MUF	PRF	PUR 1	PUR 2	PUR 3	PVAc	UF	
20	90	100	100	90	40	90	20	80	100	
50	100	100	100	90	10	90	0	0	80	
70	70	100	100	90	10	90	0	0	70	
110	90	100	100	100	20	90	70	0	100	
150	90	100	100	100	20	100	40	0	60	
200	40	100	100	100	40	100	40	0	70	
220	40	100	70	100	0	90	20	0	0	

During the drying of wood and the corresponding shrinkage, residual stresses occur that interact with the external shear stress. These influences are hardly separable.

With regard to the strain of the bond lines, it is shown that the adhesives PVAc, PUR 1, PUR 3 and EPI caused higher strains in the whole temperature range, compared to the polycondensation adhesives (Fig. 4). Maximum values for the shear strain were reached at a temperature of 70°C, which can be ascribed to the combination of increased temperature at a constant moisture content of about 12%.

3.2.1 PVAc

As shown in the box plot (Fig. 5), the shear strength strongly decreased at 50°C. The wood failure percentage nearly dropped to 0%. Due to the thermoplastic behaviour of PVAc,

higher strains occurred in the lower temperature range than for all other adhesives (Fig. 4).

3.2.2 EPI

Up to 150°C, EPI showed a good thermal stability (Fig. 6). Compared to the reference specimens, EPI showed a 15% lower strength throughout the whole temperature spectrum. Up to 150°C, the wood failure percentage was higher than 70% and dropped below 50% above this temperature. From about 200°C, it is assumed that the failure of the glued wood joints is caused by the adhesive. Due to the PVAc component, EPI shows a partly thermoplastic behavior, however it shows no obvious evidence for softening. From a chemical standpoint it is unclear if crosslinkings are destroyed or if the remaining thermoplastic behaviour dominates.

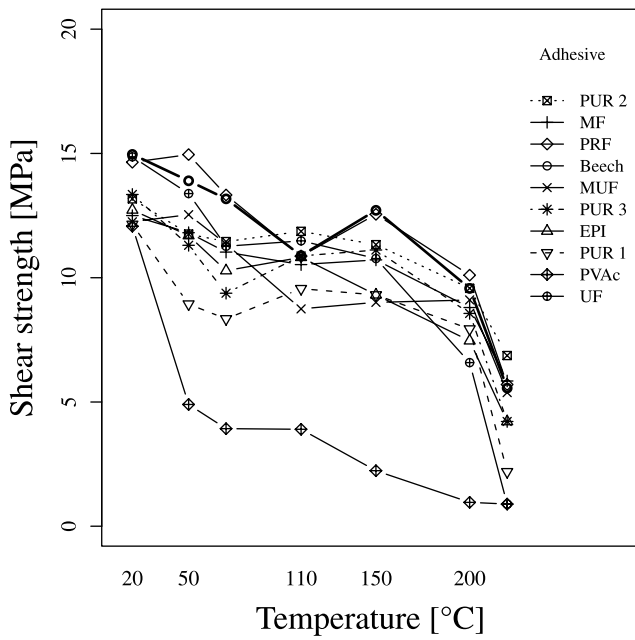


Fig. 3 Shear strength of specimens against temperature
Abb. 3 Zugscherfestigkeit der Prüfkörper in Abhängigkeit der Temperatur

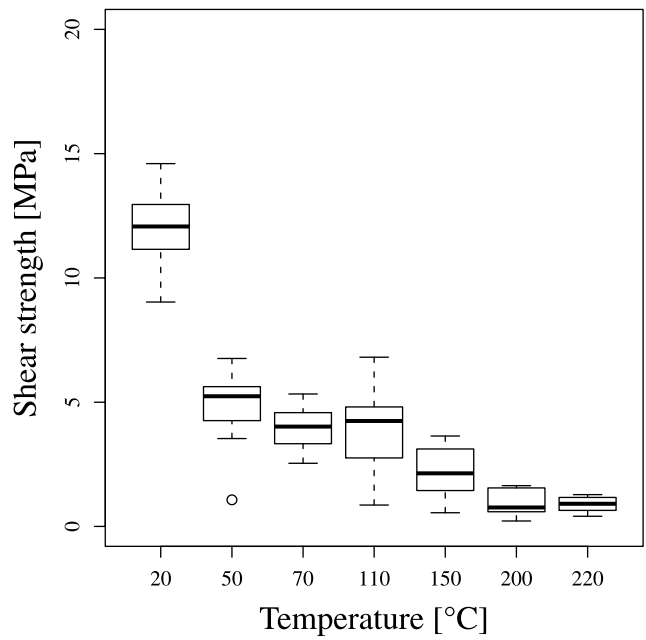


Fig. 5 Shear strength of PVAc against temperature
Abb. 5 Zugscherfestigkeit der Verklebungen mit PVAc in Abhängigkeit der Temperatur

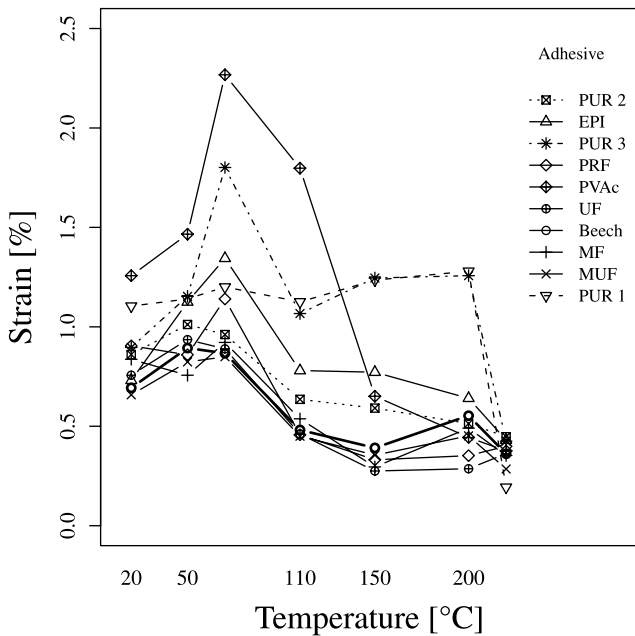


Fig. 4 Shear strain of specimens against temperature
Abb. 4 Schubdehnung der Prüfkörper in Abhängigkeit der Temperatur

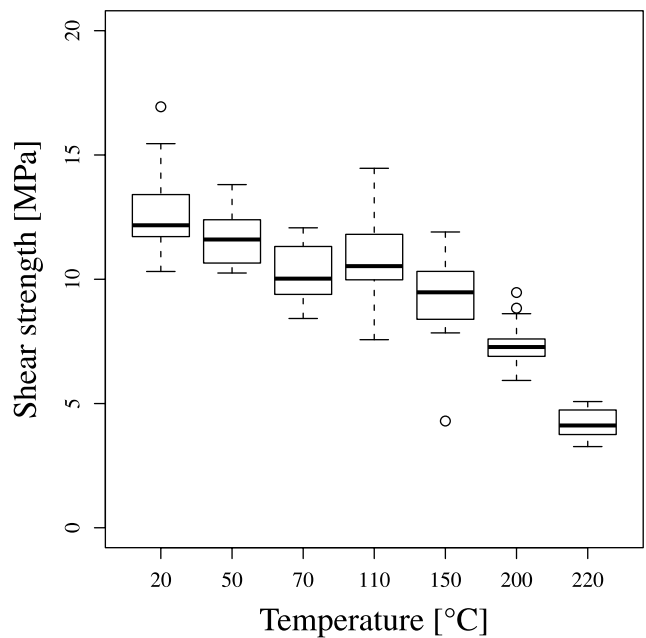


Fig. 6 Shear strength of EPI against temperature
Abb. 6 Zugscherfestigkeit der Verklebungen mit EPI in Abhängigkeit der Temperatur

3.2.3 UF

Up to 150°C, UF showed a high thermal stability (comparable with MF or MUF resins). In the case of lower temperatures, the adhesive reached just like PRF maximum values (Fig. 7), which comply with the values of beech wood.

At 200°C, the strength decreased more distinctly in comparison to the other adhesives. At 220°C the adhesive failed completely. Due to the short temperature exposure, the failure is probably not caused by hydrolysis effects. In contrast to MF, the fracture surface of UF (Fig. 10) shows a heavy

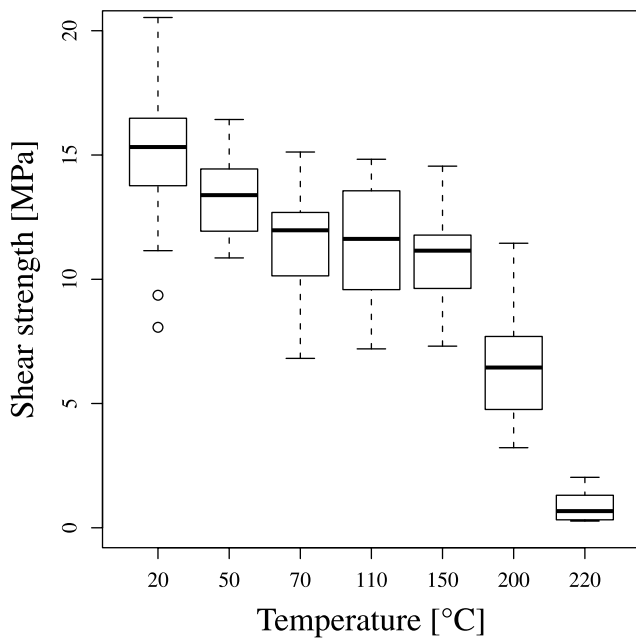


Fig. 7 Shear strength of UF against temperature
Abb. 7 Zugscherfestigkeit der Verklebungen mit UF in Abhängigkeit der Temperatur

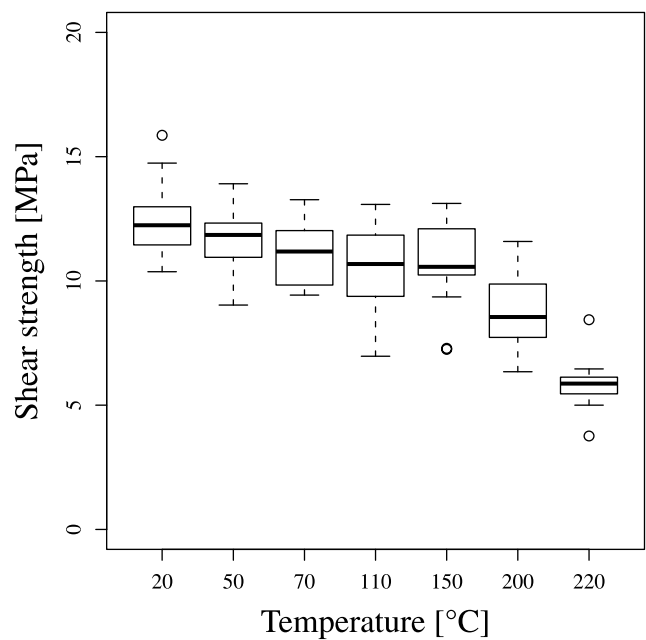


Fig. 8 Shear strength of MF against temperature
Abb. 8 Zugscherfestigkeit der Verklebungen mit MF in Abhängigkeit der Temperatur

discolouration of the adhesive caused by a thermal degradation.

3.2.4 MF

The tested adhesive reached excellent shear strength at all temperatures (Fig. 8). The wood failure percentage was nearly 100% throughout the whole temperature range. It is clearly shown that the shear strength of the bondline was higher than the strength of beech wood. The images of the MF fracture surfaces (Fig. 10) show that even at 220°C no discolouration occurred and that wood fibres were pulled out all over the adherend.

3.2.5 MUF

Up to 70°C, the bondings with MUF reached a shear strength above 10 MPa, which is the minimum shear strength according to EN 301 under standard climatic conditions (classification type I). Figure 9 shows a slight drop at 110°C to 9 MPa on average, which was below the values reached by MF und UF. In the temperature range above 150°C, the bonding strength was similar to the shear strength of beech wood. The wood failure percentage was up to 200°C 100%. The lower shear strengths (compared to MF) at 110 and 150°C were caused by the failure of wood and not by the failure of the adhesive. The images of MUF fracture surfaces (Fig. 10) show like UF a heavy discolouration, but still high shear strength was observed. It can be

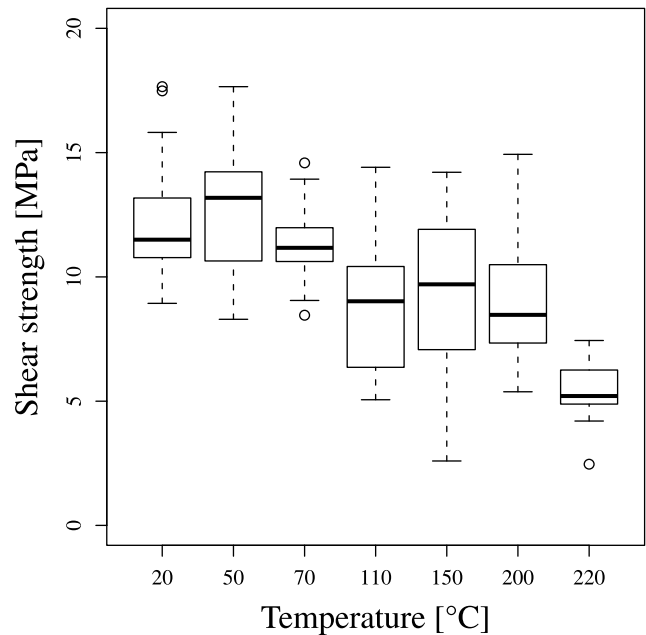


Fig. 9 Shear strength of MUF against temperature
Abb. 9 Zugscherfestigkeit der Verklebungen mit MUF in Abhängigkeit der Temperatur

argued that the degradation process (as indicated by the discolouration of the bond line) was delayed, due to the addition of melamin, whereas for UF this degradation process occurred at much higher rate.

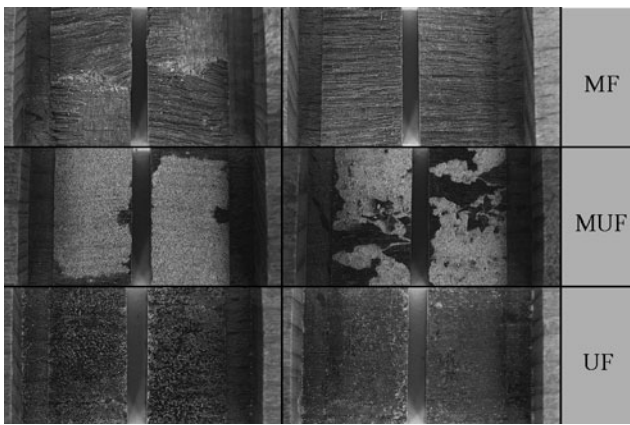


Fig. 10 Fracture surfaces of MUF, MF and UF at a temperature of 220°C

Abb. 10 Bruchflächen von MUF, MF und UF bei 220°C Temperierung

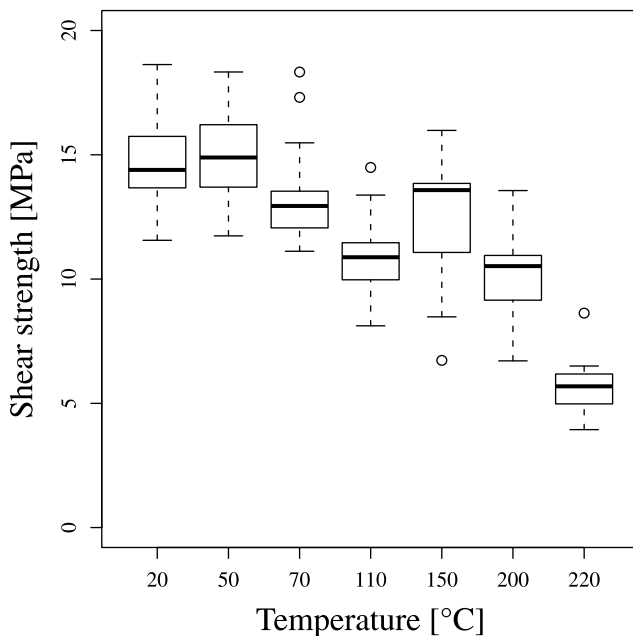


Fig. 11 Shear strength of PRF against temperature

Abb. 11 Zugscherfestigkeit der Verklebungen mit PRF in Abhängigkeit der Temperatur

3.2.6 PRF

The bondings with PRF reached excellent shear strengths throughout the whole temperature range (Fig. 11). Furthermore, nearly exclusively wood fracture occurred up to 220°C. The shear strength exceeded the limit value of 10 MPa, according to EN 301 under standard climatic conditions, up to 200°C.

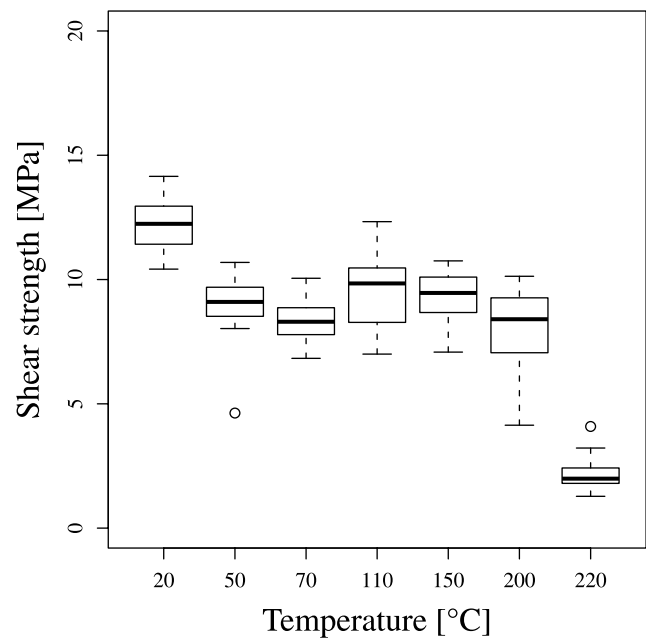


Fig. 12 Shear strength of PUR 1 against temperature

Abb. 12 Zugscherfestigkeit der Verklebungen mit PUR 1 in Abhängigkeit der Temperatur

3.2.7 1C PUR

The 1C PUR adhesives from different producers showed diversity in their behaviour. Under standard climatic conditions, all adhesives reached shear strengths between 12.0 and 13.5 MPa, which corresponds to 80–90% of the shear strength of beech wood. Above 50°C, the strength of PUR 1 dropped significantly in comparison to the other PUR adhesives (Fig. 12). The minimum shear strength, according to EN 301 for classification type I, was reached only under standard climatic conditions. In the temperature range from 50 to 200°C, the adhesive withstood the temperature load at a shear strength above 7.5 MPa. At 220°C, the bonding suffered a clear decline compared to the other two 1C PUR adhesives. The wood failure percentage of PUR 1 was very low throughout the whole temperature range.

The PUR 2 reached, compared with the other PUR adhesives, the best results independent of temperature. Up to 150°C, the adhesive reached values significantly above 10 MPa (Fig. 13) and thereby showed excellent thermal stability. Within the temperature range above 150°C, it also reached the highest overall shear strength. Above 200°C, the bonding reached a shear strength comparable to beech wood. The wood failure percentage was at least 90% in the overall temperature range. This shows, in contrast to the other polyurethane adhesives, that primarily the wood material failed, even though at 20 and 50°C, nearly the same shear strength was reached compared to PUR 3.

The PUR 3 from a second producer reached high shear strengths as well, compared to the shear strength of beech

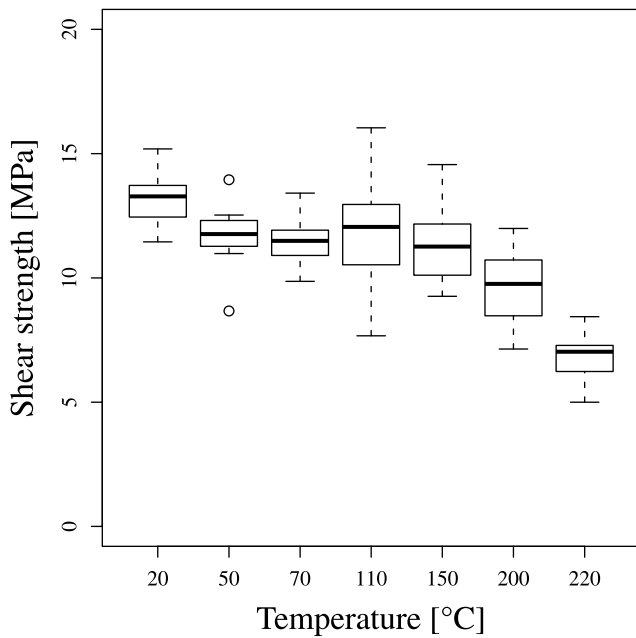


Fig. 13 Shear strength of PUR 2 against temperature
Abb. 13 Zugscherfestigkeit der Verklebungen mit PUR 2 in Abhängigkeit der Temperatur

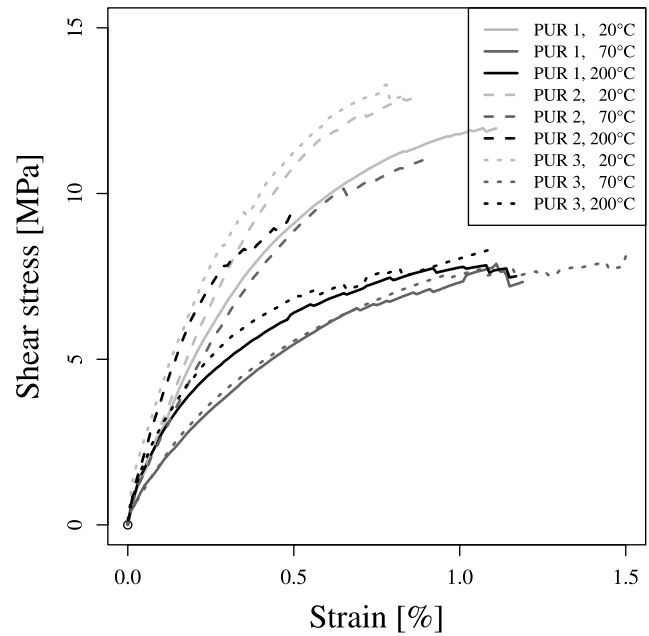


Fig. 15 Strain-stress curves of PUR adhesives at 20, 70 and 200 °C
Abb. 15 Spannungs-Dehnungs-Diagramm der PUR Klebstoffe bei 20, 70 and 200 °C

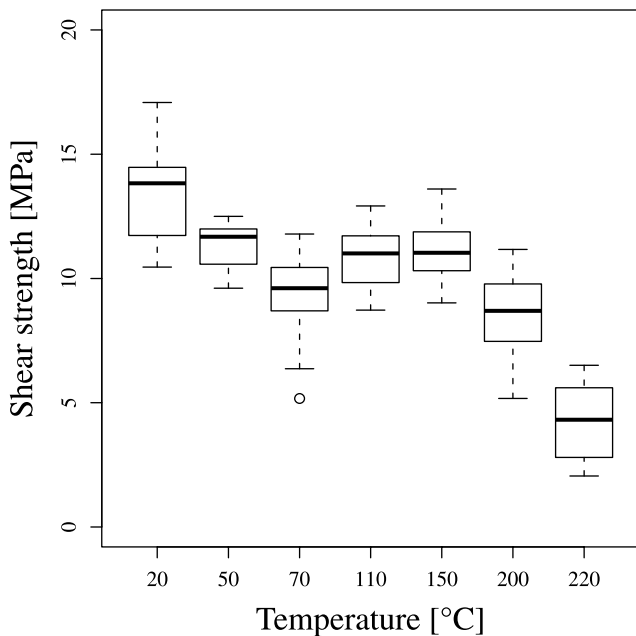


Fig. 14 Shear strength of PUR 3 against temperature
Abb. 14 Zugscherfestigkeit der Verklebungen mit PUR 3 in Abhängigkeit der Temperatur

wood (Fig. 14). However, the adhesive showed significant disadvantages in the range between 70 and 110 °C. The reason therefore might be found in the adhesive’s chemical structure. At 220 °C, the shear strength of the bonding dropped sharply. The wood failure percentage was considerably lower than that of the polycondensation adhesives.

Furthermore, it turned out that the wood failure percentage increased at higher temperatures (Table 3).

The stress-stain-curves of the adhesives PUR 1 and PUR 3 (Fig. 15) indicate a lower shear resistance at the temperatures 70 and 200 °C, which is shown by the lower slope of this curves. The maximum strains of PUR 1 and PUR 3 at these temperatures (especially PUR 3 at 70 °C) were also increased, compared to PUR 2. However, PUR 2 showed a higher maximum strain than beech wood as well (Fig. 4). In the range of low deformation ($\epsilon \leq 0.5\%$), the slope of PUR 2 remained nearly constant independent of temperature. That confirms the higher thermal stability of this adhesive. The reduced stiffness of two of the polyurethanes is possibly caused by a plasticising effect due to the coaction of the remaining wood moisture content and the elevated temperature. To confirm this assumption, further investigation is needed.

4 Summary and conclusion

In the lower temperature range, all adhesives showed sufficient shear strengths above 10 MPa (Fig. 16). The best results compared to the average wood strength were reached by PRF and UF adhesives. The wood failure percentage reached at least 80%, with the exception of PUR 1 and PUR 3.

In the range between 50 and 150 °C, the adhesives showed good thermal stability. Only PVAc failed at 50 °C due to its thermoplastic behaviour. Thereby it must be pointed out that

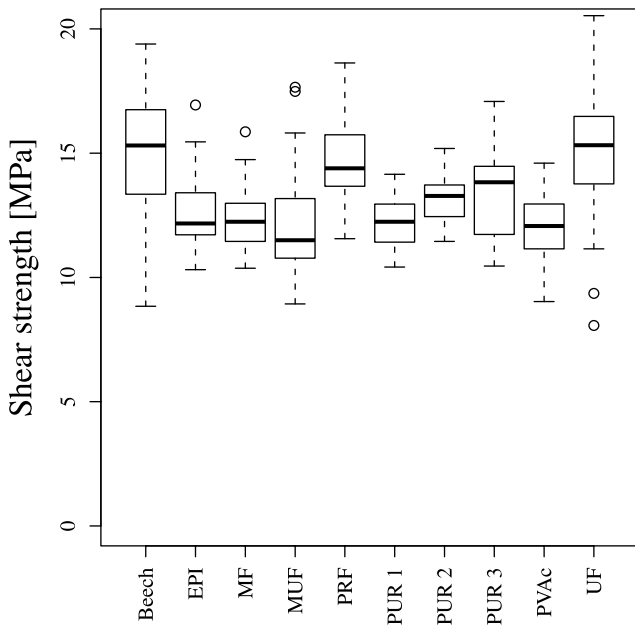


Fig. 16 Comparison of shear strength of adhesive bonds at 20°C
Abb. 16 Vergleich der Zugscherfestigkeiten verschiedener Verklebungen bei 20°C

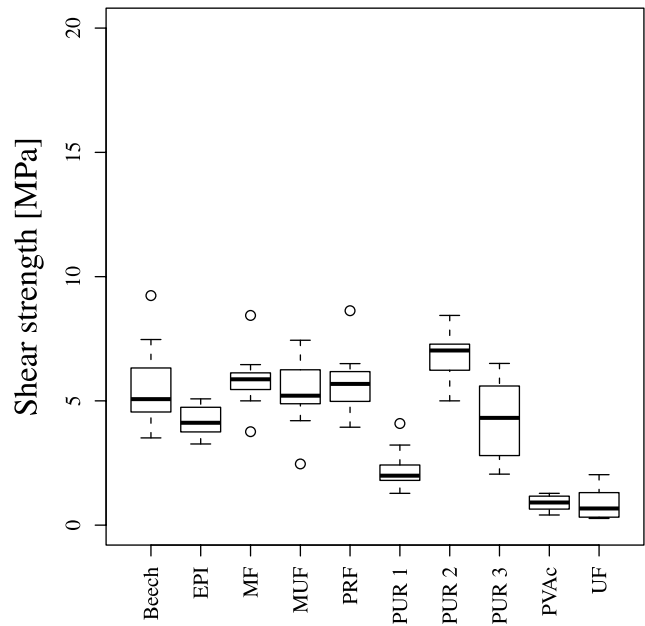


Fig. 18 Comparison of shear strength of adhesive bonds at 220°C
Abb. 18 Vergleich der Zugscherfestigkeiten verschiedener Verklebungen bei 220°C

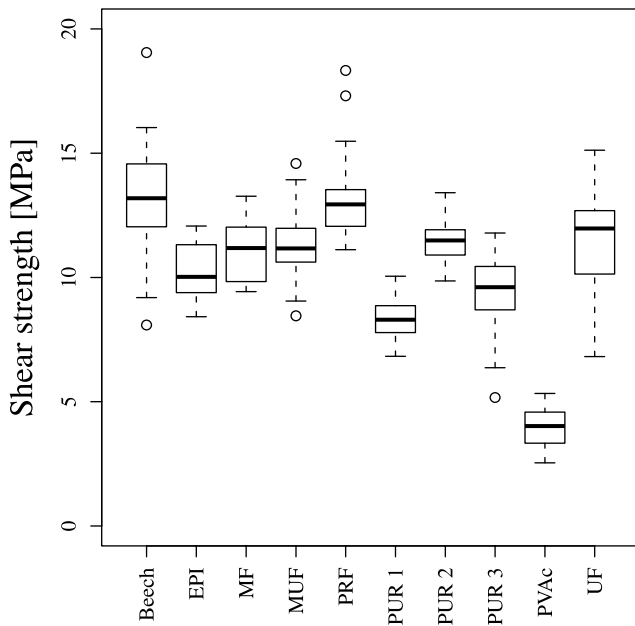


Fig. 17 Comparison of shear strength of adhesive bonds at 70°C
Abb. 17 Vergleich der Zugscherfestigkeiten verschiedener Verklebungen bei 70°C

temperatures up to 70°C are in a range of practical relevance. From about 70°C (Fig. 17), two of the polyurethane adhesives showed a growing decrease in strength. The wood failure percentage of these adhesives (PUR 1, 20%; PUR 3, 30%) also differed significantly from that of PUR 2 and the polycondensation resins. A possible reason for this behav-

our is the different reactivity of the PUR adhesives. PUR 1 (60 min) and PUR 3 (45 min) have up to half the open time compared to PUR 2 (120 min). Furthermore, the viscosity of the adhesives increases from PUR 1 (3000 mPas) to PUR 3 (12000 mPas) to PUR 2 (17000 mPas). Since exact information about the chemical structure of the adhesives is not known to the authors, more detailed research is necessary to explain the observed effects.

At 200°C, PUR 1 and UF showed a decreased thermal stability. The shear strengths of these adhesives differed significantly from the rest. The decrease in strength was also reflected in the wood failure percentage, which descended to 0%. Compared to the average wood strength of all tested adhesives, also EPI and PUR 3 slightly decreased in strength. Up to 220°C, MF, MUF, PUR 2 and PRF showed mostly wood failure and reached shear strengths similar to beech wood (Fig. 18). Thereby it must be considered that in case of PRF, MUF, MF and PUR 2 not the adhesive but rather the wood properties were tested. Thus a comparison of the adhesives' properties is not feasible. To deal with this problem and to get more information about the adhesive properties Konnerth et al. (2006) used a different specimen geometry. Pizzo et al. (2003) on the other hand used a different testing set up to compare the glue line and the solid wood with the same specimen. This procedure offered the advantages that a direct comparison becomes possible and the influence of wood variability is minimized. For the practical relevance, it is only sufficient to exceed specific values which guarantee a suitable strength.

The 1C PUR adhesives showed a high variation within their adhesive group. This also applies for the shear strength and the wood failure percentage. While PUR 1 only reached a shear strength above 10 MPa at 20°C, PUR 2 reached values comparable to beech wood up to 220°C. In conclusion, 1C PUR adhesives exhibit a wide range of properties caused by their spectrum of assembly possibilities.

Apart from the temperature, some other influencing factors, such as wood moisture and raw density, were present under the applied experimental circumstances. Their impact on the results must be considered. Up to 70°C, the moisture content was approx. 12%. By contrast, above 110°C the specimens were oven-dried. Due to the change in wood moisture and the corresponding shrinkage of wood, residual stresses occur and lead to an additional decrease of shear strength. Apart from the bonding, the wood moisture itself influences the shear strength (Schrödter and Niemz 2006). Investigations on beech wood (Horvath et al. 2007) revealed an increasing compressive shear strength beginning from oven-dried specimens up to 6% wood moisture. By contrast, with a further increase of the moisture content, the compressive shear strength decreased. This fact makes it difficult to derive a dependency of shear strength on the temperature. The influencing factors are difficult to separate over such a wide range of temperatures. A possible way could be to oven-dry the specimens and to test them subsequently. By changing this experimental procedure, the influence of wood moisture can be eliminated but the initial drying may cause damage to the specimens.

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