FIRENWOOD

Improved fire design of engineered wood systems in buildings

Sub report D3.4
Test series 1

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1 Testing setup

Within the research project Firenwood, four different test series are carried out to investigate the adhesive behavior of glued in rods under temperature load including fire exposure. The test series 1 described in this partial report includes preliminary small scale tests in order to be able to define the test parameters for the further investigations. In particular, the influence of the adhesive type, the glue line thickness, the temperature level, the test configuration and the load level are considered.

In addition, the material characteristics for the used adhesives are to be determined under standard conditions and compared with the behavior under thermal stress.

In the following series of tests, test specimens with glued in rods are examined and corresponding characteristic values for numerical simulations as well as the basis for a design model for a fire protection model are created.

2 Materials and Test Methods

2.1 Experiment Overview

Within test series 1, the tensile shear strength of two adhesives is tested based on EN 302-1. The testing temperature as well as the glue line thickness and the mechanical load level are varied. 10 specimens were tested for each variant. The results were then subjected to a statistical outlier test. The corresponding values were sorted out and are no longer listed in the following results and illustrations.

2.1.1 Materials

The test specimens were made from beech wood panels. Before gluing, the wood was stored in normal climate conditions (20 °C / 65% RH) until equilibrium moisture content was reached. Additional issues concerning the tempering of adhesives arose during the tests, which is why additional test modifications were included in the test configuration. This increased the number of different test scenarios from eight to a total of eleven. The bonding of the panels for all test specimens was made in three different batches. The configuration, which originally consisted of eight test modifications, was manufactured in the first two batches. Batch three panels were used for the extended tests. The mean density was 712.75 kg/m³ for batch 1, 729.03 kg/m³ for batch 2 and 775.19 kg/m³ for batch 3 (see also Appendix A.1).

Two different adhesive systems were used for bonding. The batch numbers and the bonding and pressing times are also shown in Appendix A.1:

- 2K-EP
- 2K PUR

The adhesives are referred to as Adhesive 1 (2K-EP) and Adhesive 2 (2K-PUR).

2.1.2 Production

To produce ten test specimens, two wooden panels each with the external dimensions 300 mm x 130 mm are bonded. The height of the first panel is 5.0 mm, while the second panel is additionally increased by the height of the target glue line thickness. With the three glue lines of 0.1 mm, 1.0 mm and 3.0 mm, this results in panel thicknesses of 5.0 mm, 6.0 mm and 8.0 mm respectively. Before the adhesive was applied, the panels were sanded, cleaned with compressed air and sorted in pairs to ensure a similar combination of growth ring layers per pair. Two joints are milled into one of the panels with the required glue line thickness. The adhesive is applied on one side and manually distributed using a notched scraper with an application quantity of 15.6 g per panel. The panels were weighed before and after the adhesive was applied to ensure the appropriate amount of adhesive. The adhesive in the joints was spread and worked in with a spatula to prevent the formation of air bubbles. The two types of adhesive are mixed with the help of static mixers placed on the double cartridges, which guarantee the mixing ratio specified by the manufacturer. The bonding took place under normal climatic conditions. After applying the adhesive, the panels were pressed with a hydraulic press under a pressure of 0.8 N/mm² (see Figure 1). The bonding times for each batch until application of the pressure is listed in Appendix A.1.

Figure 1: Left: compression of the panels; Right: Pressed and cured panels before the test specimens were cut to size

Before the panels were cut to the test specimen dimensions (see Figure 2), the bonded panels were stored in a normal climate for at least seven days. There was a period of at least 28 days between the bonding of the panels and the testing of the test specimens in order to ensure the maximum strength and temperature resistance of the adhesives. Further details on the bonding of the three batches and the labeling of the test specimens are given in Appendix A.1.

Exactly ten test specimens can be produced from a bonded panel. Immediately after cutting, the specimens were divided among the different test modifications in ascending order. This ensured that the various batches and boards were mixed for each test scenario, so that the influence of, for example, high densities or strengths in the wood is distributed during the different test scenario. The labeling and batch number for the plates from the individual test specimens is shown in Appendix A.2. The allocation of the test specimens to the individual test scenarios is listed in the test report in Appendix A.3.

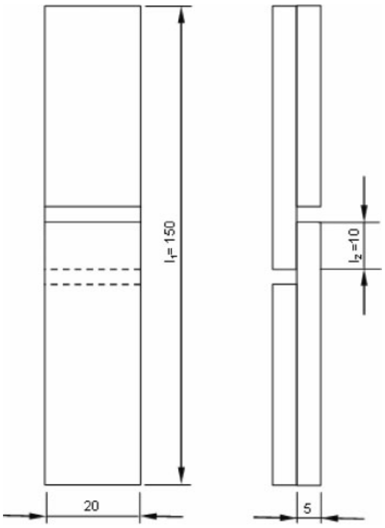


Figure 2: Dimensions of the specimens of the tensile shear tests in [mm]

Type K thermocouples were also embedded in some of the specimen in order to be able to determine the temperature within the glue line during the tests. For this purpose, a 2 mm deep groove was sawn into the panel with the help of a table saw, which extends to the milled joint for the adhesive (see Figure 3). After the adhesive had been applied and distributed, the thermocouple was inserted into the sawn joint so that the measuring point of the twisted tip was in the middle of the joint. The thermocouples were taped to the frame of the press to ensure that they would not change position as the panels were subsequently pressed.

Figure 3: Inserting the thermocouples into the panel

2.1.3 Test configurations

A total of two different test configurations with different modifications were carried out. In test configuration 1 (tension tests at elevated temperatures), the test specimens were heated to the target temperature level in an oven before testing. After they reached the temperature they were clamped into the testing machine. A displacement-controlled tensile load of 2.5 mm/min or 5 mm/min was applied until the test specimens failed. The relatively high speed was selected in order to keep the influence of the cooling of the test specimens as low as possible. The test speed was reduced after the heated test specimens with a glue line thickness of 3.0 mm had failed almost immediately after the load was applied (see also Appendix A.3). In each case, the longitudinal deformation was recorded using the universal testing machine from Zwick. The maximum tensile load up to failure of the test specimen and the percentage of fractured wood fibers per test specimen (estimated in 10% steps) were measured.

Three glue line thicknesses (0.1 mm; 1.0 mm; 3.0 mm) are tested. In the tension tests at elevated temperatures the specimens are tested at 20 °C for reference. For the tests with temperature load the test specimens are heated to the four temperature levels of 60 °C (according to EN 1995-1-1), 70 °C and 90 °C (according to EN 301) and 110 °C. At the temperature level of 90 °C, the extent to which the heating time affects the strength of the glue line was also assessed. Here, a distinction was made between a slow (90_s: 65 minutes until 90 °C was reached) and a fast heating period (90_f: 10 minutes until 90 °C was reached). [1, 2]

With the slow heating, a tempering effect was observed for both adhesives, resulting in post-curing of the adhesive. For this reason, three further test series were carried out at 70 °C with a glue line thickness of 1.0 mm, in which the test specimens were kept at this temperature for 30 min, 60 min or 120 min after reaching the target temperature level, before the mechanical load was applied (70_30, 70_60, 70_120). The spare specimens were finally used at the 40°C temperature level. However, since only about three test specimens per temperature level were used here, they are not considered representative.

A slight brownish discoloration could be detected from the temperature level of 70 °C and higher within the outer edge areas of the bondline. In addition, a slight gap formed at the test specimen ends (see Figure 4). These only occurred with Adhesive 1. This was not observed with the larger glue line thicknesses in the middle of the test specimens. However, it is assumed that the discoloration did not affect the measurement results, since the affected areas were clamped in the clamping jaws of the testing device and did not have to transfer any loads.

Figure 4: Discoloration of the adhesive and splitting of the glue line at the two ends of the test specimen for Adhesive 1

Table 1 shows an overview of the carried-out tension tests at elevated temperatures. The number of specimens is less than 10 if statistical outliers have been sorted out or the specimens have broken during installation (see also Appendix A.3).

Even before the actual series of tests was carried out, four test specimens of each of the three glue line thicknesses with glued in thermocouples were placed in the thermo ovens and heated to the target temperature levels. The ovens were preheated to the respective temperature level in advance. The time required for the target temperature to be measured in the glue line was measured with the thermocouples. The heating time was determined on the basis of the test specimen which needed the longest time to reach the target temperature and was extended by an additional minute so that the target temperature in the joint was reached with a high degree of probability (see also Appendix A.4). It is noticeable that the glue line thickness of 3.0 mm takes on average a longer time to reach the same temperature level as the smaller glue line thicknesses.

The test specimens with thermocouples were also heated up parallel to the normal test procedure in order to measure and check if there are changes in the glue line temperature.

Table 1: Test configuration 1 of the tension tests at elevated temperatures

		Adhesive 1		Adhesive 2	
Temp.	Glue line [mm]	Number of specimens	loading speed [mm/min]	Number of specimens	loading speed [mm/min]
20	0.1	10	5	10	5
	1.0	9	5	9	5
	3.0	10	5	10	5
40	0.1	-	2.5	3	2.5
	1.0	4	2.5	4	2.5
	3.0	3	2.5	3	2.5
60	0.1	10	5	10	5
	1.0	9	5	10	5
	3.0	10	5	9	5
70	0.1	5	2.5 & 5	10	2.5
	1.0	9	2.5	8	2.5
	3.0	10	5	10	2.5
70_30	1.0	10	2.5	10	2.5
70_60	1.0	10	2.5	9	2.5
70_120	1.0	9	2.5	9	2.5
90_s*	0.1	9	2.5	10	2.5
	1.0	10	2.5	10	2.5
	3.0	10	2.5	8	2.5
90_f*	0.1	8	2.5	10	2.5
	1.0	10	2.5	10	2.5
	3.0	9	2.5	9	2.5
110	0.1	9	2.5	9	2.5
	1.0	8	2.5	10	2.5
	3.0	10	2.5	10	2.5

* s – slow, f – fast

In test configuration 2 (creep tests under temperature load), the test specimens were clamped into the testing machine and subjected to a constant mechanical tensile load (derived from test configuration 1 at 20 °C) using a universal testing machine. The thermo box which was built into the test rig was heated to a temperature of 110 °C beforehand. Cooling down to room temperature and heating up the thermo box again for each testing process was not considered practicable due to the high time and additional effort, since a maximum of three test specimens could have been tested per day under these conditions. The load level was set at 40 % or 60 % of the maximum load from the reference tests. Due to the fast failure before the load level was reached for the test specimens with a 3.0 mm glue line with Adhesive 1 under a load of 0.6 F_{max}, a new load level of 20 % was considered for this reason in this test scenario.

In addition to the longitudinal deformation, the temperature in the glue line and the tensile load were recorded. The proportion of fractured wood fibers (visually in 10% increments) was noted. The setup of the tests is shown in Table 2.

Table 2: Test configuration of the creep tests under temperature load

		Adhesive 1		Adhesive 2	
Temp. [°C]	Glue line [mm]	Number of specimens	Load	Number of specimens	Load
110	0.1	8	0.4 F_{max}	10	0.4 F_{max}
	1.0	8	0.4 F_{max}	10	0.4 F_{max}
	3.0	10	0.4 F_{max}	10	0.4 F_{max}
	0.1	3	0.6 F_{max}	8	0.6 F_{max}
	1.0	10	0.6 F_{max}	9	0.6 F_{max}
	3.0	10	0.2 F_{max}	8	0.6 F_{max}
130	1.0	10	0.4 F_{max}	10	0.4 F_{max}

The internal stresses that occur due to changes in humidity when the test specimens are heated and the associated restricted swelling and shrinkage processes were not considered in this study, although they can influence the internal stresses during the test. The deformation due to thermal expansion of the materials was also not analyzed.

2.1.4 Testing equipment and testing procedure

To heat up the test specimens in test configuration 1, two thermal ovens were used. Thermal oven 1 has a high level of air circulation and can therefore bring the test specimens to the target temperature more quickly, but only reaches temperatures of 70 °C. The test specimens with the temperature levels of 60 °C and 70 °C were therefore heated in thermal oven 1.

Thermal oven 2 was used for the other test scenarios with higher target temperatures. In order to shorten the heating time for the variant with 90 °C target temperature and faster heating, thermal oven 2 was set to a higher temperature of 120 °C.

Thermocouples were not attached to the test specimens during the test, as they weaken the adhesive surface and can therefore distort the tensile strength results. As already described, before the tests in configuration 1, the test specimens with glued in thermocouples of all three glue line thicknesses were placed in the two thermal ovens and the heating times for reaching the respective temperature level were recorded. The heating times for the individual temperature levels were determined on the basis of the heating times obtained from these pretests (see Appendix A.4).

In order to prevent a drop in temperature in the glue line in the period which is needed to clamp the specimens in the testing machine, the specimens were thermally insulated after the removal from the thermal oven. In addition, a heating box was installed in the testing machine, which was preheated to the same target temperature in each testing scenario (see Figure 5). Due to these actions, it could be determined that even at the highest temperature level of 110 °C, there was only a maximum drop of 3 °C in the glue line after the installation of the test specimen.

An influence of the wrapping of the test specimens with the insulating material on the shear strength due to frictional forces could not be determined.

Figure 5: Built-in thermal box in test facility

The test specimens of test configuration 2 were heated by the thermal box built into the testing gig. Depending on the scenario, the applied temperature was 110 °C or 130 °C. The air temperature in the thermal box was measured using a sheathed thermocouple in the middle of the oven just in front of the specimen at the same level of the glue line. However, the temperature in the glue line was not measured in the clamped test specimen, but by an unloaded test specimen with a type K thermocouple at the same height behind the clamping device, to not weaken the glue line (see Figure 6). The temperature differences that occurred (on average 7 °C) at the two measuring points were recorded in advance with unloaded samples clamped in the testing machine and considered in the evaluation.

The test specimens were installed in the heated testing machine. The target tensile load was then applied until the test specimen failed due to the effects of temperature.

Figure 6: Temperature measurement of the glue line behind the clamping device during the creep tests under temperature load and air temperature measurement next to the clamping with a sheathed thermocouple

The test was carried out using a Zwick universal testing machine. A thermal box was installed in the testing machine in order to maintain the test specimen temperature in the case of test configuration 1 or to warm up the test specimen in the case of test configuration 2. The heating was convective. The supplied hot air was transferred to the thermal box by means of a blower type MD10 from Herz. A flow heater PH62 from Herz was connected behind the blower, which heated the supplied air flow to the necessary temperature. The air flow was in a closed circuit and the exhaust air from the thermal box was returned to the fan inlet. The temperature in the heater was controlled by the digital temperature controller E.T.R. 4824 from Herz. It is automatically readjusted based on the air temperature in the supplied air flow.

The frequency of the blower could be adjusted with the low-voltage converter Commander C200 from Control Techniques. This was set to 45 Hz in the tests to ensure a large volume flow. With a maximum frequency of 50 Hz, a volume flow of up to 4.9 m^3 can be generated by the fan.

The temperature was measured using sheathed thermocouples to measure the air temperature and thermocouples of type K for the glue line. The thermocouples were connected via a measuring module to the multi-channel data logger midiLogger GL840 from Graphtec or via a temperature measuring device K204 from VOLTCRAFT. The data could be retrieved in real time.

3 Results of test configuration 1

3.1 Strength

3.1.1 Shear strength

The maximum shear strength achieved in the tests was determined using the following formula:

$$\tau = \frac{F_{max}}{a \cdot b} = \frac{F_{max}}{A} \quad (1)$$

with:

τ	Shear strength in N/mm²
F_{max}	Maximum load in N
a, b	Dimensions of the shearing surface in mm
A	Shear area in mm²

A shear area of 200 mm² was used in the calculation.

First of all, the reference tests were carried out in a normal climate (20 °C, 65 % RH) in order to get results about the load-bearing behavior of the two adhesives and the influence of the glue line thickness. It could be determined that Adhesive 1 with small glue line thicknesses of 0.1 mm and 1.0 mm has a load-bearing capacity that is almost 20 % higher than the comparable Adhesive 2 (see Table 3). With higher glue line thicknesses of 3.0 mm, on the other hand, this effect was no longer present. The increase in glue line thickness from 1.0 mm to 3.0 mm reveals a drop in shear strength of almost 40 %. One reason for this is probably an additional stress on the glue line due to a torsional moment. As can be seen in Figure 7, this creates an additional force due to an eccentricity e and the tensional force F. The bending caused by this moment causes additional transverse stresses. Since this moment depends on the glue line thickness t (increases with increasing glue line thickness), a large glue line thickness has a negative effect on the load-bearing capacity of this test configuration and cannot be transferred to the load-bearing behavior of glued in rods. This thesis is also supported by the high wood fiber fraction, which does not occur in the smaller glue line thicknesses (see also 4.3 Wood fiber fraction).

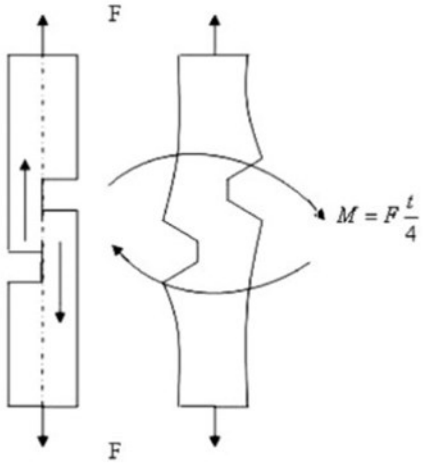


Figure 7: Additional moment from test configuration with increasing glue line thickness [3]

In addition to the heating times of the individual tests, Table 3 also shows the average shear strength achieved in N/mm² and the relative standard deviation in %. Overall, the scattering of the strength for all glue line thicknesses and temperature levels was higher for Adhesive 1 than for Adhesive 2.

Table 3: Average shear strength of the tension tests at elevated temperatures

T [°C]	time [min]		τ [N/mm²]	Adhesive 1			Adhesive 2		
	0.1mm; 1.0mm	3.0 mm		0.1 mm	1.0 mm	3.0 mm	0.1 mm	1.0 mm	3.0 mm
20	-	-	$\bar{\tau}$	12.67	11.10	6.37	10.45	9.63	6.75
			s_τ	25%	8%	18%	16%	10%	10%
40	6'00''	6'00''	$\bar{\tau}$	-	8.24	6.22	10.90	7.33	5.60
			s_τ	-	14%	4%	4%	18%	14%
60	5'20''	6'00''	$\bar{\tau}$	7.78	8.81	3.64	8.62	8.45	5.42
			s_τ	37%	13%	20 %	19%	21%	1%
70	6'30''	7'30''	$\bar{\tau}$	5.37	3.56	2.00	8.05	7.54	4.67
			s_τ	28%	32%	17%	18%	11%	9%
70_30	6'30'' + 30'	7'30'' + 30'	$\bar{\tau}$	-	7.33	-	-	6.94	-
			s_τ	-	22%	-	-	19%	-
70_60	6'30'' + 60'	7'30'' + 60'	$\bar{\tau}$	-	7.36	-	-	7.24	-
			s_τ	-	25%	-	-	7%	-
70_120	6'30'' + 120'	7'30'' + 120'	$\bar{\tau}$	-	8.38	-	-	7.52	-
			s_τ	-	15%	-	-	20 %	-
90_s	65'	65'	$\bar{\tau}$	9.32	5.46	2.84	10.24	8.26	4.72
			s_τ	34%	30%	24%	12%	12%	6%
90_f	10'	12'	$\bar{\tau}$	3.75	1.74	1.31	7.08	5.34	3.13

			s_τ	40 %	49%	11%	14%	18%	6%
110	70'	70'	$\bar{\tau}$	4.21	2.49	1.45	7.67	6.15	2.86
			s_τ	55%	24%	16%	13%	14%	17%

Figure 8 shows the boxplots of the carried out tension tests at elevated temperatures. The values sorted out using the statistical outlier method are no longer included in these. Values that are 1.5 times outside the interval of the lower and upper quartile (75% - 25% quartile) were eliminated. The different temperature profiles are indicated on the horizontal axis. The shear strengths are displayed on the y-axis. The diagrams show that Adhesive 1 achieves a somewhat higher average strength than Adhesive 2 in the reference tests. This is approximately 20 % higher for a glue line thickness of 0.1 mm and approx. 15% for a glue line thickness of 1.0 mm. This is not the case with a glue line thickness of 3.0 mm. However, due to the load situation, this must be viewed in a differentiated manner and, with the changed load-bearing behavior, confirms to the previously described problem of the additional moment load.

For Adhesive 1 with a glue line thickness of 0.1 mm, a high reduction in shear strength can already be seen at 60° C., which decreases further as the temperature level rises. The very low values for the temperature level of 40 °C presumably represent an error in the test specimens, since the drop is atypical and is below the determined values of 60 °C. The test with a temperature level of 90 °C with slow heating of the test specimen shows an increase in shear strength compared to the test with fast heating. A post-curing effect is considered to be the reason for this. This is due to the tempering of the adhesive. The heating of the test specimens in the thermal oven for the temperature levels 90 °C and 110 °C took about an hour. If adhesives cure at room temperature, subsequent temperature exposure can lead to a post-curing effect, which increases the degree of crosslinking and the glass transition temperature. Post-curing at temperatures of around 70°C is possible, especially with 2K-EP adhesives, since the OH-groups of the epoxy component do not yet take part in the reactions leading to higher crosslinking at room temperature. The same effect is evident for the 1.0 mm glue line.

In the tests at a temperature level of 70 °C with subsequent storage of the test specimens in a thermal oven for 30, 60 and 120 minutes, post-curing is also observed. The longer the storage period, the higher the shear strength. It can be deduced that the crosslinking process is not completely completed after cold curing.

A non-significant increase in shear strength can be seen at 110 °C. This is probably due to the long heating time of 70 minutes, which resulted in a slight post-curing effect compared to the tests with faster heating and a temperature of 90 °C. However, since the increase in strength is only slight, it is assumed that the decomposition of the adhesive already takes place in this temperature range and post-curing plays only a minor role or has no major effect on the increase in strength.

With a glue line thickness of 3.0 mm, a decrease in shear strength with increasing temperature can be seen despite the unfavorable load situation. A slight increase can be seen in the slow heating for the temperature level 90 °C, which also speaks for a tempering effect here.

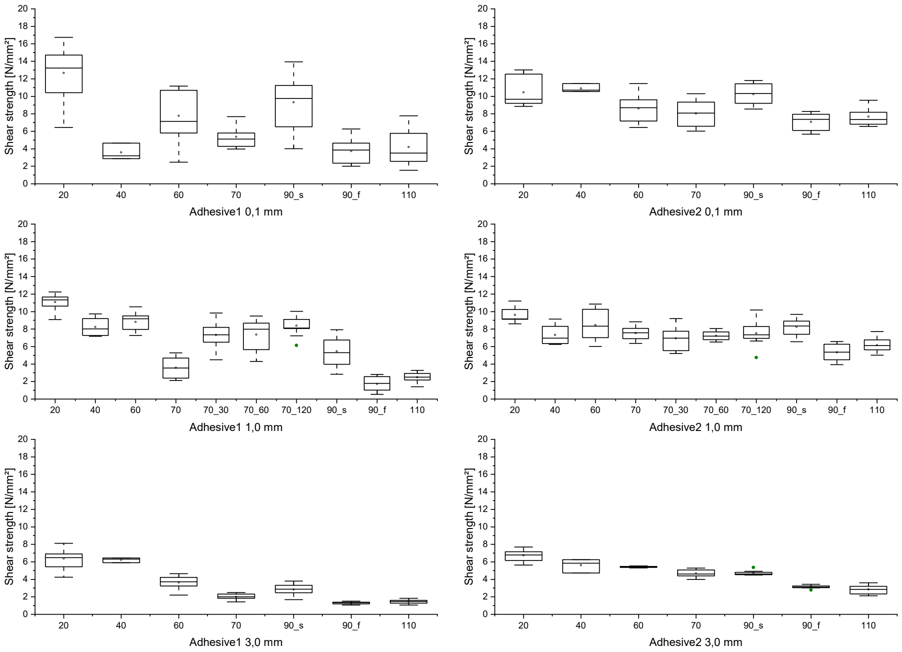


Figure 8: Shear strength of the tests within the tension tests at elevated temperatures

For Adhesive 2, a reduction in shear strength for 60 °C can also be seen for all three glue line thicknesses. However, this is not as strong as for Adhesive 1. The overall decrease in strength in the case of 110 °C is also lower than for Adhesive 1.

With slow heating to 90 °C, a slight increase in shear strength can be seen for the glue line thicknesses of 0.1 mm and 1.0 mm. However, this post-curing is not as significant as with Adhesive 1. In contrast, the test specimens at a temperature level of 70 °C show no considerable increase in shear strength when stored in the thermal oven. A slight increase can only be seen after a storage period of 120 minutes. For this reason, it is assumed that Adhesive 2 requires higher temperatures to get a post-curing effect.

3.1.2 Failure load ratio

Based on the shear strengths shown in Table 3, the percentage decrease in the failure load was determined as a function of the temperature based on the reference tests at 20 °C. The temperature levels are listed on the x-axis in the following figures. The different glue line thicknesses are represented by the different colored graphs.

For Adhesive 1 (blue) it can be seen in Figure 9 that at 60 °C there is already a strong reduction in the failure load. At 70 °C for a glue line thickness of 0.1 mm it is only approx. 35% compared to room temperature. For the two thicker glue lines of 1.0 mm and 3.0 mm, there is even a greater drop in the load-bearing capacity. In the area marked red at the temperature level of 90 °C, an increase in the average failure load for the glue line thicknesses of 0.1 mm and 1.0 mm can be seen. For the temperature level of 110°C, there is no longer a considerable increased failure load, which is why it is assumed that the decomposition of the adhesive components begins in this temperature range, so that the effect of tempering cannot lead to an increase in strength or is no longer decisive.

Adhesive 2 (green) also shows a reduction in the failure load for the two temperature levels 60 °C and 70 °C, but this is not as high as for Adhesive 1 and is between approx. 20 % and 25% for all three glue line thicknesses. A tempering effect during slow heating at 90 °C can also be seen. This effect is not as pronounced as for Adhesive 1. However, it should be noted that the test specimens with a glue line thickness of 0.1 mm have almost the same strength as at room temperature and there is no weakening. At 110 °C, there was no increase in strength despite a comparatively longer heating time. Rather, a decrease in the load-bearing strength can be seen, which means that the adhesive decomposes in this temperature range and no increase in strength through tempering is possible.

With both adhesives, the decrease in strength is comparatively smallest at a glue line thickness of 0.1 mm. With the tempering effect, on the other hand, the increase in strength is greatest.

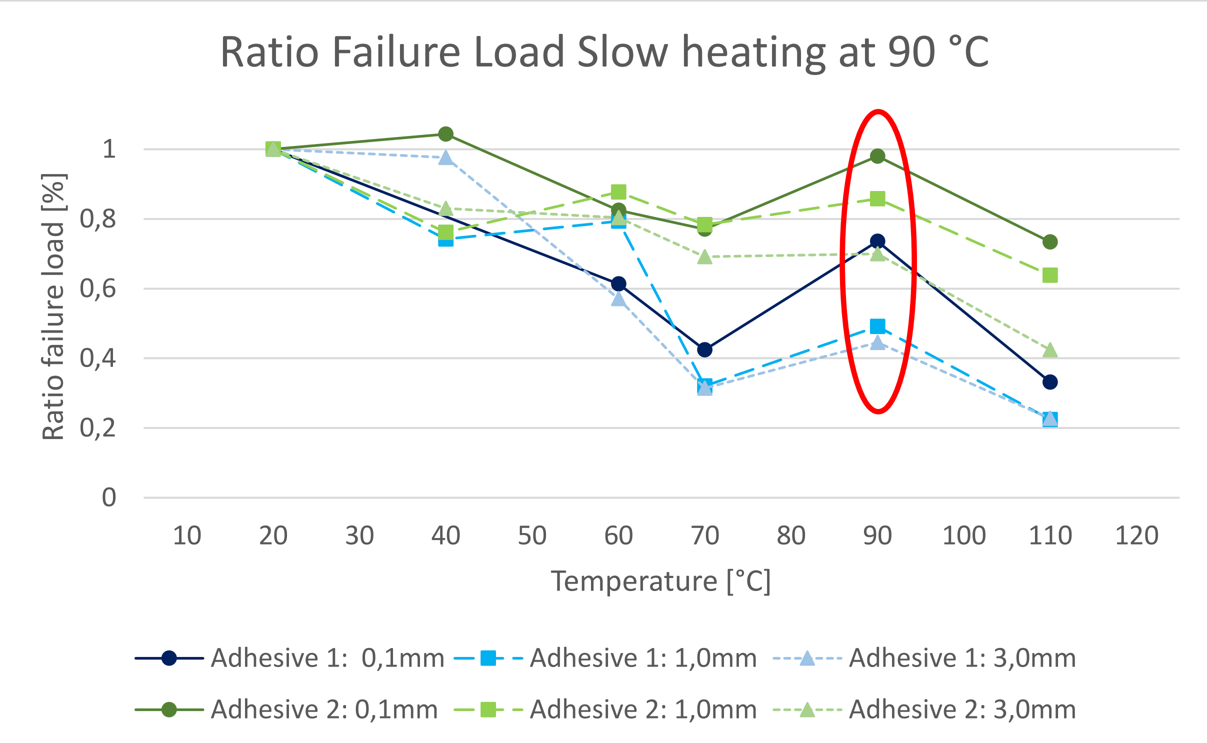


Figure 9: Proportional strength in relation to reference tests with slow heating

Figure 10 shows the decrease in the failure load of the same test configurations. Only the values for the temperature level at 90 °C were exchanged for the test results with faster heating of the test specimens. In this case the heating to reach the temperature was 10 minutes instead of 65 minutes.

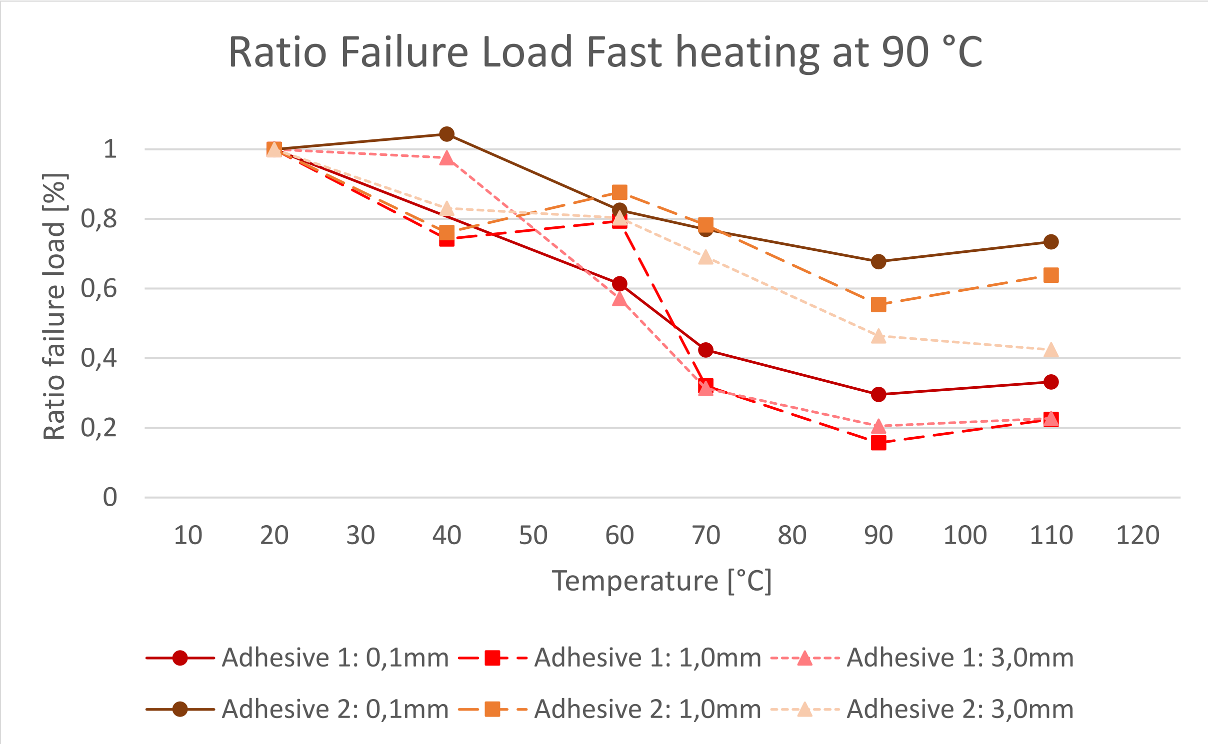


Figure 10: Proportional strength in relation to reference tests with fast heating

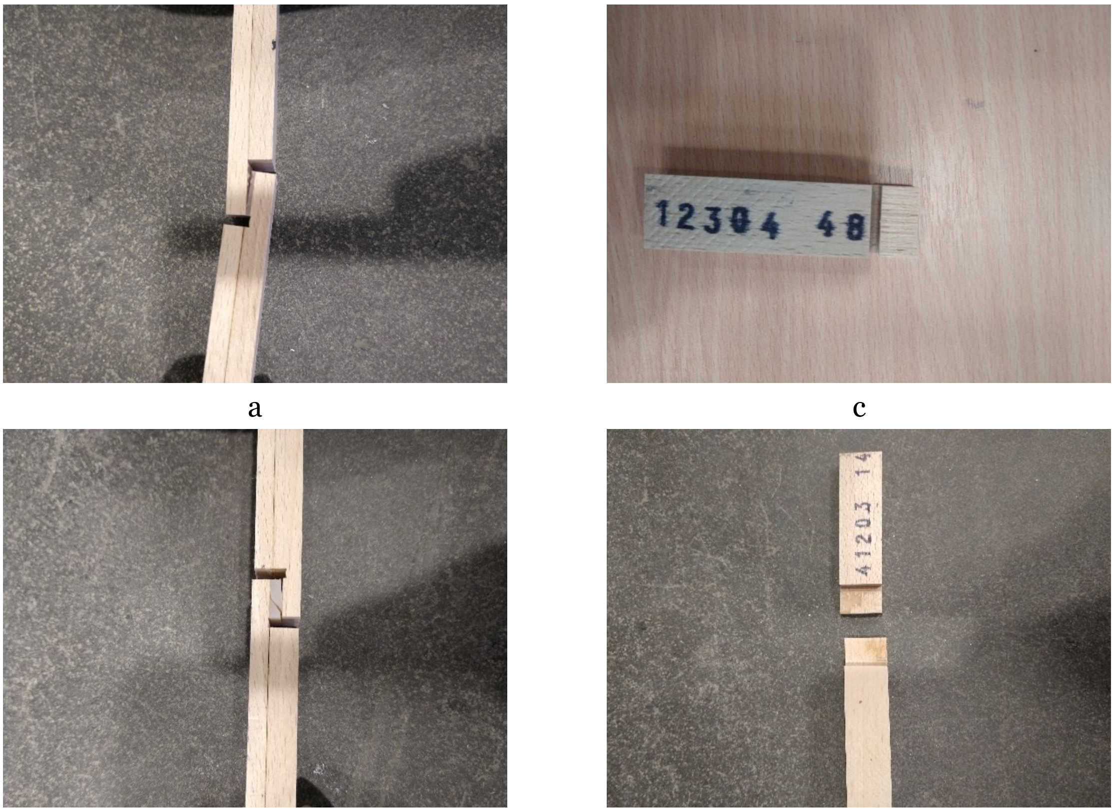
It becomes clear that with fast heating there is no tempering effect for both adhesives. The failure load decreases to a value between 20 % and 35% for Adhesive 1 and 50% - 70% for Adhesive 2 (depending on the glue line thickness) compared to the original strength at room temperature.

Overall, the drop for Adhesive 2 is not as great as for Adhesive 1. In comparison, for a glue line thickness of 1.0 mm, which is typical for threaded rods, Adhesive 1 at a temperature level of 110 °C only achieves approx. 20 % of the failure load at room temperature, while Adhesive 2 has a high residual strength of approx. 70% to its reference value. It's visible that fast heating of the adhesive leads to a high decrease in strength. The occurrence of post-curing effects in the event of a fire can therefore generally be ruled out due to the high temperatures and steep temperature gradients. However, there is a possibility to post-treat adhesive joints to increase the load-bearing capacity, glass transition temperature and the resistance to higher temperatures beforehand.

3.2 Modes of failure

After the tests had been carried out, the type of failure of the test specimens was determined. A distinction was made between six modifications (see also Figure 11):

- Adhesive failure (a)
- Cohesive failure (b)
- Wood failure (c)
- Mixed failure as soon as one type of failure covered more than 20 % of the fracture surface
    - Mixed failure mode from adhesive and cohesive failure (a-b)
    - Mixed failure mode from adhesive and wood failure (a-c)
    - Mixed failure mode from cohesive and wood failure(b-c)



a c

a-b a-c

Figure 11: Failure modes of the specimens

Furthermore, test specimens with a large proportion of bubbles (occurred more frequently with thick glue line thicknesses and with Adhesive 1, as it is more viscous during processing) were examined (see Figure 12). The maximum failure load and the corresponding fracture figure were considered. If it could be assumed that the bubble had a negative impact on the failure load, the test specimens were sorted out and not included in the analysis.

In the case of Adhesive 2, it is assumed that the more liquid viscosity during processing prevents the formation of bubbles.

Some test specimens did not show complete separation of the bonded surfaces at failure. For these, the failure load and the resulting strengths were included in the analysis. A subsequent, manual separation of the specimen can lead to falsifications in the result, since a different load is applied. Therefore, these results were not used in the evaluation of the failure type or the proportion of wood fiber fraction.

Figure 12: Bubbles in test specimens with a glue line thickness of 3.0 mm (PK 12304 48)

The failure modes determined are shown in the next diagrams. Bluish discolorations indicate failure of the adhesive and yellowish discolorations indicate failure of the wood.

With the glue line thickness of 0.1 mm, it is noticeable for Adhesive 1 that under normal climate half of the test specimens show pure wood failure and that a further 40 % show mixed failure with wood failure (see Figure 13). It can be assumed that the wood is decisive for the failure. The shear strengths determined in Chapter 3.1 do not reflect the actual shear strength of the adhesive for the majority of cases, but that of the beech wood. It is assumed that even greater load-bearing capacities could be achieved with the adhesive if a different substrate was used. The portion for wood failure decreases to approx. 10% for the target temperature of 60 °C. The proportion of pure adhesive failure, on the other hand, increases to 50%. If the temperature exceeds 70 °C, a pure cohesive failure was observed in all test specimens. The only exception here is the test at 90 °C and slow heating of the test specimen (70 minutes). A mixed fracture between wood and adhesive can be seen. It is expected that the slow heating will result in post-curing of the adhesive, which will increase its strength and glass transition temperature. Both adhesives are two-component systems in which a chemical reaction is set in motion by mixing the resin and the hardener, in which the two components react with each other. The reactive groups combine to form long and branched polymer chains. The introduction of elevated temperatures increases molecular mobility within the adhesives. Since the test specimens were bonded at room temperature (cold-curing adhesives), the monomers that have not fully reacted can be integrated into the molecular network with the remaining reactants. The degree of cross-linking of the polymer network increases, thereby increasing the strength of the adhesive.

Compared to Adhesive 2, Adhesive 1 shows primarily a cohesive failure, while Adhesive 2 largely fails due to adhesion. However, it must be considered that due to the small glue line thickness, it was difficult to clearly differentiate between the two types of failure. At a glue line thickness of 1.0 mm, Adhesive 1 only shows adhesive failure, in contrast to the lower glue line thickness. However, in the case of the 0.1 mm joint, it was decided to classify it as a cohesive fracture, since both surfaces of the fractured test specimen show discoloration at the glue line due to the application of the adhesive.

In contrast to Adhesive 1, Adhesive 2 also shows a significantly lower proportion of wood failure at room temperature. Pure adhesion failure was decisive with 60 %. This is confirmed by the evaluation of the achieved shear strengths, where on average approx. 20 % lower values were achieved than with Adhesive 1 (see also Chapter 3.1), which indicates a weaker connection between the substrates. With increasing temperature, the proportion of pure wood failure continues to decrease. However, 100% adhesive failure can only be seen at the temperature level of 110 °C. With slow heating and 90 °C as the target temperature, the proportion of wood and mixed fracture failure corresponds approximately to that in the reference tests under normal climate, which would indicate post-curing of the adhesive.

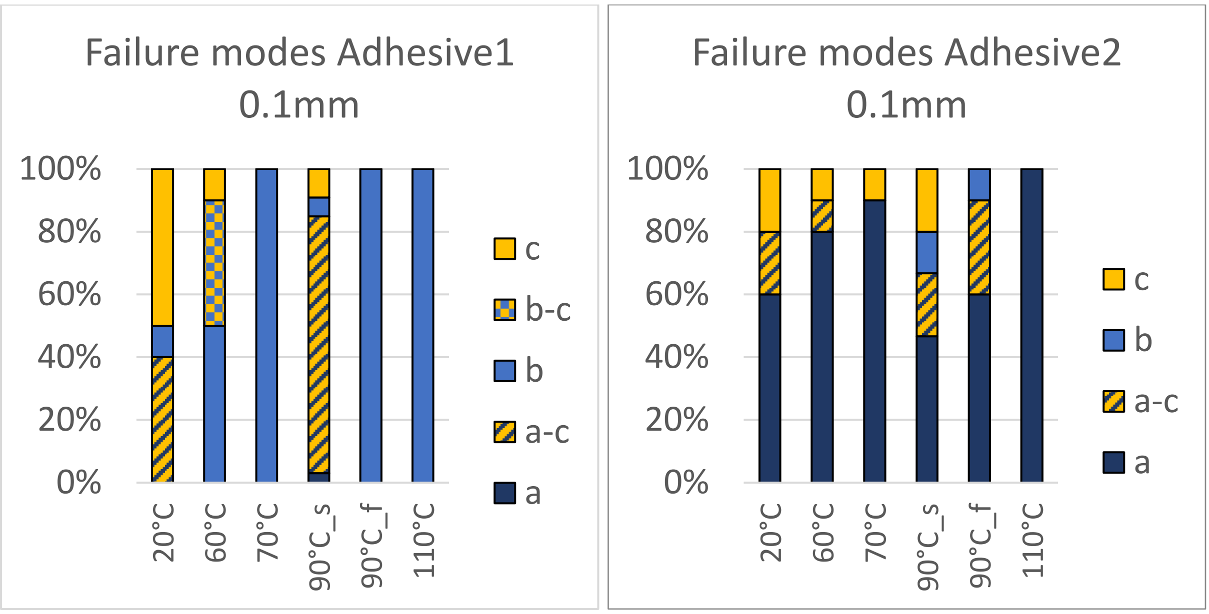


Figure 13: Failure modes for Adhesive 1 and Adhesive 2 with a 0.1 mm glue line thickness (a: adhesion, b: cohesion, c: wood)

A similar failure pattern is shown for the tests with a glue line thickness of 1.0 mm (see Figure 14). At room temperature, Adhesive 1 has a larger proportion of wood and mixed failure (approx. 90 %) than Adhesive 2 (approx. 40 %). A greater strength of Adhesive 1 at normal temperature can be assumed.

For Adhesive 1, an increase in adhesive failure is observed at a temperature of 60°C. This proportion increases to 100 % at 70 °C. A wood failure in any form no longer occurs from this temperature level onwards. Above 90 °C, the failure mode in the adhesive changes from adhesive to cohesive failure, suggesting that the internal strength of the adhesive decreases. Only in the scenarios for post-curing with either slow heating to the target temperature of 90 °C or the storage of the test specimens at 70 °C does the proportion of wood failure increase again. It can be seen that after a longer heating period, post-curing takes place. It can also be assumed that with a storage duration of 60 minutes, a large part of the post-curing process has already taken place, since almost every specimen failed in the wood.

Adhesive 2 does not exhibit pure wood failure compared to Adhesive 1 at room temperature. The shear strength is about 15 % lower than for Adhesive 1 (see Section 3.1.1). Above a target temperature of 60 °C, the adhesive is responsible for the failure of the connection in 90 % of the cases. An adhesive failure to the wood mainly occured. In contrast to the shear strength values, there are signs of post-curing of the adhesive over the longer heating period or the series of tests with storage in the thermal oven, since there is an increase in the proportion of fractured wood fibers. However, this is not as pronounced as for Adhesive 1. No significant differences in the failure behavior were determined after a storage for 120 minutes at 70 °C, from which it can be concluded that a large part of the post-curing process is also completed for Adhesive 2 after approx. 60 minutes.

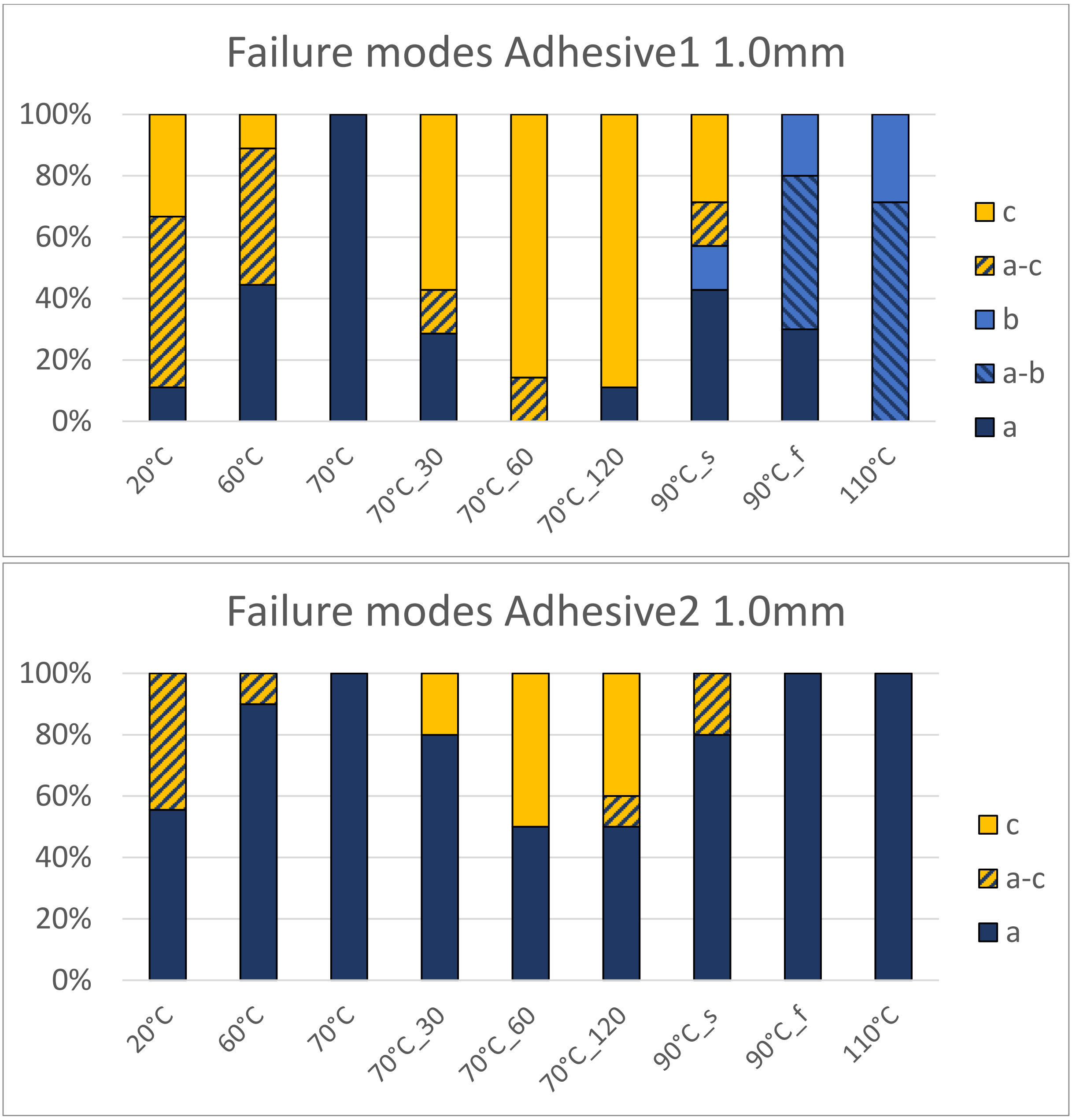


Figure 14: Type of failure of the two adhesives with a glue line thickness of 1.0 mm (a: adhesion, b: cohesion, c: wood)

With the glue line of 3.0 mm, wood failure mainly occurred for both adhesives in normal climate conditions. It is assumed that the moment load that occurs as a result of the test setup generates additional tensile forces transverse to the wood fiber direction that exceed the transverse tensile strength of the wood, which is the reason why there is no adhesive failure for Adhesive 2, in contrast to the other two glue line thicknesses (see Figure 15). Despite the increased lateral forces, the tests with Adhesive 1 show that adhesion failure of almost 80% becomes significant at a temperature level of 60 °C. At 70 °C there is 100% adhesive failure present. It is also noticeable that the proportion of cohesive failure increases with increasing temperature, which indicates a reduction in the internal strength of the adhesive. In contrast to the other glue line thicknesses, slow heating to a temperature level of 90 °C is the only test configuration that shows no increase in the proportion of wood fiber fraction.

In the case of Adhesive 2, adhesive failure only becomes relevant above a target temperature of 70 °C. At 60 °C, wood failure in the joint still occurs with almost 80%. Adhesive failure occurs in all specimens for temperatures above 90 °C. For the slow heating tests approximately 20 % of the test specimens failed in the wood area, which could indicate a post-curing effect in the adhesive.

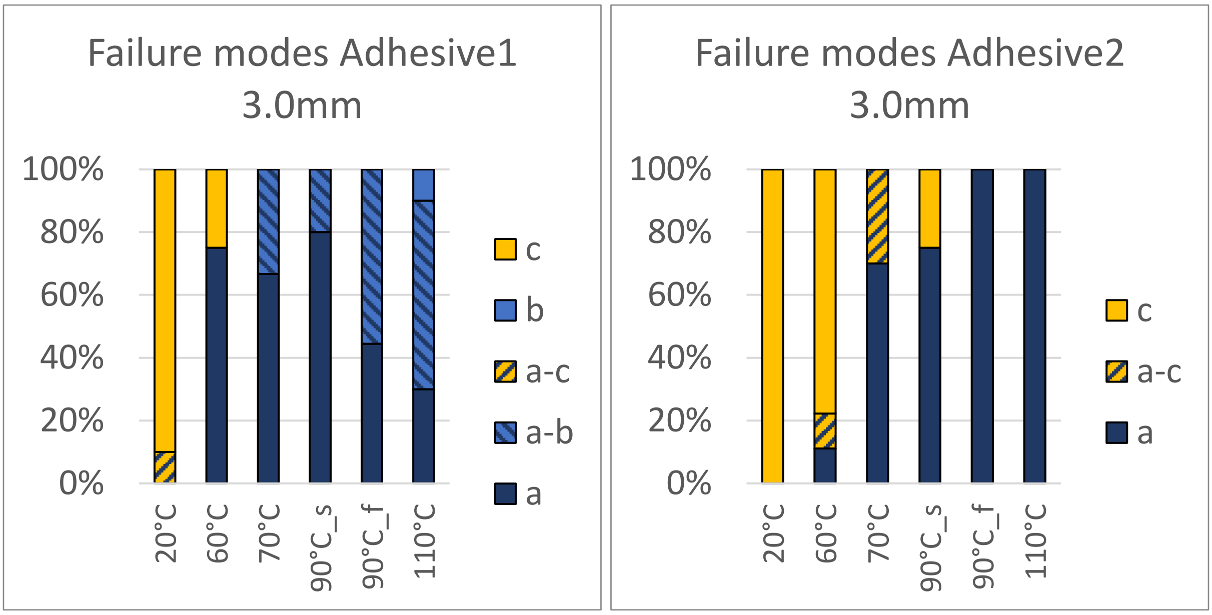


Figure 15: Type of failure of the two adhesives with a glue line thickness of 3.0 mm (a: adhesion, b: cohesion, c: wood)

3.3 Wood fiber fraction

The proportion of fractured wood fibers indicates how many wood fibers are involved in the failure of the joint. If this value is 100 %, the wood component is mainly responsible for the failure of the connection, whereas if the value equals 0 %, it can be assumed that the adhesive has failed. The proportion of fractured wood fibers was recorded visually and in 10 % steps. Figure 16 shows the average value of the wood fiber fraction for Adhesive 1 (blue) and Adhesive 2 (green) on the y-axis. The individual temperature levels are displayed on the x-axis. In addition, the standard deviation is shown.

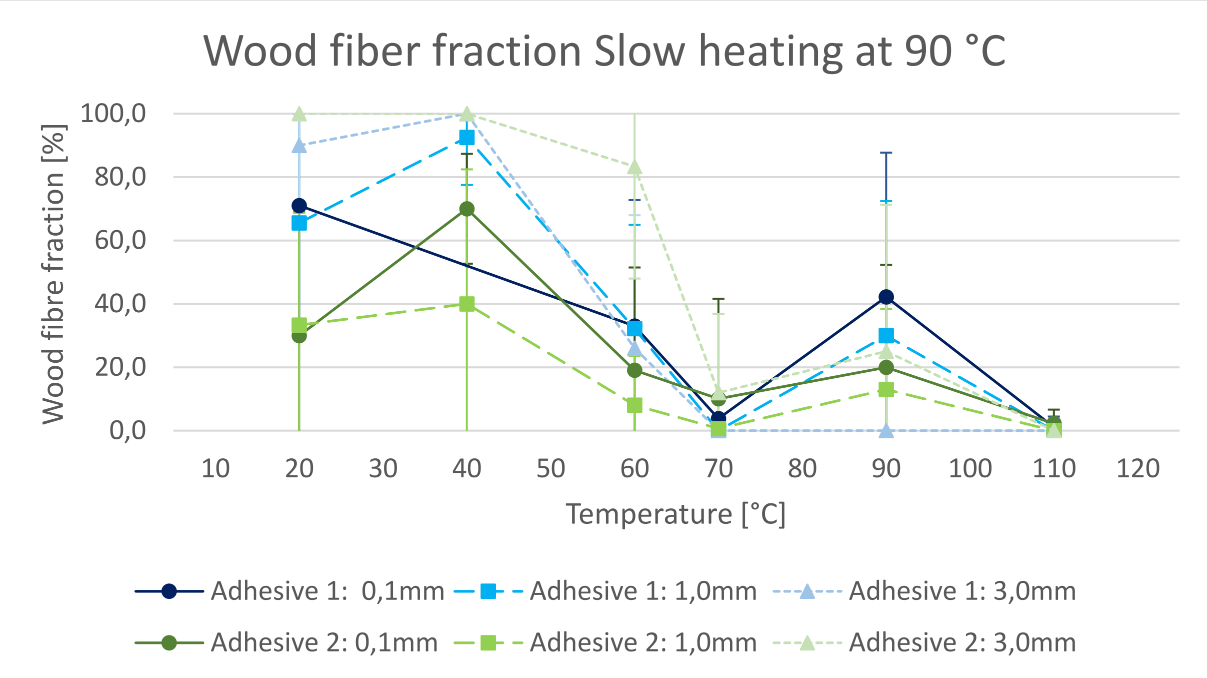


Figure 16: Wood fiber fraction for slow heating of the tension tests at elevated temperatures

For Adhesive 1, a drop in the proportion of fractured wood fibers can be seen for the higher temperature levels, which means that the adhesive is responsible for the failure. A reduction in the average wood fiber fraction below 40 % can be seen for all glue line thicknesses at a temperature of 60 °C, which speaks for a decrease in the load-bearing capacity of the adhesive. Especially at 70 °C and 110 °C only a small standard deviation can be determined. Due to the slow heating of the test specimen at the temperature level of 90°, an increase in the proportion of fractured wood fibers can be seen, which indicates the tempering of the adhesive and the associated increase in strength. At 110 °C this effect no longer occurs and the adhesive is 100% decisive for the failure of the connection for all glue line thicknesses.

With Adhesive 1 it can be seen that at a temperature of 20 °C for a glue line thickness of 3.0 mm in the majority of the test specimens the wood as the decisive component is responsible for the failure of the connection. This can be explained by the test setup and the resulting additional transverse loads, since wood has no significant load-bearing capacity perpendicular to the grain. It should also be noted that for the 3.0 mm glue line at 90 °C there is no increase in the proportion of fractured wood fibers. Therefore, it can be assumed that there was no or just an insignificant post-curing effect.

Fast heating of the test specimens at a temperature of 90 °C in the thermal oven prevents tempering and thus an increase in the proportion of fractured wood fibers for Adhesive 1 (see Figure 17).

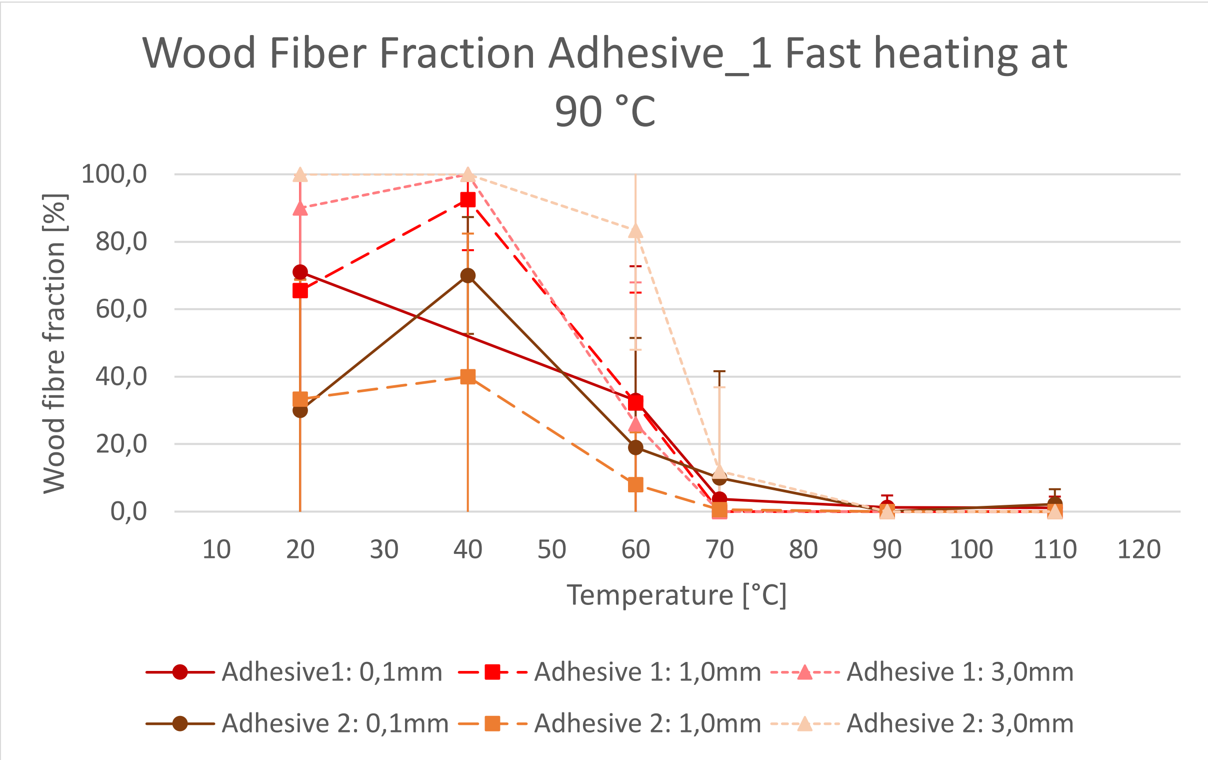


Figure 17: Wood fiber fraction for fast heating of the tension tests at elevated temperatures

A similar behavior can be observed for Adhesive 2 (see Figure 16 and Figure 17). However, the proportion of fractured wood fibers at 20 °C for glue line thicknesses of 0.1 mm and 1.0 mm is only 30 %, which speaks for a higher proportion of adhesive failure. An exception is the 3.0 mm thick glue line. At room temperature, a wood fiber fraction of 100 % is seen.

In contrast to Adhesive 1, the proportion of fractured wood fibers in the 3.0 mm thick glue line is also decisive the temperature level of 60 °C. At 90 °C there is a slight increase in the proportion of fractured wood fibers due to tempering. This value is 0% for the faster heating tests. The standard deviation from temperature level 70 °C is greater than for Adhesive 1.

Table 4 shows the average percentage of fractured wood fibers determined in the individual test series. The proportions of the individual test specimens are shown in Annex A.5.

Table 4: Wood fiber fractions in tension tests at elevated temperatures

T [°C]	**Time [min]**		**Wood fiber fraction [%]**	**Adhesive 1**			**Adhesive 2**		
	0.1mm; 1.0mm	3.0 mm		0.1 mm	1.0 mm	3.0 mm	0.1 mm	1.0 mm	3.0 mm
20	-	-	$\bar{\tau}$	71.0	65.6	90.0	30.0	33.3	100.0
			s_τ	39.3	34.3	21.1	38.9	35.4	0.0
40	6'00''	6'00''	$\bar{\tau}$	-	92.5	100.0	70.0	40.0	100.0
			s_τ	-	15.0	0.0	17.3	42.4	0.0
60	5'20''	6'00''	$\bar{\tau}$	33.0	32.2	26.0	19.0	8.0	83.3

			s_τ	39.7	32.7	42.0	32.5	15.5	35.4
70	6'30''	7'30''	$\bar{\tau}$	6.0	0.0	0.0	10.0	0.6	12.0
			s_τ	5.5	0.0	0.0	31.6	1.8	24.9
70	6'30'' + 30'	7'30'' + 30'	$\bar{\tau}$	-	45.5	-	-	22.0	-
			s_τ	-	46.6	-	-	41.3	-
70	6'30'' + 60'	7'30'' + 60'	$\bar{\tau}$	-	65.0	-	-	48.8	-
			s_τ	-	45.5	-	-	52.2	-
70	6'30'' + 120'	7'30'' + 120'	$\bar{\tau}$	-	85.6	-	-	51.1	-
			s_τ	-	28.8	-	-	45.4	-
90_s	65'	65'	$\bar{\tau}$	42.2	30.0	0.0	20.0	13.0	25.0
			s_τ	45.5	42.4	0.0	32.3	25.4	46.3
90_f	10'	12'	$\bar{\tau}$	1.3	0.0	0.0	0.0	0.0	0.0
			s_τ	3.5	0.0	0.0	0.0	0.0	0.0
110	70'	70'	$\bar{\tau}$	1.1	0.0	0.0	2.2	0.0	0.0
			s_τ	3.3	0.0	0.0	4.4	0.0	0.0

3.4 Deformation behavior

The stiffness of the connection can be deduced from the deformation behavior of the test specimens. The following diagrams show the stress-strain curves of the individual test scenarios. For better clarity, an enlarged area of the initial deformation is shown on the right-hand side. A steep curve stands for a higher stiffness of the connection, since a larger load occurs with a smaller deformation. Overall, a linear increase can be observed, which ends in a sudden failure of the connection. A complete overview of the results with all glue line thicknesses can be found in Appendix A.6. The glue line thicknesses of 0.1 mm and 3.0 mm are not described in detail in this section, but they show a similar behavior without any deviations. The associated load-deformation curves are summarized in Appendix A.7.

Figure 18 shows the stress-strain curves of the individual test specimens from Adhesive 1 with a glue line thickness of 1.0 mm. It can be seen that higher temperature levels lead to a decrease in shear strength or earlier failure. Above 70 °C in particular, a strong reduction in the achieved maximum strength can be seen. Only with the slow heating to the target temperature of 90 °C (marked yellow) there is an increase.

A similar behavior can be seen for the stiffness of the adhesives. At a temperature level of 20 °C the greatest stiffness can be observed (steepest curve). This is where the greatest shear strength is achieved with the least deformation. With increasing temperature, the maximum shear strength as well as the slope decreases continuously. At the temperature level of 90 °C with slow heating, a slight increase in stiffness can be observed due to the post-curing effect.

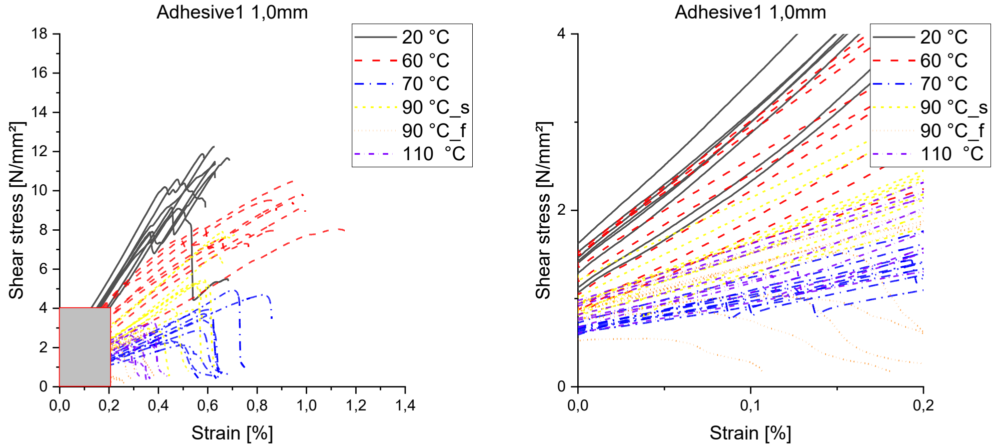


Figure 18: Stress-strain diagram of Adhesive 1 with a glue line thickness of 1.0 mm

The post-curing effect is also visible in the test specimens that have been stored in the oven for a longer period of time. Figure 19 shows that the lowest shear strength is achieved for a temperature level of 70 °C without a storage time, but with a fast heating of only six and a half minutes. The slope of the graphs is also the lowest, which speaks for a lower stiffness of the connection. The graphs also show that the length of the heating period has an impact on the stiffness development. The shear strength for a storage period of 120 minutes does not increase significantly compared to a storage period of 60 minutes. However, there is a greater slope in the graphs, which speaks for a further increase in the stiffness of the adhesive.

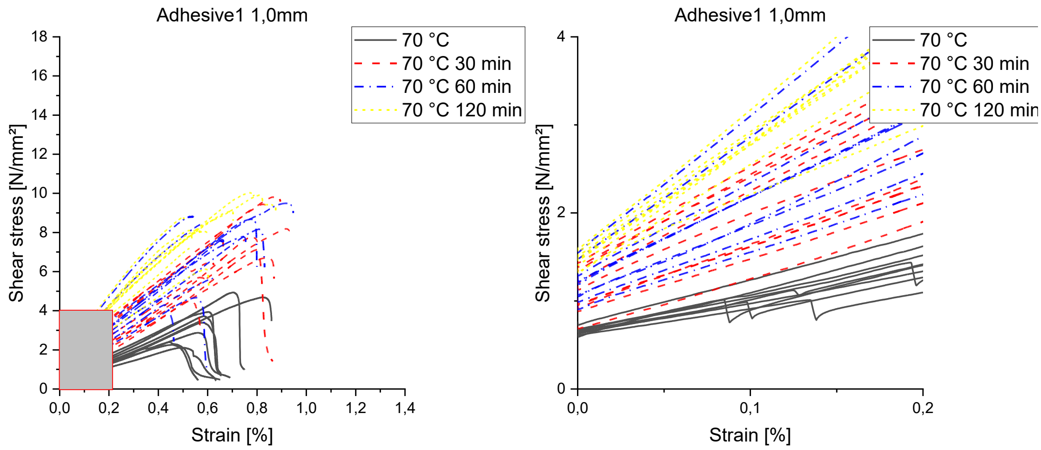


Figure 19: Stress-strain diagram of Adhesive 1 with a glue line thickness of 1.0 mm at a temperature of 70 °C

A similar behavior can be seen for Adhesive 2 (see Figure 20). With a glue line thickness of 1.0 mm, the test specimens achieve the greatest shear strength and the greatest stiffness (steepest stress-strain curves) under ambient conditions. Both values and curves decrease with increasing temperature. However, the reduction is not as great as for Adhesive 1. A post-curing effect can also be seen in the 90°C tests with slow heating, since the shear strength values slightly exceed those of the 70°C tests and a steeper slope is visible. In the tests at 110 °C, the shear stresses achieved are in some cases significantly higher than those of the 90 °C tests with a faster heating time and also show a steeper gradient. This behavior was not observed with Adhesive 1, which is why it is assumed that Adhesive 2 has a higher temperature resistance than Adhesive 1. Since the 110 °C tests also included a long heating-up period of approx. 70 minutes, it can be assumed that post-curing effects in the adhesive also occur here, resulting in increased stiffness. However, no significant increases could be detected in the failure loads or shear strengths (see 3.1.1). No increase in the percentage of wood fiber fraction was found for the types of failure either (see 3.1), so it can be assumed that post-curing effects are possible in this temperature range, but they no longer contribute to any significant increase in the load-bearing capacity of the adhesive. For this purpose, however, more detailed investigations are necessary in order to be able to deduce the optimal post-curing conditions.

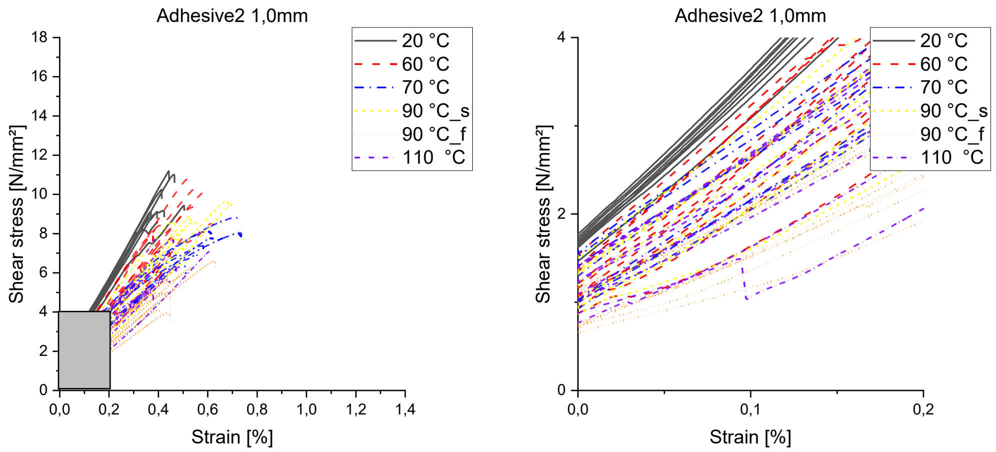


Figure 20: Stress-strain diagram of Adhesive 2 with a glue line thickness of 1.0 mm

In the case of the series of tests with longer storage times in the oven at a temperature level of 70 °C, increased stiffness can be seen for Adhesive 2 with a glue line thickness of 1.0 mm similar to Adhesive 1 (see Figure 21). However, the increase is not as high as for Adhesive 1. Overall, the stiffness increases with increasing storage time. For a storage time of 120 minutes, the greatest stiffness is achieved in comparison.

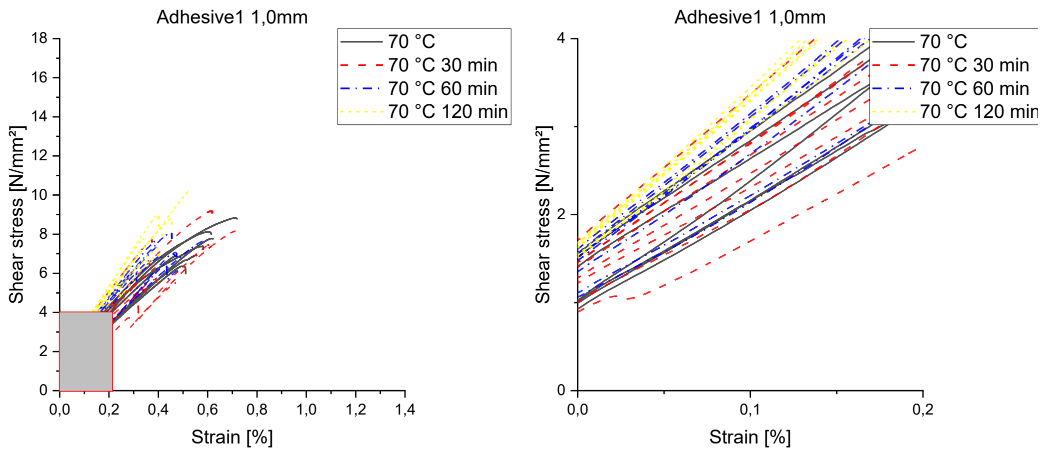


Figure 21: Stress-strain diagram of Adhesive 2 with a glue line thickness of 1.0 mm at a temperature of 70 °C

4 Results of test configuration 2

4.1 Load level

In test configuration 2, the specimens were heated under a constant mechanical tensile load within the thermo box until the specimen failed under the given load. Two load levels were assessed to examine the influence of the mechanical load on the failure behavior of the adhesives. Based on the tests of test configuration 1 under normal temperature conditions, the tensile load to be applied for the creep tests under temperature load was derived from the maximum failure loads achieved for the individual glue line thicknesses. The load was set to 40 % and 60 % of the maximum load. The corresponding values are shown in Table 5. The test report is given in Appendix B.1.

Table 5: Applied tensile load in test configuration 2

	Glue line	0.6 F_{max} [N]	0.4 F_{max} [N]	0.2 F_{max} [N]	Comparison to F_{mean}
Adhesive 1	0.1 mm	2007	1338	-	+ 30 %
	1.0 mm	1469	979	-	+ 17 %
	3.0 mm	931	621	310	+ 28 %
Adhesive 2	0.1 mm	1520	1013	-	+ 26 %
	1.0 mm	1284	856	-	+ 17 %
	3.0 mm	899	599	-	+ 14 %

In the tests with Adhesive 1 and a glue line thickness of 3.0 mm with a load of 60 % of the maximum load of the reference tests, it was determined that the test specimens failed before the target tensile load was reached. For this reason, the load for this test series was reduced to 20 % of the maximum load level. In the test series with Adhesive 1 and a glue line thickness of 0.1 mm, early failure of the test specimens also was determined for a load of 60 %, so that in many cases failure occurred just before the target load was reached. In total, there were only two attempts that reached the target load. It is assumed that the selected test conditions could be related to this cause. Since the thermal box already had a temperature of 110 °C when the test specimens were installed, they were already thermally stressed in the period from installation to the application of the mechanical load, which resulted in a certain weakening in the edge areas of the glue line. Furthermore, it's possible that the test load was set too high with the relation to the maximum load. For the two affected glue line thicknesses of 0.1 mm and 3.0 mm, the highest standard deviations of 25 % and 18 % were found in the reference tests (see also Table 3). It is therefore possible that the maximum load comes from a sample with above-average resistance and the resulting test load is too close to the mean value of the glue line strength at room temperature. The percentage of increased load that results from the comparison of the maximum loads and mean values of the test results of test configuration 1 is shown in Table 5. In this case, the combination of these two factors can lead to early failure of the test specimen before the target load is reached. These two failure patterns only occurred for Adhesive 1. It can be assumed that it has a lower thermal resistance than Adhesive 2. This failure pattern doesn't show up for Adhesive 2 with a glue line thickness of 0.1 mm, although the applied load was 26% higher than when it would have been referred to the mean values. Three tests were also run for Adhesive 2 with a load of 0.2 F_{max}. In comparison to Adhesive 1, however, no failure of the test specimens could be determined after a test duration of almost 3.5 hours. It can be assumed that the residual load-bearing capacity of Adhesive 2 is above the tested mechanical load value. Due to the long duration of the test, it is also conceivable that post-curing could have taken place in the adhesive, which increased the strength even further.

During the tests with Adhesive 2, for specimens with a glue line thickness of 1.0 mm and a load of 40 % of the maximum load, the thermocouples in the control specimens showed an error. Since it was known from control measurements from test configuration 1 that the glue line thicknesses of 0.1 mm and 1.0 mm require approximately the same heating time the corresponding temperature values were derived from the calculated mean temperature values of the tests with a glue line thickness of 0.1 mm and transferred to the test duration of the tests with 1.0 mm glue line thickness.

4.2 Failure modes

As with test configuration 1, the different types of failure that occurred in the individual test series are shown below. A differentiation was made between the six modes (see also Figure 11):

- Adhesive failure (a)
- Cohesive failure (b)
- Wood failure (c)
- Mixed failure mode from adhesive and cohesive failure (a-b)
- Mixed failure mode from adhesive and wood failure (a-c)
- Mixed failure mode from cohesive and wood failure(b-c)

For Adhesive 1, a pure cohesive failure was seen when loaded with 40 % of the reference load (see Figure 22). Differentiating the type of adhesive failure was difficult due to the small glue line thickness. However, it was determined to be a cohesive failure because both sides of the fractured specimen showed uniform discoloration due to adhesive application. In the case of Adhesive 2, there was only one-sided discoloration, which is why there was clearly a failure of adhesion to the wood surface. At the higher load of 60 % of the reference load, only mixed failures can be detected. In this series of tests, however, the target load was only achieved by two test specimens, which means that it can be assumed that the selected reference value based on the maximum load was set too high. Since both components of the connection are involved in the fraction and this takes place shortly after the target load has been reached, it is assumed that the increased mechanical load leads to a failure in the wood (wood fiber fraction percentage in test configuration 1 was 30 %) and the initial temperature load to the simultaneous weakening of the adhesive leading to a mixed fracture. Due to the small number of test specimens, however, these are not to be regarded as representative.

Even with the increased load, there is a high proportion of adhesive failure with Adhesive 2. For the higher load level, the proportion of wood failure increases to around 10%. In addition, there is another 10% with a mixed failure of adhesion and wood failure. In both tested load levels, the adhesive is still primarily responsible for the failure of the connection.

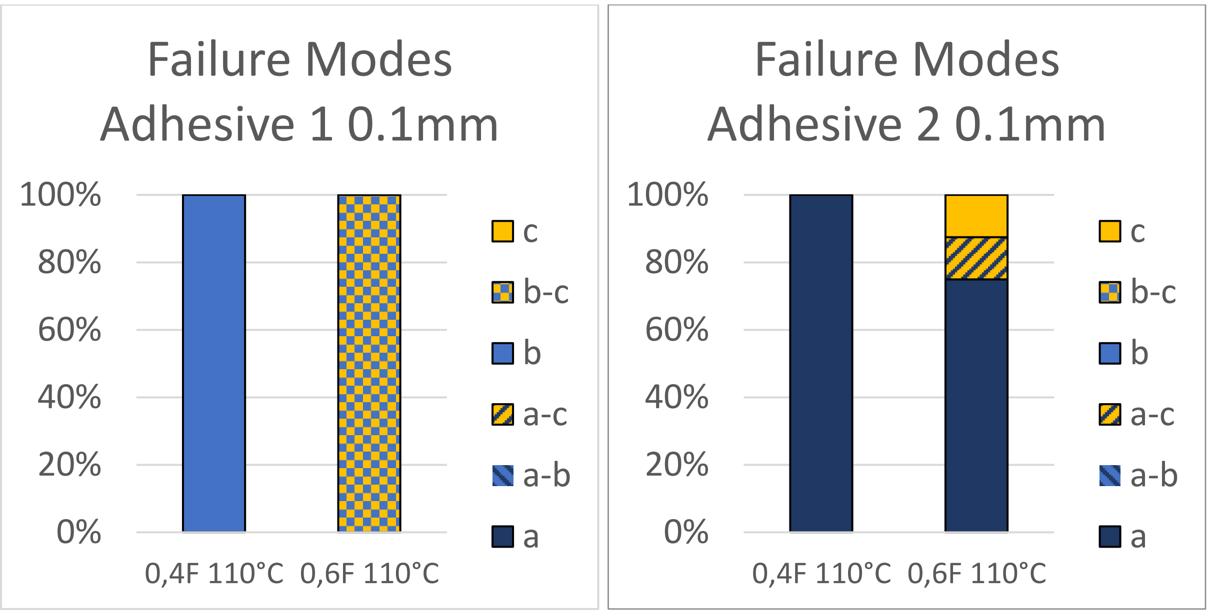


Figure 22: Types of failure for the specimens of test configuration 2 with a glue line thickness of 0.1 mm

Also, in the case of the test specimens with a glue line thickness of 1.0 mm, mainly an adhesive failure was determined for all tested variants with a changed load level or an increased temperature load of 130 °C. For Adhesive 1, the wood failure ratio only increased to approx. 10% with a higher mechanical load or a higher temperature load. Adhesive 2 shows the same result. However, at the higher temperature load of 130 °C, there is just a pure adhesion failure (see Figure 23).

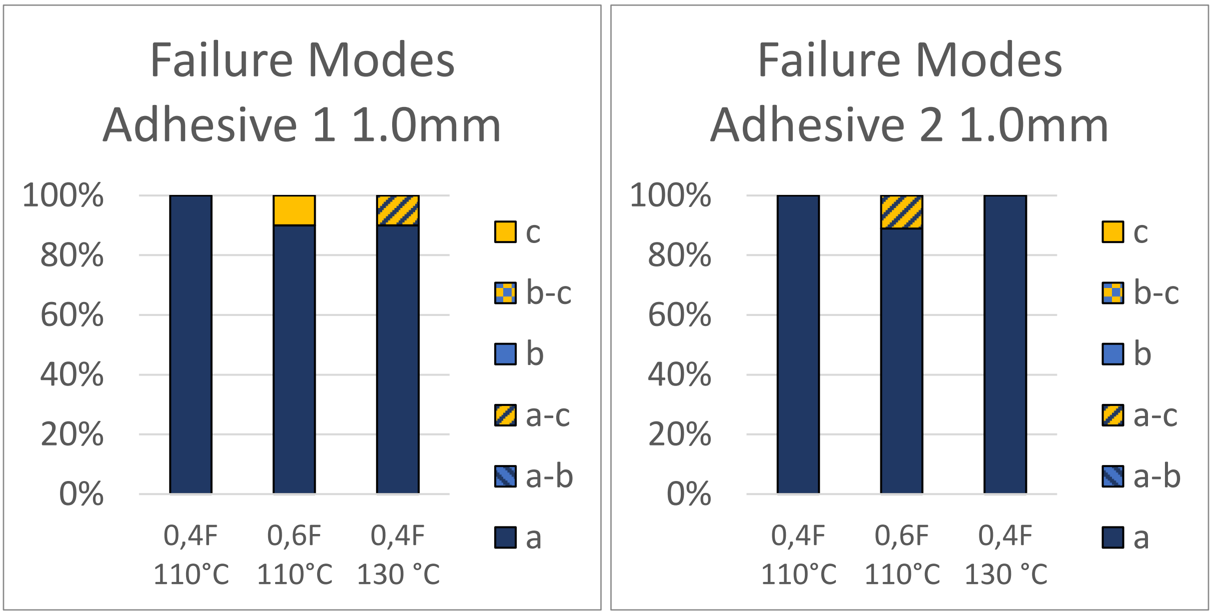


Figure 23: Types of failure for the specimens of test configuration 2 with a glue line thickness of 1.0 mm

A change in the previous failure pattern can be seen in the test specimens with a glue line thickness of 3.0 mm (see Figure 24). In the case of Adhesive 1, there is an increased proportion of approx. 30 % fractured wood at the tests with the lower load level. This behavior does not occur in the tests with the load levels of 20 % of the maximum load of the reference tests. It can be assumed that the additional transverse forces from the torsional moment leads to increased stresses perpendicular to the grain in the wooden substrate. Since wood also loses its original strength with increasing temperatures, it is therefore plausible that the increased mechanical stress also causes the wood to fail. When loaded with 20 % of the reference load for Adhesive 1, in contrast to the other test series, there is no wood fracture, but an increase in the proportion of cohesive fractures. It is therefore assumed that the load-bearing capacity of the wood exceeds the loads that are appliad mechanically.

In the case of Adhesive 2, on the other hand, pure adhesive failure occurs for the lower tensile loads. Only with a mechanical load of 60 % of the reference load does the proportion of fractured wood increase to almost 40 %. The applied tensile load was based on the maximum load reached. Adhesive 2 shows a lower deviation of 14 % compared to the mean value. Since this means that comparatively lower loads are applied than for Adhesive 1, it is possible that the strength of wood is only exceeded with the load level of 60 % of the reference load.

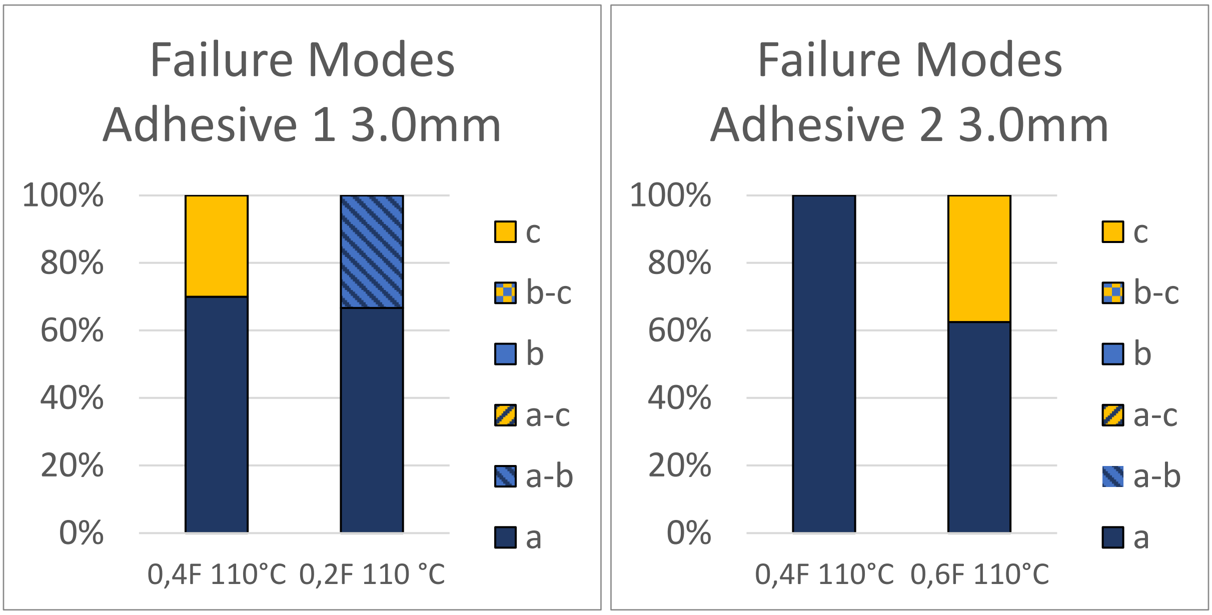


Figure 24: Types of failure for the specimens of test configuration 2 with a glue line thickness of 3.0 mm

4.3 Deformation

Deformation-time diagrams for the individual test series were created on the basis of the data from the measured machine path and the testing time until the test specimens failed.

Overall, the deformation curves can be divided into four sections (see Figure 25). The test specimens were not clamped under tension in order to enable easier and a more precise installation. For this reason, the deformation curves initially show an almost vertical rise in the graphs until the test specimen is subjected to tensile stress (Section I). After that, the curves gradually rise to a horizontal base area. During this period, the load is constantly increased to the set target load. The length of this area varies depending on the test variant, since different target loads are approached. With the constant speed of the machine, the duration is shortened the smaller the target load is (Section II). This section is followed by an almost horizontal progression of the graph. The slope increases with increasing test duration. The strength of the adhesive decreases as a result of the temperature load, which means that as the temperature rises in the glue line, the deformation increases and creep occurs (Section III). After initially only slight increases in the deformation curve, there is a significantly increase that ends in an almost vertical deformation curve (Section IV). From this point on, a critical temperature range (glass transition temperature) in the adhesive is probably exceeded. As a result, its physical state changes from a rigid, glassy state to a soft, rubbery state, severely reducing the load-bearing capacity of the adhesive, such that the applied load causes the specimens to fail.

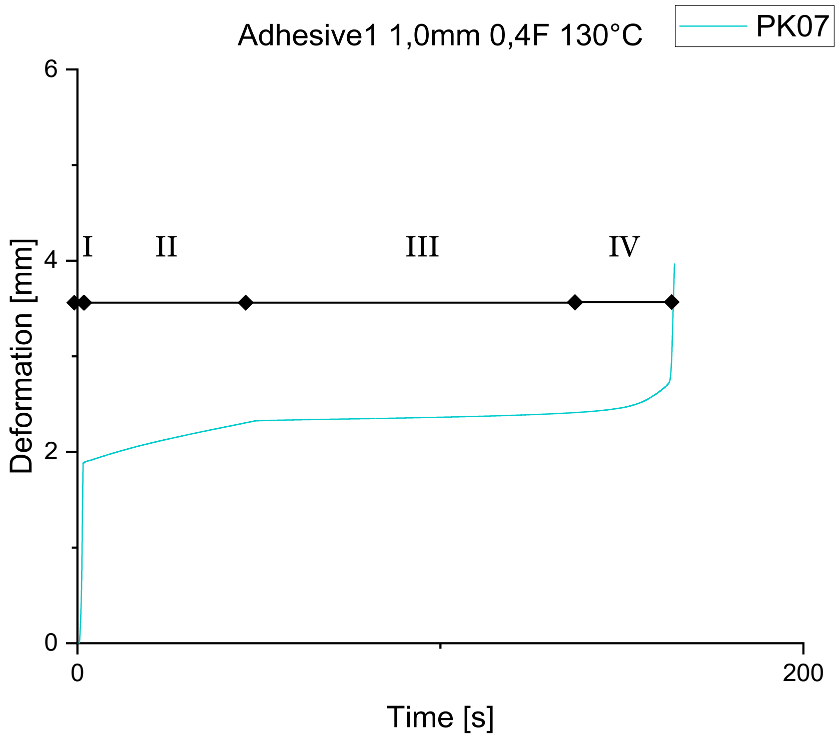


Figure 25: Exemplary deformation curve of a creep test under temperature load

The following Figure 26 shows the deformation curves for the load of 40 % of the respective maximum load of the reference tests at 20 °C. On the left are the diagrams for Adhesive 1, while on the right are the data for Adhesive 2. The x-axis reflects the testing time. However, the scaling is different for Adhesive 2, since longer test durations were required before the test specimens failed. The deformation in mm is plotted on the vertical axis. The two adhesives show a similar deformation behavior for all glue line thicknesses. In the case of Adhesive 1, the creep deformations before failure are not as great as in Adhesive 2. After the target load has been reached, almost horizontal graphs can be seen for all glue line thicknesses of Adhesive 1, which suddenly or in a very short period of time become vertical. In contrast, Adhesive 2 has longer test durations which, in agreement with the tension tests at elevated temperatures, indicate a higher failure temperature. However, from a certain point in time, a constant deformation can be seen in the graphs after the horizontal progression when the target load is reached, which does not occur with Adhesive 1. Softening takes place which does not yet lead to the test specimens failing (creep). From the tension tests at elevated temperatures it is known that the strength decrease occurs at higher temperatures than with Adhesive 1. At the same time the strength decreases to a lesser extent and at 70 °C it still has approx. 70 % - 80 % of the original strength according to test configuration 1. Therefore, it can be assumed that a softening takes place in the adhesive, which leads to a slow deformation. However, the tensile load applied is too small to cause an immediate failure. Only at higher temperatures does the residual strength decrease to such an extent that the adhesive can no longer withstand the load.

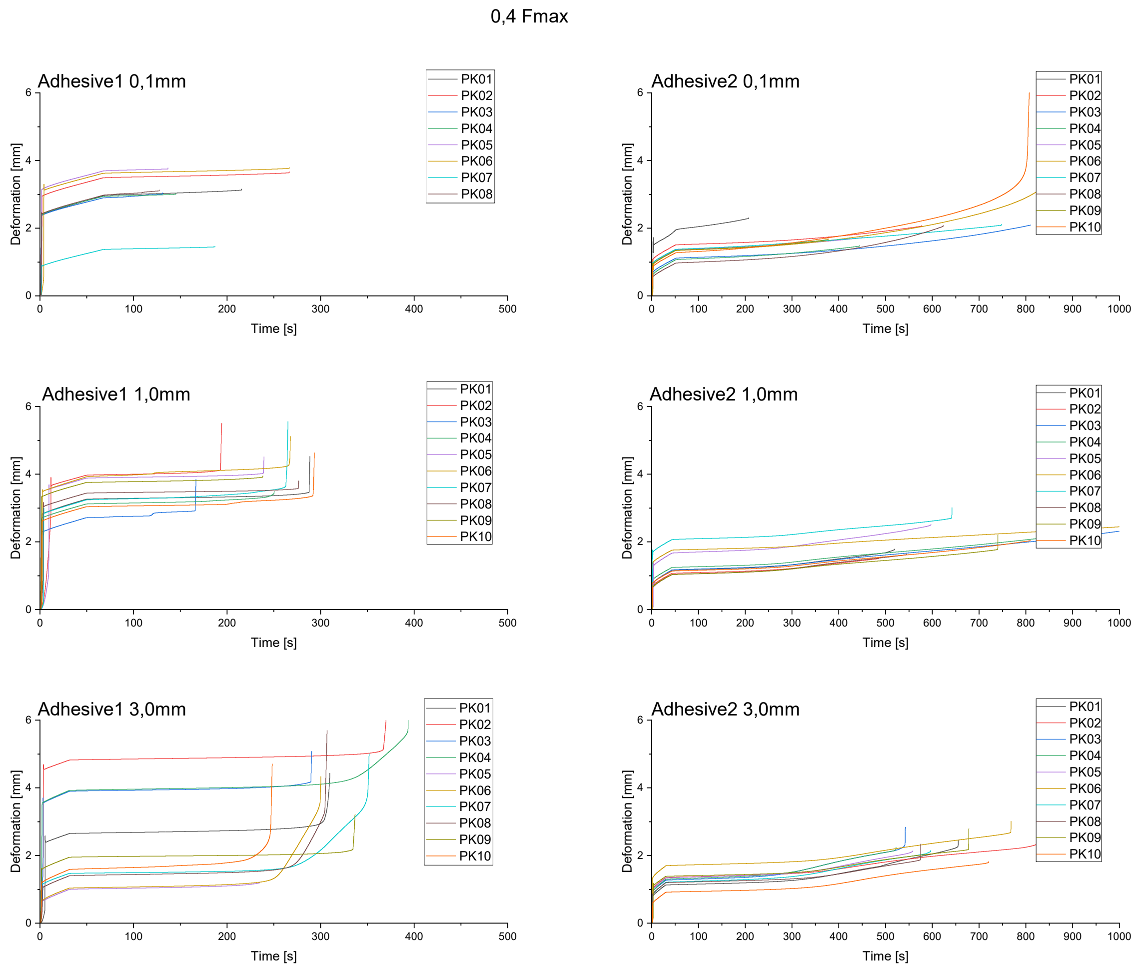


Figure 26: Deformation-time curves of the specimens under the load of 0.4 F_{max} at 110 °C

When comparing the test series with a glue line thickness of 1.0 mm under different temperatures of 110 °C and 130 °C, similar deformation curves show for Adhesive 1 (see Figure 27). In the 130 °C tests, in particular for Adhesive 2, the test durations are shorter than in the 110 °C tests. Because there is a higher air temperature in the oven, there is greater heat transfer, causing the specimens to heat up more quickly. As a result, the critical temperature is reached earlier, which leads to a faster failure. In the case of Adhesive 2, the area with the slowly increasing deformation curve is shortened, since the critical temperature is apparently reached more quickly. However, the failure times are still longer than those of Adhesive 1, which means that it can be assumed that Adhesive 2 has a higher temperature resistance and consequently only fails at higher temperatures.

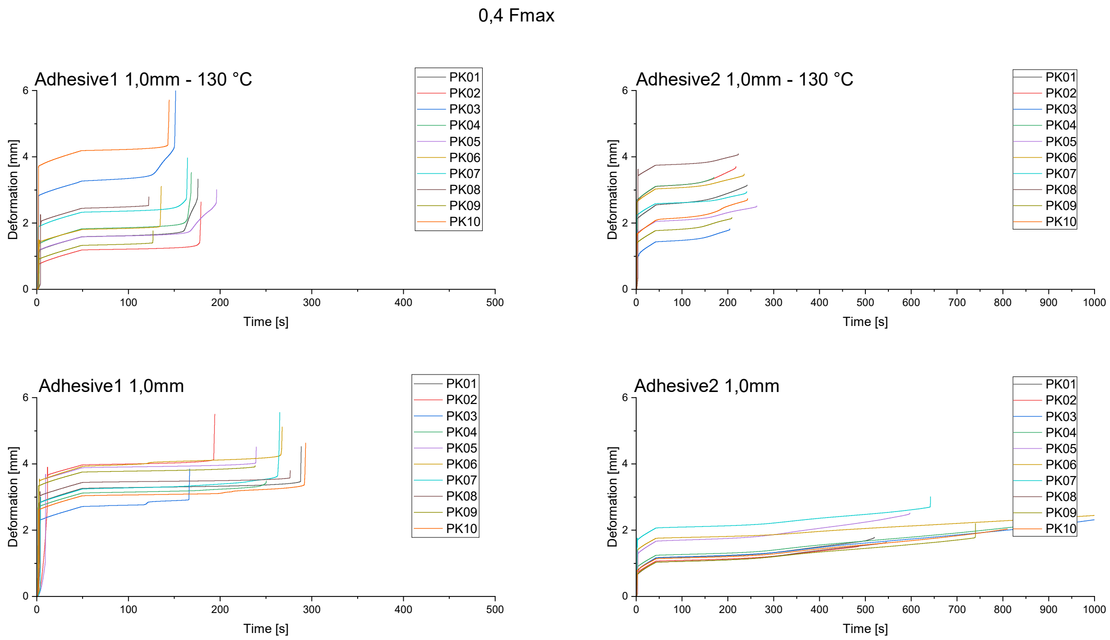


Figure 27: Deformation-time curves of the test specimens with a glue line thickness of 1.0 mm under a load of 0.4 F_{max} at 110 °C and 130 °C

For a higher load of 60 % of the reference tests, shorter test durations can also be observed for both adhesives. The scaling for Adhesive 2 is reduced to 500 seconds (see Figure 28). The shortened failure times result in lower failure temperatures (see also 4.5 failure temperature). As also determined in the tension tests at elevated temperatures, Adhesive 1 reacts to temperature stress with a greater loss of strength than Adhesive 2. Due to the increased tensile load, the target loads are only achieved by two test specimens with a glue line thickness of 0.1 mm. In the rest of the cases, the specimens failed shortly before the load was reached. A similar behavior was determined for the glue line thickness of 3.0 mm, which is why the test specimens were subjected to a lower load level of 20 % of the reference load. In the tension tests at elevated temperatures, it was found that the test specimens only have approx. 60 % of their original strength at a temperature of 60 °C. It can therefore be assumed that an increase in mechanical load over this area will lead to premature failure of the connection when the critical temperature is reached.

The graphs of Adhesive 2 show a different development for the increased load compared to the previous tests. After the target load has been reached, an almost horizontal curve appears, similar to Adhesive 1, in which there is hardly any deformation in the test specimen. A high incline or creep deformation as in the previous diagrams cannot be seen. It is assumed that when the critical temperature is exceeded, the mechanical load exceeds the residual strength of the adhesive, so that no pronounced creeping process can occur, but the test specimen fails immediately.

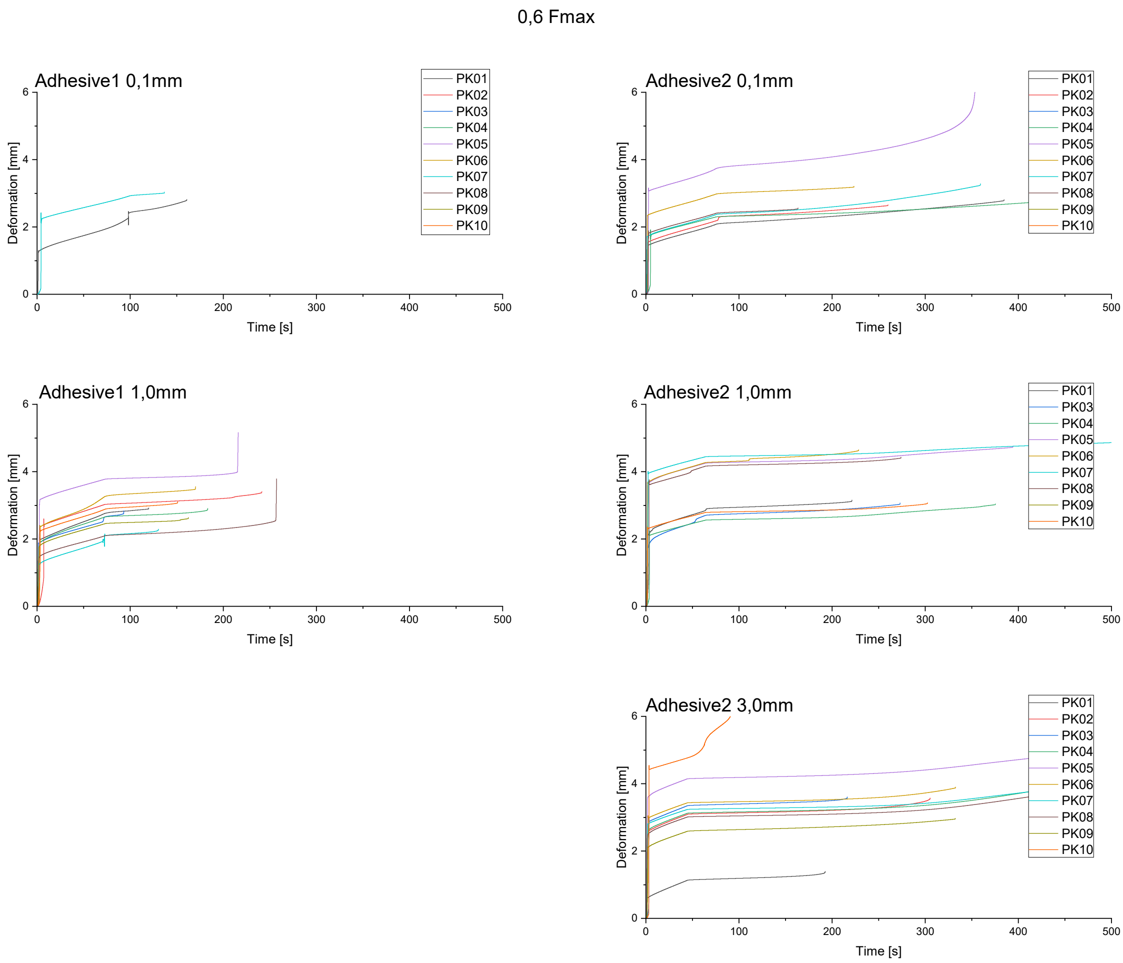


Figure 28: Deformation-time curves of the specimens under the load of 0.6 F_{max} at 110 °C

For the test series of Adhesive 1 with a glue line thickness of 3.0 mm and a reduced load of 20 % of the reference load, the deformation curves are shown in Figure 29. After reaching the target load, the graphs initially show an almost horizontal progression. This increases sharply and flattens out again briefly before the final failure, so that the graph resembles the shape of a quadrant. The different deformation process compared to the previous test series is attributed to the low mechanical load on the one hand and the high glue line thickness on the other hand. The adhesive softens as a result of the heating, so that at a certain point in time a deformation becomes apparent. In addition to the low tensile load and the larger glue line thickness, the adhesive heats up at different speeds. The temperatures inside should be lower than in the directly stressed edge area. For this reason, the inner area of the adhesive still has enough strength or load-bearing capacity not to fail. An indication of this would be the increase in the proportion of cohesive failure in the adhesive shown in 4.2 which did not occur in any other series of tests. Another factor could be the additional lateral force introduced due to the torsional moment, which leads to an eccentric displacement perpendicular to the load direction and reduces the proportion of displacement in the load direction, which is why the gradient within the deformation curve decreases again.

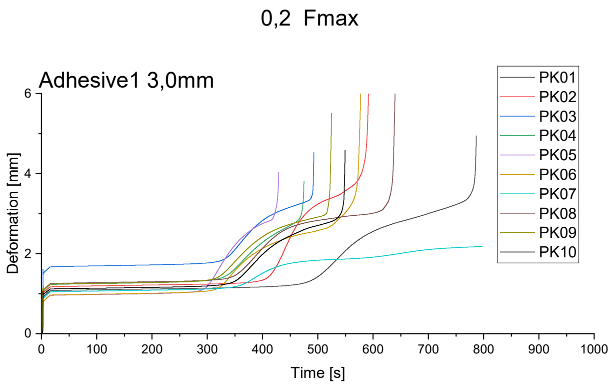


Figure 29: Deformation-time curves of the specimens under the load of 0.2 Fmax at 110 °C

4.4 Stiffness behavior

Based on the recorded deformation curves, the decrease in stiffness of the individual data series was derived. The stiffness was determined using the following formula.

$$S = \frac{F}{w} \tag{2}$$

With:

S:	Stiffness [N/mm]
F:	Target load level [N]
w:	Deformation on reaching the target load level or on fraction of the test specimen [mm]

The stiffness values calculated were set in relation to one another (initial stiffness/final stiffness) in order to obtain the decrease in the connection stiffness.

The individual values are shown in the following diagrams. The ratio of the stiffnesses is plotted on the y-axis. The blue coloring of the symbols represents Adhesive 1, while a greenish coloring is used for Adhesive 2. An overview of all stiffness ratios is given in Appendix B.2.

Figure 30 shows the calculated values for the specimens under a load of 40 % of the reference tests. Adhesive 1 shows a much smaller drop in stiffness before failure than Adhesive 2. This is consistent with the observations from the deformation curves, where the adhesive shows little deformation before failure. With Adhesive 2, the stiffness decreases to a greater extent with increasing glue line thickness and is on average between approx. 70 % and 60 %. It is suspected that, in addition to the increased critical temperature, the lower reduction in strength is also responsible for this. According to the deformation curves, the adhesive softens, which, due to the low load, does not lead to failure, but to small deformations within the adhesive, which reduces the stiffness ratio.

If the temperature rises faster, the strength decreases correspondingly faster and earlier, so that the creep deformation behavior can no longer occur. No deformation is therefore detected before the connection suddenly fails. As a result, the reduction in stiffness is significantly lower than in the tests with slower heating of the glued joint.

For Adhesive 1, there are no significant differences in the stiffness ratio for the temperature levels, since the deformation behavior was similar.

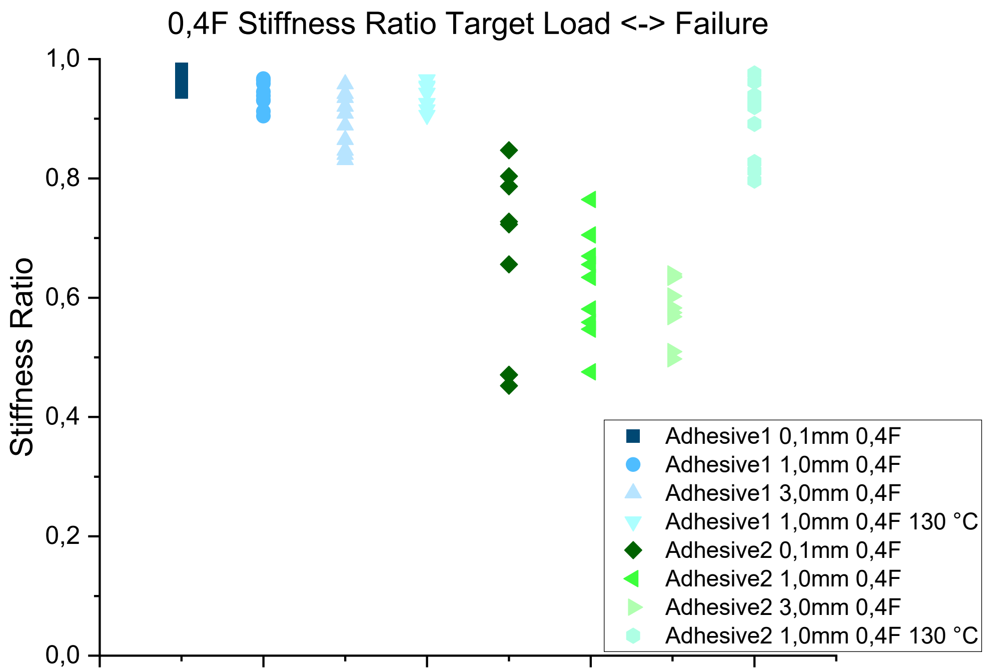


Figure 30: Stiffness ratio for a test specimen loading with 40 % of the reference load

At the higher load level of 60 % of the reference load, similar stiffness ratios result for Adhesive 1 for the two glue line thicknesses of 0.1 mm and 1.0 mm (see Figure 31). For Adhesive 2, in contrast to the tests with 40 % of the reference load, the ratio does not decrease with an increasing glue line thickness, but remains at a similar level. Nevertheless, there is a greater reduction in stiffness than for Adhesive 1. It can be assumed that the residual load-bearing capacity of the adhesive decreases and is exceeded as a result of the temperature load. Due to the higher applied mechanical load no major deformation in the adhesive can occur due to its softening before failure. Since the critical temperature is higher and the decrease in strength is lower than for Adhesive 1, larger deformations are still possible, which lead to the lower stiffness ratio than for Adhesive 1.

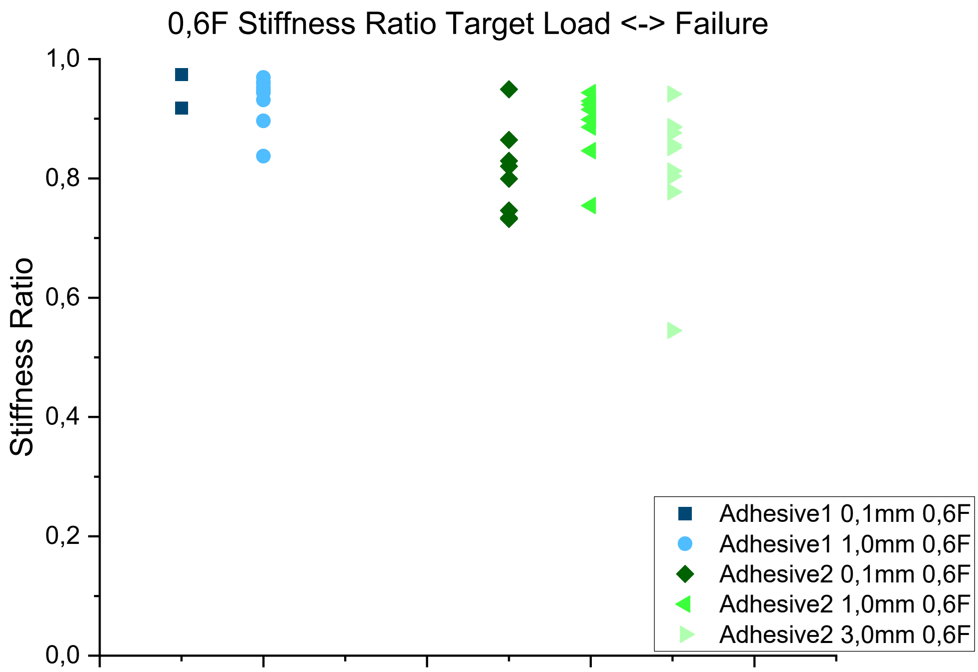


Figure 31: Stiffness ratio for a test specimen loaded with 60 % of the reference load

For the tests with a load level of 20 % of the reference load for Adhesive 1 with a glue line thickness of 3.0 mm, the stiffness ratio decreases significantly, in contrast to the other test series. Furthermore, a larger scatter can be seen. The reason for this is believed to be the low applied load combined with the additional torsional moment, which allows greater deformations as the adhesive softens.

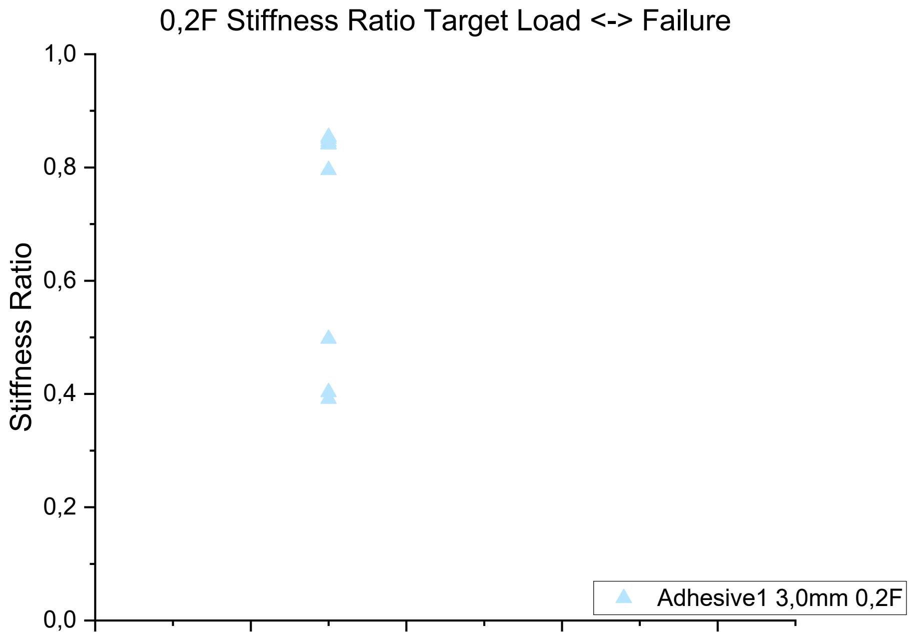


Figure 32: Stiffness ratio for a test specimen loading with 20 % of the reference load

4.5 Failure temperature

Within the tests, the times at which the test specimens failed were determined and the failure temperature prevailing in the bonded joint was deduced. The results are presented in Table 6. A summary of the mean values and the individual values for the test specimens are shown in Appendix B.3.

Table 6: Mean failure temperature in test configuration 2

Load	Temperature [°C]	Glue line [mm]		Adhesive 1		Adhesive 2	
				Specimens	Failure temperature	Specimens	Failure temperature
0.2 F_{max}	110	0.1	$\bar{\tau}$	10	65.1	-	
			s_τ		8%		
0.4 F_{max}	110	0.1	$\bar{\tau}$	8	54.6	10	79.6
			s_τ		13%		8%
		1.0	$\bar{\tau}$	8	56.5	10	82.0 [1]
			s_τ		7%		3%
		3.0	$\bar{\tau}$	10	55.5	10	71.1
			s_τ		7%		3%
	130	1.0	$\bar{\tau}$	10	57.1	10	65.8
			s_τ		7%		5%
0.6 F_{max}	110	0.1	$\bar{\tau}$	2	55.5	8	60.6

		s_τ		4%		15%
	1	$\bar{\tau}$	10	54.4	9	65.7
		s_τ		14%		7%
	3	$\bar{\tau}$	-		8	69.0
		s_τ				10%

1 No temperature measurement possible and derived from other tests

The temperatures measured in the tests for each test specimen are shown in the following figures. The blue filled symbols represent Adhesive 1, while the green symbols represent Adhesive 2.

Figure 33 shows the failure temperatures of the creep tests carried out with 40 % of the maximum load from the reference tests. The vertical axis represents the failure temperature, while the horizontal axis represents the test duration.

It can be seen that Adhesive 1 fails earlier than Adhesive 2 and therefore also at lower temperatures, which correlates with the results and the greater reduction in strength from the tension tests at elevated temperatures which speaks for a lower resistance to the effects of high temperature loads.

The values of Adhesive 1 are in a similar temperature range for all glue line thicknesses. At the same time, it is noticeable that the 3.0 mm thick glue line for Adhesive 1 shows longer testing times, which can be related to the larger dimensions of the test specimen and the associated slower heating. Initial temperature measurements for test configuration 1 in the thermal oven led to a four-minute longer heating time in the joint to reach a temperature of 70 °C compared to glue line thicknesses of 0.1 mm and 1.0 mm (approx. six minutes each). This effect is also evident for Adhesive 2, since the failure temperatures are lower than for the test specimens with thin glue lines, although the test durations are similar.

Due to the short duration of the test and the low failure temperatures in the range below 60 °C, it can be assumed that post-curing or tempering of the adhesive does not take place under these boundary conditions. Transferred to the case of fire, where significantly higher temperatures prevail, post-curing of the adhesive to temporarily increase its strength is not to be expected.

For the tests with fast heating to 130 °C, it is noticeable that the test durations are shorter for both adhesives. The critical temperature is reached earlier due to the faster heating of the glue line. The failure temperatures of Adhesive 1 are in a similar range to the 110 °C tests. For Adhesive 2, a reduction of around 5 °C on average is observed.

The applied load of 20 % of the reference tests for the glue line thickness of 3.0 mm for Adhesive 1 leads to a longer test duration with increased failure temperatures. It is assumed that the reduced shear strength in the temperature range of 60 °C is sufficient to bear the lower mechanical load. Only higher temperatures can weaken the adhesive to such an extent that failure occurs.

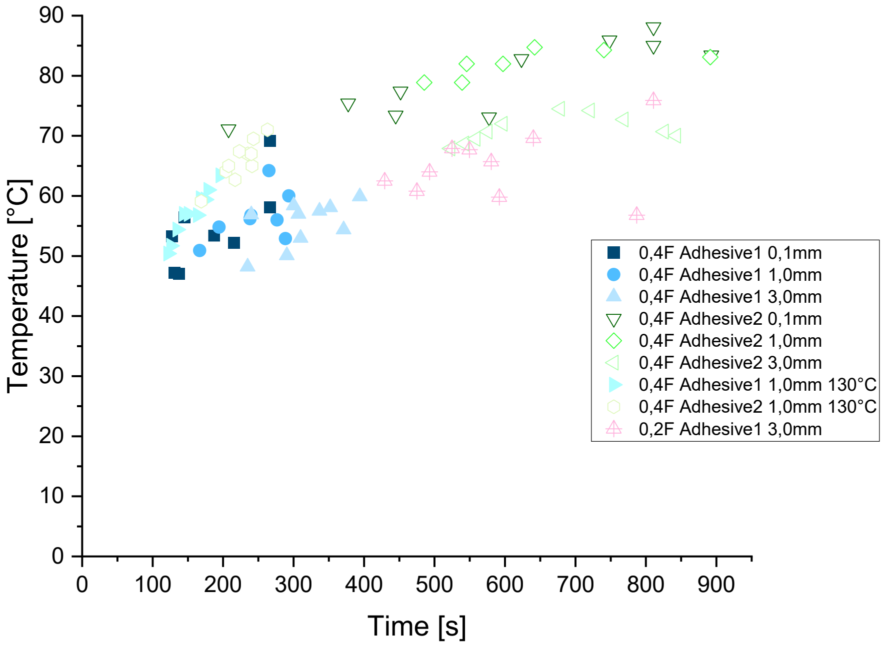


Figure 33: Failure temperatures of the creep tests under temperature load for a load of 20 % and 40 % of the reference load

A similar result emerges in the area of tests with increased tensile loads. Adhesive 1 shows lower failure temperatures than Adhesive 2 (see Figure 34). For both glue line thicknesses of 0.1 mm and 1.0 mm, the mean failure temperatures are below 60 °C and are at about the same level as in the tests with 40 % of the reference load. It is concluded that the residual load-bearing capacity of Adhesive 1 is reduced drastically at temperatures around 60 °C, which means that failure occurs in the same temperature range even in the tests with lower load levels. If the target load level had been set below 20 % of the specified reference load, higher failure temperatures would likely have been possible.

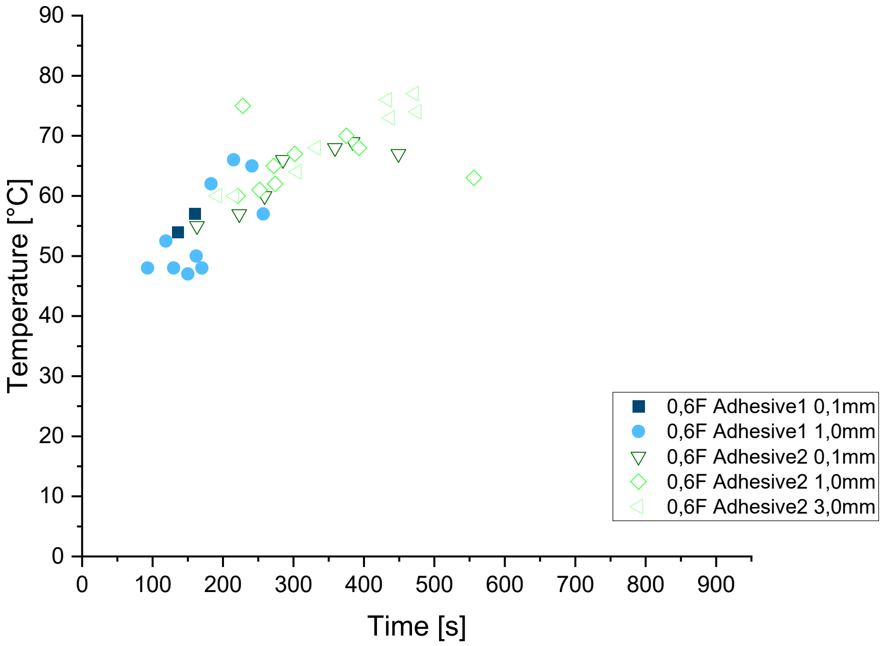


Figure 34: Failure temperatures of the creep tests under temperature load for a load of 60 % of the reference load

Adhesive 2 shows significantly shorter failure times than in the tests with lower loads. Since the adhesive loses strength with increasing temperature and at the same time there is a higher mechanical load, it seems plausible that the residual load-bearing capacity of the adhesive is already exceeded at lower temperatures (see also Figure 35). The failure temperatures are between 60 °C and 70 °C, depending on the thickness of the joint. It can be assumed that the stress ratio of the connection plays a major role for the failure of the connection.

In conclusion the failure temperature is dependent on the applied load level or rather the stress ratio of the connection and simultaneously on the heat resistance of the adhesive.

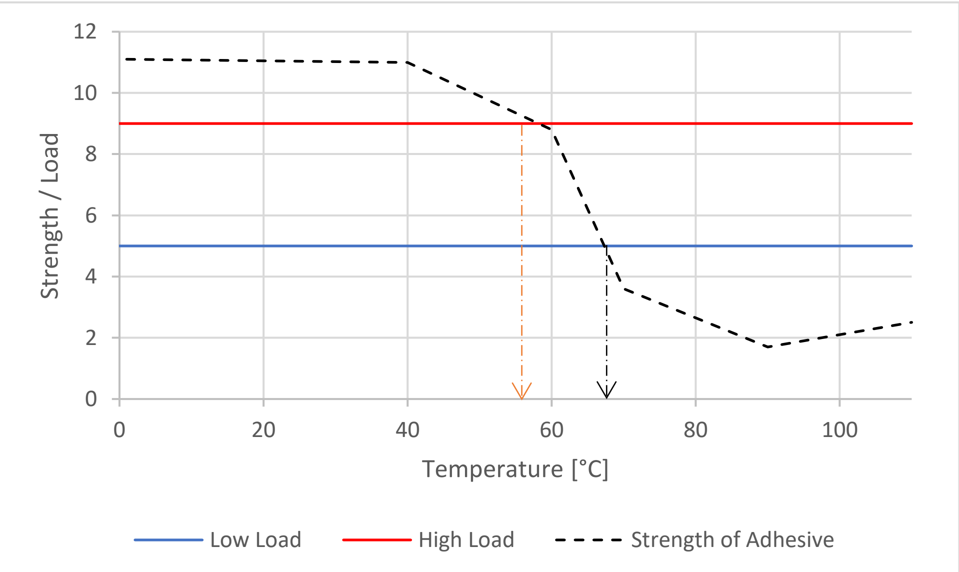


Figure 35: Sketch of the relationship between the decrease in strength, the target load level and the failure temperature

4.6 Wood fiber fraction

Finally, the visually determined wood fiber fractions of the test specimens are presented. The corresponding mean values can be found in Table 7. The proportion of fractured wood fibers was determined visually in 10% steps immediately after the tests. The individual values can be found in Appendix B.4.

Table 7: Wood fiber fractions of the tests in the test configuration 2

Load	Temperature [°C]	Glue line [mm]	Wood fiber failure [%]	Specimens	Adhesive 1	Specimens	Adhesive 2
0.2 F_{max}	110	0.1	$\bar{\tau}$	10	0.0	-	-
0.4 F_{max}	110	0.1	$\bar{\tau}$	8	1.3	10	7.5
		1	$\bar{\tau}$	8	7.1	10	2.0
		3	$\bar{\tau}$	10	28.0	10	2.0
	130	1	$\bar{\tau}$	10	15.8	10	0.0
0.6 F_{max}	110	0.1	$\bar{\tau}$	2	45.0	8	0.0
		1	$\bar{\tau}$	10	28.8	9	1.1
		3	$\bar{\tau}$	-	-	8	37.5

The following Figure 36 graphically shows the proportion of fractured wood fibers in the tests with 20 % and 40 % of the reference loads. For almost all test series, the proportion of fractured wood fibers is almost 0%, from which an adhesive failure can be regarded as decisive and is identified as a weak point of the connection under the influence of temperature. Since in test configuration 1 an increase in the proportion of fractured wood fibers was determined as a result of the tempering with slow heating, it can be assumed on the basis of the available data that this effect does not occur in the creep tests under temperature load and that post-curing of the adhesive is not to be expected in the event of fire. For this reason, creep tests under thermal load are a good way of determining the critical temperature of the bondline under mechanical stress.

With the glue line thickness of 3.0 mm for Adhesive 1, a high deflection can be seen in the diagram. This results from the opposite failure behavior of some test specimens. In the majority of the test specimens, the proportion of fractured wood fibers was determined to be 0 %. On the other hand, the samples that showed wood fiber fraction had values of 80% to 90 %, which results in the large area in the box diagram. The increased proportion of wood fiber fraction is in turn attributed to the transverse load as a result of the greater torsional moment resulting from the test setup. Since no wood fiber fraction occurs at a load of 20 % of the reference load, it is assumed that the applied transverse load does not yet exceed the tensile strength of the wood perpendicular to the grain, which means that the adhesive becomes decisive for the failure.

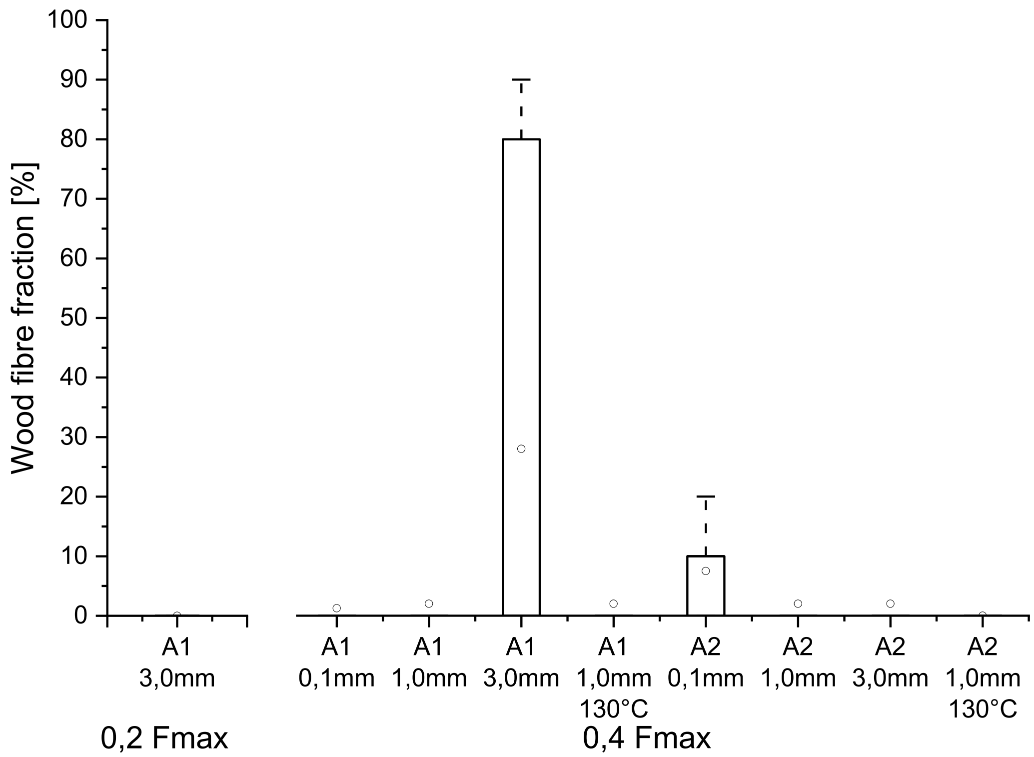


Figure 36: Wood fiber fractions of the creep tests under temperature load for a load of 20 % or 40 % of the reference load

A similar pattern is shown for the tests with increased mechanical loads (see Figure 37). Normally, there is a wood fiber fraction rate of almost 0%, which means that the adhesive is decisive for the failure behavior. For Adhesive 2 with a glue line thickness of 3.0 mm, most of the tests failed with a wood fiber fraction of 0%. The remaining test specimens, on the other hand, each have a proportion of 100%, which results in the large-area distribution in the box diagram. It is assumed that, on the one hand, the transverse load due to the torsional moment plays a role in the failure behavior. On the other hand, due to the relation of the reference load to the maximum load, it's possible that a too high load level was applied, which can result in complete wood fraction in the case of weaker wood strength. The latter explanation is also plausible for the glue line thickness of 0.1 mm for Adhesive 1, since only two test specimens reached the target load level and showed a high proportion of mixed fractures. The test specimens that showed early failure also had a high proportion of wood fiber fraction, which would indicate excessive mechanical stress. These failure patterns are also in contrast to the evaluation of previous tests under temperature load, from which it can be assumed that the adhesive is the vulnerable factor in the connection.

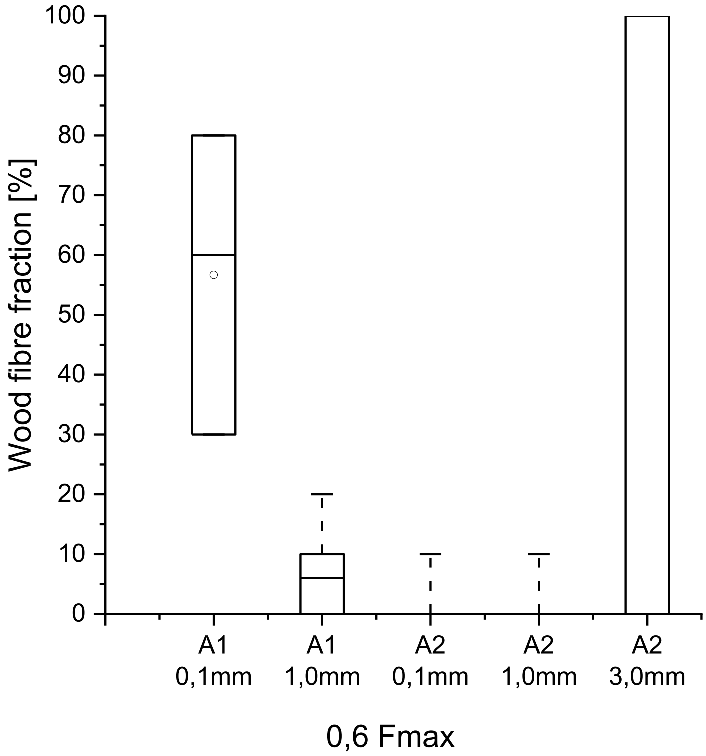


Figure 37: Wood fiber fractions of the creep tests under temperature load for a load of 60 % of the reference load

5 Influence of test configuration

The following diagrams compare the results from both test configuration 1 and test configuration 2. For this purpose, in the case of the tension tests at elevated temperatures (constant temperature), the mean values of the shear strength achieved are related to the individual constant temperature levels (20 °C, 60 °C, 70 °C, 90 °C, 110 °C) during the tests. In the case of the creep tests under temperature load (constant load), the applied constant target load is converted into the corresponding shear strength of the connection using formula 1 and combined with the measured failure temperatures. The tests with post-curing effects from test configuration 1 are listed separately and are not included in the logarithmic trend line for strength loss.

Figure 38 shows the values for a glue line thickness of 0.1 mm. It can be seen that Adhesive 1 shows a greater drop in strength than Adhesive 2 in the tests at a constant temperature level (test configuration 1). At a temperature of 90 °C, there are two different values in both diagrams. The higher corresponds to the tests with a long heating time and indicates the increased strength properties due to the post-curing effect. If you compare the values of the creep tests under temperature load with the next higher shear strength of the tension tests at elevated temperatures, it is noticeable that despite the lower load in test configuration 2, there is a lower failure temperature (red marking). The creep test with a higher load is an exception for Adhesive 1, since there is no comparable value for this.

However, in the creep tests under temperature load at both load levels, the failure temperatures are approximately the same. It is assumed that the load-bearing capacity is reduced below the level of the applied load if the adhesive is heated to approx. 58 °C.

Adhesive 2 for the tests with constant load (test configuration 2) has two different failure temperatures. It shows apparently that the weakening of the adhesive is not as high, which means that failure occurs only at a later point in time and at a higher temperature.

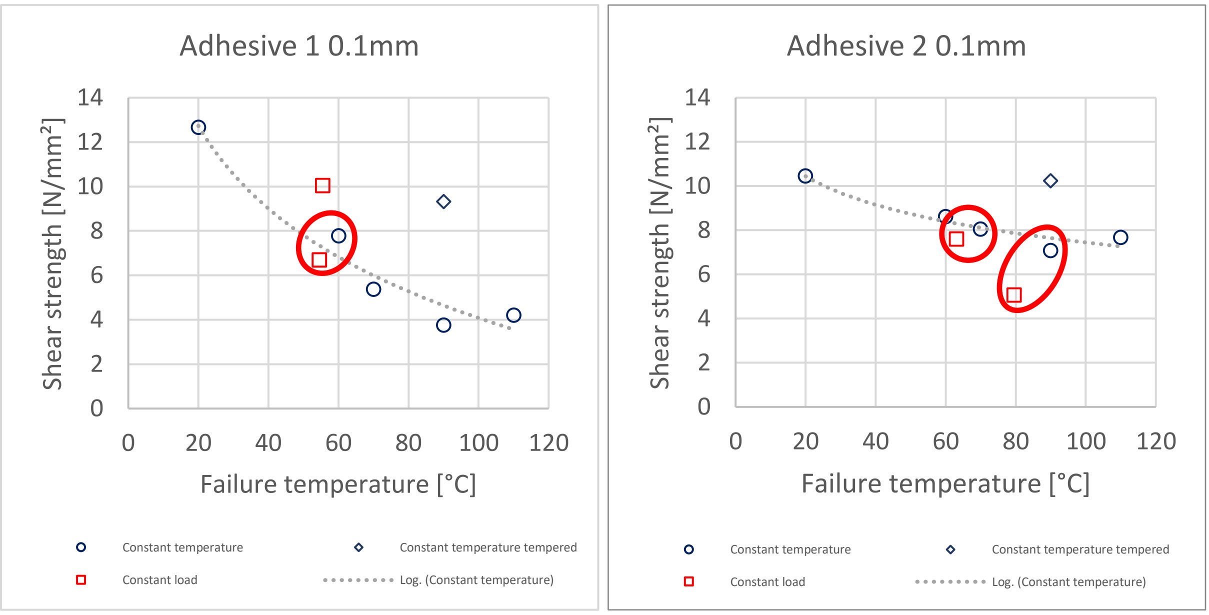


Figure 38: Comparison of the results from the two test configurations for the test specimens with a glue line thickness of 0.1 mm

Similar results are shown for a glue line thickness of 1.0 mm (see Figure 39). The creep tests with a temperature load of 130 °C are visualized in orange. At the temperature levels of 70 °C and 90 °C, several values are shown for the tests with constant temperature (test configuration 1) due to the tests with post-curing effects.

Adhesive 2 does not show such a large decrease in strength in the tension tests at elevated temperatures as Adhesive 1. However, Adhesive 1 has a higher overall load-bearing capacity at room temperature. If one compares the values of test configuration 2 for Adhesive 1 with those of test configuration 1 (marked in red), a lower failure temperature is noticeable. The failure temperatures of the creep tests are at a similar level for both load levels. It can be assumed that the load-bearing capacity of the adhesive is no longer given for both applied loads. The constant temperature range in the creep tests (even with fast heating to 130 °C) suggests a critical temperature at which the load-bearing capacity of the adhesive decreases fast. This observation also agrees with the deformation curves, in which no or only an insignificant creep deformation occurs, but instead a sudden failure of the test specimens can be seen (see 4.3).

With Adhesive 2, no significant increase in strength can be seen in the tension tests at elevated temperatures at a temperature level of 70 °C. This only occurs in the tests with slow heating to 90 °C, which means that higher temperatures are necessary to stimulate the post-curing process. The comparison of the creep tests under temperature load with the next higher values of the tensile tests from test configuration 1 shows lower failure temperatures. However, the failure temperatures differ depending on the prevailing load level. If the temperature increases, there are sufficient load-bearing reserves in the adhesive to absorb the load level of 40 % of the reference load, so that the further decrease in strength only leads to failure at higher temperatures.

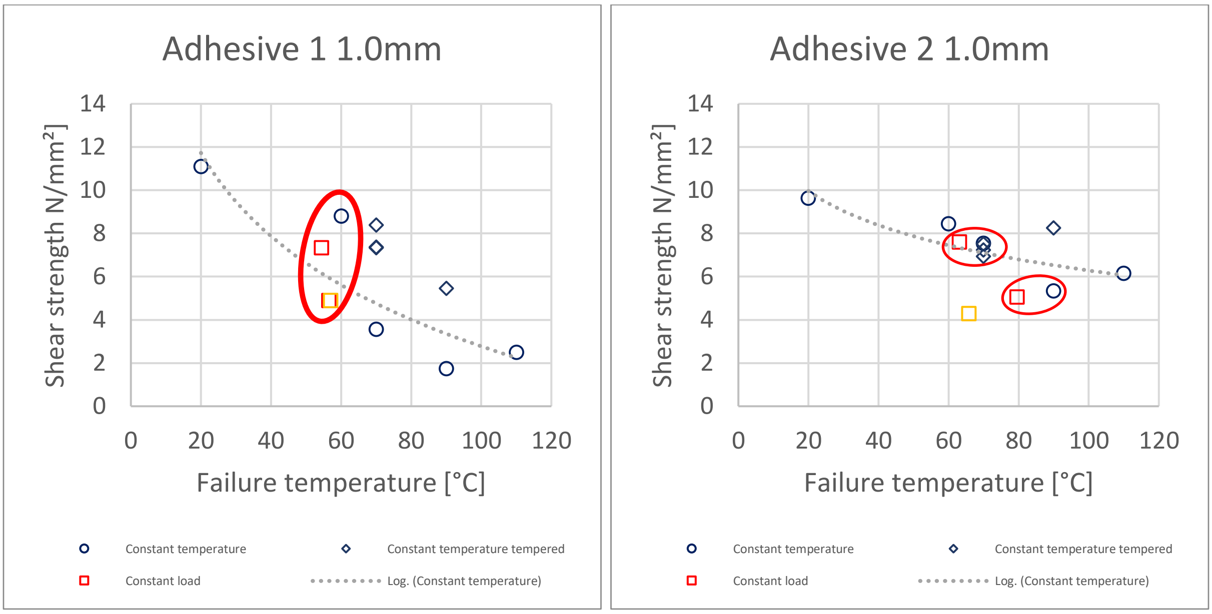


Figure 39: Comparison of the results from the two test configurations for the test specimens with a glue line thickness of 3.0 mm

With a glue line thickness of 3.0 mm, a comparison of the test modifications for Adhesive 1 shows that the creep tests have lower failure temperatures. The same result occurs with Adhesive 2. Overall, Adhesive 2 shows the higher strength values and failure temperatures depending on the test configuration, which speaks for better thermal resistance.

In the case of the creep tests under temperature load, however, there are contradictory results compared to the smaller glue line thicknesses. In the case of Adhesive 1, two different failure temperatures are reached depending on the load level, while for Adhesive 2 a similar range of failure temperatures prevails for both levels. For Adhesive 1, however, a load level of only 20 % of the reference load was used in these tests. The adhesive therefore apparently has the necessary residual load-bearing capacity, which only leads to failure if the increase in temperature to lower the load-bearing capacity even further. In the tests with the 40 % load, the range of the failure temperature at around 58 °C is similar to that in the previous tests with smaller glue line thicknesses. For Adhesive 2, it is assumed that the similar failure temperatures for both load levels are connected with the testing setup where additional forces due to a torsional moment rise the inner stresses in the connection. These higher stresses result in an earlier failure of the specimens.

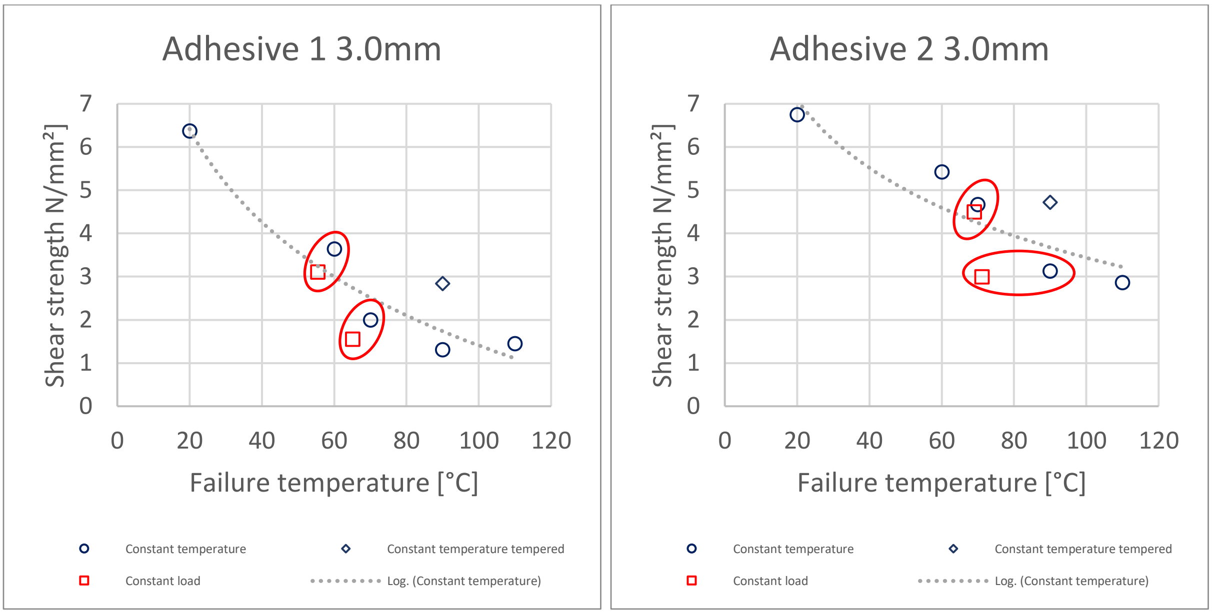


Figure 40: Comparison of the results from the two test configurations for the test specimens with a glue line thickness of 3.0 mm

In summary, the comparison between the two configurations shows that the testing method has an influence on the failure behavior. The creep tests under temperature load show lower values for adhesive failure and should therefore be on the safe side. Furthermore, the tests reflect the load situation in reality better, since building components are also already subjected to mechanical load.

6 Summary and conclusion

The individual results from the previous sections are summarized below. A distinction is made between two test configurations. In the tension tests at elevated temperatures in test configuration 1, the test specimens are heated to a predefined temperature and then mechanically loaded until they fail. Five temperature levels between 20 °C and 110 °C were considered. The duration of the heating process can have an impact on the strength of the adhesive.

In contrast, the specimens of the creep tests under temperature load in test configuration 2 are first subjected to a constant mechanical load. The test specimens are then heated to a predetermined temperature. Two load levels of 0.4*F_{max} and 0.6*F_{max} related to the reference tests at 20 °C and two temperature levels of 110 °C and 130 °C were considered.

Two adhesives and three different glue line thicknesses of 0.1 mm, 1.0 mm and 3.0 mm were examined. The test specimens were manufactured according to EN 302-1. [4]

6.1 Influence of temperature

At normal climate conditions Adhesive 1 has a higher load-bearing capacity than Adhesive 2. Since the majority of the test specimens failed in the wood at this temperature level, it can be assumed that even higher shear strengths would have been achieved with the adhesive.

However, the tests have also clearly shown that the strength of both adhesives decreases as the temperature rises. This process is not constant and depends on the adhesive. With both adhesives examined, a reduction in load-bearing capacity can already be observed at 60 °C, which steadily decreases with increasing temperature.

For Adhesive 1, a decrease in strength to approx. 60 % of the originally achieved load-bearing capacity at room temperature was determined in the tension tests at elevated temperatures at 60 °C. This reduces further to around 40 % at 70 °C and has around 20 % of the original load-bearing capacity at 110 °C.

Adhesive 2 therefore has a higher temperature resistance. At a temperature level of 60 °C, the load-bearing capacity drops to approx. 80% compared to the values at room temperature. This value reduces continuously to approx. 65% at a temperature of 110 °C. However, it should be noted that Adhesive 1 has an overall higher load-bearing capacity at room temperature (approx. 20 % greater for glue line thicknesses of 0.1 mm and 1.0 mm).

If the test specimen is heated slowly, a tempering effect or post-curing occurs in the adhesive, since reactive groups in the molecules are stimulated to undergo another chemical reaction, which means that the polymer network can be further compressed. The extent of the increase in strength and the temperatures required for this process are dependent on the adhesive. Two different modifications were considered. For variant 1, the test specimens were heated to 70 °C and then left at this temperature for a period of 30, 60 and 120 minutes. In the second variant, the test specimens were slowly heated to 90 °C over a period of 70 minutes. With Adhesive 1, an increase in strength was achieved in all four test series for post-curing compared to the tests at the same temperature level without longer heating times. The greatest strength was found after the storage for 120 minutes in combination with a storage temperature of 70 °C. However, the most significant increase in strength and a doubling of the shear strength was achieved after a storage time of 30 minutes compared to the tests without storage at 70 °C.

With Adhesive 2, no significant strength increases were found at temperatures of 70 °C. These only occurred at a temperature of 90 °C. It is assumed that higher temperatures are necessary for this adhesive and that the process for tempering adhesives must therefore be adapted to the respective type of adhesive. Overall more tests are necessary to determine the optimum post-curing parameters. The tests have shown that these are dependent on the type of adhesive, the temperature and the duration of the temperature load and that these have a major influence on the strength of the adhesive.

The creep tests carried out also show that this post-curing effect does not occur with fast heating times. Therefore, no positive influence on the load-bearing capacity of the adhesive is expected during a fire. However, tempering is seen as a good post-treatment option for the connections in order to permanently increase their glass transition temperature and the strength of the adhesive.

6.2 Impact of the testing scenario

It was found that the selected test scenario has an influence on the results. Tensile tests under elevated temperatures and creep tests under temperature load were carried out. The creep tests under temperature load provided lower failure temperatures for both adhesives than the tension tests at elevated temperatures and are therefore more on the safe side. Due to the type of loading, the creep tests are closer to practice, since the temperature is continuously increased. Furthermore, the test specimens are under a constant mechanical load.

The tension tests at elevated temperatures offer the advantage that they can be easily repeated, as there is a simple testing setup that can be easily reproduced, so that different studies can be compared.

A thermal oven which fits in the testing machine must be available for the creep tests under temperature load. However, differences can arise depending on the capacity, size and heat transfer mechanism, which means that the heating process can develop differently. Furthermore, cooling the heating device to room temperature before each test is not considered to be economical or practical since it is time consuming. As a result, the test specimen is thermally stressed as soon as it is clamped in the testing machine, which can lead to differentiated results depending on the time needed for installation.

6.3 Influence of the load level

During the creep tests under temperature load, the test specimens were subjected to two load levels. These were 40 % and 60 % of the maximum loads achieved in the reference tests at room temperature. The level of mechanical stress influences the failure behavior of the adhesive under temperature load. The adhesive loses strength with increasing temperature when a post-curing effect can be ruled out. The extent of the reduction depends on the adhesive type and the temperature, which can result in different residual strengths compared to normal temperature. If the residual load-bearing capacity is exceeded by the load level, a failure of the connection can be assumed. A higher load level or a higher stress ratio can therefore lead to earlier failure of the connection at lower temperatures, since the residual strength of the adhesive is exceeded more quickly.

If the adhesive has higher thermal resistance or the load level is below the residual load-bearing capacity of the adhesive connection, the failure pattern can also change. In this case, there is no abrupt failure, but a creep process. The adhesive still has sufficient load-bearing capacity. As the temperature rises, the adhesive softens, increasing its deformation until the residual load-bearing capacity reduces further until failure occurs.

With a higher temperature load and the associated faster temperature increase in the adhesive, it could be shown that the conditions for a creep process are no longer given, since the load-bearing capacity of the adhesive decreases more quickly and therefore is faster exceeded.

6.4 Influence of glue line thickness

Different failure patterns and load-bearing capacities were sometimes determined for the different glue line thicknesses examined for 0.1 mm, 1.0 mm and 3.0 mm. The thinner glue line thicknesses showed a similar behavior in terms of failure and shear strength achieved. In the reference tests at room temperature, the test specimens with a glue line thickness of 3.0 mm had a comparatively significantly lower shear strength. It is assumed that due to the greater eccentricity based on the thickness of the joint, an additional torsional moment is added which generates transverse forces in the connection that cause premature failure. The high proportion of fractured wood fibers in these test series confirms this statement. However, even with these test specimens, failure of the adhesive and a reduction in shear strength can be observed under thermal load.

Since it is known from other researches that a thicker glue line thickness in combination with threaded rods has a positive influence on the load-bearing capacity, which is in contrast to the small scale tests carried out, this testing method is not considered suitable for investigating glue lines with a thickness of more than 1.0 mm.

6.5 Prospects

During the tests, neither the moisture in the test specimens nor the deformation perpendicular to the load direction was measured. The decrease in moisture leads to internal stresses and at the same time to increases in the strength of the wood. However, since the adhesive was decisive for the failure from an increased temperature range of 60 °C, the influence for these tests can be assessed as low. In the case of other adhesives with greater thermal resistance for temperatures above 100 °C, however further investigation is necessary, particularly because of the evaporation of the bound water. Its dependency on the heating duration is also interesting for a future moisture analysis.

The decrease in moisture can have a further influence on the internal stresses within the test specimen. It is assumed that during the tests carried out, the proportion of moisture in the wood decreased as a result of the heating, since this was not prevented by suitable measures. This can lead to shrinkage processes in the wood. However, this proportion was not determined by measurement.

In addition, it would be interesting to research to what extent a softening of the wood due to the increased temperatures has an influence on the fracture pattern or the failure modes when the proportion of wood fractures increases. However, this was not examined within the tests, since the two adhesives examined were decisive for the failure.

Another question concerns the strength development of the connection after the temperature load and after a cooling process if no failure occurs. Does the strength decrease permanently due to damage caused by the loading process or does the original strength return? Are post-curing effects possible, so that possibly even higher strengths can be achieved? Which load levels should not be exceeded in order to avoid permanent damage?

References

[1] *DIN EN 301:2018-01, Klebstoffe, Phenoplaste und Aminoplaste, für tragende Holzbauteile_- Klassifizierung und Leistungsanforderungen; Deutsche Fassung EN_301:2017*

[2] *DIN EN 1995-1-1:2010-12, Eurocode_5: Bemessung und Konstruktion von Holzbauten_- Teil_1-1: Allgemeines_- Allgemeine Regeln und Regeln für den Hochbau; Deutsche Fassung EN_1995-1-1:2004_+ AC:2006_+ A1:2008*

[3] GEBZE-KOCAELI, Z. Tas: *Bestimmung der interlaminaren Schubfestigkeit von Faserverbundwerkstoffen durch Zugscherversuch*. November 2006

[4] *DIN EN 302-1:2013-06, Klebstoffe für tragende Holzbauteile_- Prüfverfahren_- Teil_1: Bestimmung der Längszugscherfestigkeit; Deutsche Fassung EN_302-1:2013*

A Appendix A Test configuration 1

A.1 Details bonding

A.1.1 Batch 1

Table 8: Bonding details for Adhesive 1 and glue line thickness of 0.1 mm

Date		**06.05.2020**		
Editor		FH, PD		
Lab conditions	Temperature [°C]	20	rel. humidity [%]	65
Weight proportion resin/hardener		Static mixer		
Glue line thickness [mm]		0.1		
Density wood [kg/m³]		712.75	1962.6	14 panels 0.1 mm
Checking annual rings		X		
Date miling the grooves		06.05.2020		
Check depth of grooves		X		
Date light grinding of the panel		-		
Date bonding		06.05.2020		
Quantity resin/hardener		400 [g/m²]	Per panel [g/panel]	15.6
Duration Mixing Resin/Hardener		Static mixer		
Duration Application Adhesive [s]		15		
Open/closed time		14:35	14:45	
Pressing force [N/mm²]		0.8		
Press type		MJH/036		
Start Pressing		14:45		
Number of panels		7		
Date Cutting the panels to size		05.08.2020		

Table 9: Bonding details for Adhesive 1 and glue line thickness of 1.0 mm

Date		**06.05.2020**		
Editor		FH, PD		
Lab conditions	Temperature [°C]	20	rel. humidity [%]	65
Weight proportion resin/hardener		Static mixer		
Glue line thickness [mm]		1		
Density wood [kg/m³]		712.75	1962.6	14 panels 0.1 mm
Checking annual rings		X		
Date miling the grooves		06.05.2020		
Check depth of grooves		X		
Date light grinding of the panel		-		
Date bonding		06.05.2020		
Quantity resin/hardener		400	per panel [g/Platte]	15.6
Duration Mixing Resin/Hardener		Static mixer		
Duration Application Adhesive [s]		15	[Sek]	
Open/closed time		14:51	15:03	
Pressing force [N/mm²]		0.8		
Press type		MJH/036		
Start Pressing		11:26		
Number of panels		5		
Date Cutting the panels to size		05.08.2020		

Table 10: Bonding details for Adhesive 1 and glue line thickness of 1.0 mm_2

Date		**06.05.2020**		
Editor		FH, PD		
Lab conditions	Temperature [°C]	20	rel. humidity [%]	65
Weight proportion resin/hardener		Static mixer		
Glue line thickness [mm]		1		
Density wood [kg/m³]		712.75	1962.6	14 panels 0.1 mm
Checking annual rings		X		
Date miling the grooves		06.05.2020		
Check depth of grooves		X		
Date light grinding of the panel		-		
Date bonding		06.05.2020		
Quantity resin/hardener		400	per panel [g/Platte]	15.6
Duration Mixing Resin/Hardener		Static mixer		
Duration Application Adhesive [s]		15		
Open/closed time		15:07	15:17	
Pressing force [N/mm²]		0.8		
Press type		MJH/036		
Start Pressing		11:13		
Number of panels		2		
Date Cutting the panels to size		05.08.2020		

Table 11: Bonding details for Adhesive 1 and glue line thickness of 3.0 mm

Date		**06.05.2020**		
Editor		FH, PD		
Lab conditions	Temperature [°C]	20	rel. humidity [%]	65
Weight proportion resin/hardener		Static mixer		
Glue line thickness [mm]		3		
Density wood [kg/m³]		712.75	1962.6	14 panels 0.1 mm
Checking annual rings		X		
Date miling the grooves		06.05.2020		
Check depth of grooves		X		
Date light grinding of the panel		-		
Date bonding		06.05.2020		
Quantity resin/hardener		400	per panel [g/Platte]	15.6
Duration Mixing Resin/Hardener		Static mixer		
Duration Application Adhesive [s]		15		
Open/closed time		15:07	15:17	
Pressing force [N/mm²]		0.8		
Press type		MJH/036		
Start Pressing		11:13		
Number of panels		2		
Date Cutting the panels to size		07.08.2020		

Table 12: Bonding details for Adhesive 1 and glue line thickness of 3.0 mm_2

Date		**06.05.2020**		
Editor		FH, PD		
Lab conditions	Temperature [°C]	20	rel. humidity [%]	65
Weight proportion resin/hardener		Static mixer		
Glue line thickness [mm]		3		
Density wood [kg/m³]		712.75	1962.6	14 panels 0.1 mm
Checking annual rings		X		
Date miling the grooves		06.05.2020		
Check depth of grooves		X		
Date light grinding of the panel		-		
Date bonding		06.05.2020		
Quantity resin/hardener		400	per panel [g/Platte]	15.6
Duration Mixing Resin/Hardener		Static mixer		
Duration Application Adhesive [s]		15		
Open/closed time		15:19	15:29	
Pressing force [N/mm²]		0.8		
Press type		MJH/036		
Start Pressing		11:13		
Number of panels		5		
Date Cutting the panels to size		07.08.2020		

Table 13: Bonding details for Adhesive 2 and glue line thickness of 0.1 mm

Date		**08.07.2020**		
Editor		FH, PD		
Lab conditions	Temperature [°C]	20	rel. humidity [%]	65
Weight proportion resin/hardener		Static mixer		
Glue line thickness [mm]		0.1		
Density wood [kg/m³]		712.75	1962.6	14 panels 0.1 mm
Checking annual rings		X		
Date miling the grooves		08.07.2020		
Check depth of grooves		X		
Date light grinding of the panel		08.07.2020	10:30	
Date bonding		08.07.2020		
Quantity resin/hardener		400	per panel [g/Platte]	15.6
Duration Mixing Resin/Hardener		Static mixer		
Duration Application Adhesive [s]		15		
Open/closed time		11:02	11:13	
Pressing force [N/mm²]		0.8		
Press type		MJH/036		
Start Pressing		11:13		
Number of panels		7		
Date Cutting the panels to size		05.08.2020		

Table 14: Bonding details for Adhesive 2 and glue line thickness of 1.0 mm

Date		**08.07.2020**		
Editor		FH, PD		
Lab conditions	Temperature [°C]	20	rel. humidity [%]	65
Weight proportion resin/hardener		Static mixer		
Glue line thickness [mm]		1		
Density wood [kg/m³]		712.75	1962.6	14 panels 0.1 mm
Checking annual rings		X		
Date miling the grooves		08.07.2020		
Check depth of grooves		X		
Date light grinding of the panel		08.07.2020	10:30	
Date bonding		08.07.2020		
Quantity resin/hardener		400	per panel [g/Platte]	15.6
Duration Mixing Resin/Hardener		Static mixer		
Duration Application Adhesive [s]		15		
Open/closed time		11:15	11:26	
Pressing force [N/mm²]		0.8		
Press type		MJH/036		
Start Pressing		11:26		
Number of panels		5		
Date Cutting the panels to size		05.08.2020		

Table 15 Bonding details for Adhesive 2 and glue line thickness of 1.0 mm_2

Date		**08.07.2020**		
Editor		FH, PD		
Lab conditions	Temperature [°C]	20	rel. humidity [%]	65
Weight proportion resin/hardener		Static mixer		
Glue line thickness [mm]		1		
Density wood [kg/m³]		712.75	1962.6	14 panels 0.1 mm
Checking annual rings		X		
Date miling the grooves		08.07.2020		
Check depth of grooves		X		
Date light grinding of the panel		08.07.2020	10:30	
Date bonding		08.07.2020		
Quantity resin/hardener		400	per panel [g/Platte]	15.6
Duration Mixing Resin/Hardener		Static mixer		
Duration Application Adhesive [s]		15		
Open/closed time		11:29	11:41	
Pressing force [N/mm²]		0.8		
Press type		MJH/036		
Start Pressing		11:13		
Number of panels		2		
Date Cutting the panels to size		05.08.2020		

Table 16: Bonding details for Adhesive 2 and glue line thickness of 3.0 mm

Date		**08.07.2020**		
Editor		FH, PD		
Lab conditions	Temperature [°C]	20	rel. humidity [%]	65
Weight proportion resin/hardener		Static mixer		
Glue line thickness [mm]		3		
Density wood [kg/m³]		712.75	1962.6	14 panels 0.1 mm
Checking annual rings		X		
Date miling the grooves		08.07.2020		
Check depth of grooves		X		
Date light grinding of the panel		08.07.2020	10:30	
Date bonding		08.07.2020		
Quantity resin/hardener		400	per panel [g/Platte]	15.6
Duration Mixing Resin/Hardener		Static mixer		
Duration Application Adhesive [s]		15		
Open/closed time		11:29	11:41	
Pressing force [N/mm²]		0.8		
Press type		MJH/036		
Start Pressing		11:13		
Number of panels		2		
Date Cutting the panels to size		07.08.2020		

Table 17: Bonding details for Adhesive 2 and glue line thickness of 3.0 mm_2

Date		**08.07.2020**		
Editor		FH, PD		
Lab conditions	Temperature [°C]	20	rel. humidity [%]	65
Weight proportion resin/hardener		Static mixer		
Glue line thickness [mm]		3		
Density wood [kg/m³]		712.75	1962.6	14 panels 0.1 mm
Checking annual rings		X		
Date miling the grooves		08.07.2020		
Check depth of grooves		X		
Date light grinding of the panel		08.07.2020	10:30	
Date bonding		08.07.2020		
Quantity resin/hardener		400	per panel [g/Platte]	15.6
Duration Mixing Resin/Hardener		Static mixer		
Duration Application Adhesive [s]		15		
Open/closed time		11:42	11:51	
Pressing force [N/mm²]		0.8		
Press type		MJH/036		
Start Pressing		11:13		
Number of panels		5		
Date Cutting the panels to size		07.08.2020		

A.1.2 Batch 2

Table 18: Bonding details for Adhesive 1 and glue line thickness of 0.1 mm

Date		**21.07.2020**		
Editor		FH, PD		
Lab conditions	Temperature [°C]	20	rel. humidity [%]	65
Weight proportion resin/hardener		Static mixer		
Glue line thickness [mm]		0.1		
Density wood [kg/m³]		729.03	558.77 g	4 panels 0.1 mm
Checking annual rings		X		
Date miling the grooves		20.07.2020		
Check depth of grooves		X		
Date light grinding of the panel		21.07.2020	10:15	
Date bonding		21.07.2020		
Quantity resin/hardener		400	per panel [g/Platte]	15.6
Duration Mixing Resin/Hardener		Static mixer		
Duration Application Adhesive [s]		15		
Open/closed time		11:26	11:35	
Pressing force [N/mm²]		0.8		
Press type		MJH/036		
Start Pressing		11:19		
Number of panels		2		
Date Cutting the panels to size		05.08.2020		

Table 19: Bonding details for Adhesive 1 and glue line thickness of 1.0 mm

Date		**21.07.2020**		
Editor		FH, PD		
Lab conditions	Temperature [°C]	20	rel. humidity [%]	65
Weight proportion resin/hardener		Static mixer		
Glue line thickness [mm]		1		
Density wood [kg/m³]		729.03	558.77 g	4 panels 0.1 mm
Checking annual rings		X		
Date miling the grooves		20.07.2020		
Check depth of grooves		X		
Date light grinding of the panel		21.07.2020	10:15	
Date bonding		21.07.2020		
Quantity resin/hardener		400	per panel [g/Platte]	15.6
Duration Mixing Resin/Hardener		Static mixer		
Duration Application Adhesive [s]		15	[Sek]	
Open/closed time		11:08	11:19	
Pressing force [N/mm²]		0.8		
Press type		MJH/036		
Start Pressing		11:19		
Number of panels		2		
Date Cutting the panels to size		05.08.2020		

Table 20: Bonding details for Adhesive 1 and glue line thickness of 3.0 mm

Date		**21.07.2020**		
Editor		FH, PD		
Lab conditions	Temperature [°C]	20	rel. humidity [%]	65
Weight proportion resin/hardener		Static mixer		
Glue line thickness [mm]		3		
Density wood [kg/m³]		729.03	558.77 g	4 panels 0.1 mm
Checking annual rings		X		
Date miling the grooves		20.07.2020		
Check depth of grooves		X		
Date light grinding of the panel		21.07.2020	10:15	
Date bonding		21.07.2020		
Quantity resin/hardener		400	per panel [g/Platte]	15.6
Duration Mixing Resin/Hardener		Static mixer		
Duration Application Adhesive [s]		15		
Open/closed time		11:08	11:19	
Pressing force [N/mm²]		0.8		210
Press type		MJH/036		
Start Pressing		11:19		
Number of panels		2		
Date Cutting the panels to size		07.08.2020		

Table 21: Bonding details for Adhesive 2 and glue line thickness of 0.1 mm

Date		**21.07.2020**		
Editor		FH, PD		
Lab conditions	Temperature [°C]	20	rel. humidity [%]	65
Weight proportion resin/hardener		Static mixer		
Glue line thickness [mm]		0.1		
Density wood [kg/m³]		729.03	558.77 g	4 panels 0.1 mm
Checking annual rings		X		
Date miling the grooves		20.07.2020		
Check depth of grooves		X		
Date light grinding of the panel		21.07.2020	10:15	
Date bonding		21.07.2020		
Quantity resin/hardener		400	per panel [g/Platte]	15.6
Duration Mixing Resin/Hardener		Static mixer		
Duration Application Adhesive [s]		15		
Open/closed time		11:08	11:19	
Pressing force [N/mm²]		0.8		
Press type		MJH/036		
Start Pressing		11:19		
Number of panels		2		
Date Cutting the panels to size		05.08.2020		

Table 22: Bonding details for Adhesive 2 and glue line thickness of 1.0 mm

Date		**21.07.2020**		
Editor		FH, PD		
Lab conditions	Temperature [°C]	20	rel. humidity [%]	65
Weight proportion resin/hardener		Static mixer		
Glue line thickness [mm]		1		
Density wood [kg/m³]		729.03	558.77 g	4 panels 0.1 mm
Checking annual rings		X		
Date miling the grooves		20.07.2020		
Check depth of grooves		X		
Date light grinding of the panel		21.07.2020	10:15	
Date bonding		21.07.2020		
Quantity resin/hardener		400	per panel [g/Platte]	15.6
Duration Mixing Resin/Hardener		Static mixer		
Duration Application Adhesive [s]		15		
Open/closed time		11:08	11:19	
Pressing force [N/mm²]		0.8		
Press type		MJH/036		
Start Pressing		11:19		
Number of panels		2		
Date Cutting the panels to size		05.08.2020		

Table 23: Bonding details for Adhesive 2 and glue line thickness of 3.0 mm

Date		**21.07.2020**		
Editor		FH, PD		
Lab conditions	Temperature [°C]	20	rel. humidity [%]	65
Weight proportion resin/hardener		Static mixer		
Glue line thickness [mm]		3		
Density wood [kg/m³]		729.03	558.77 g	4 panels 0.1 mm
Checking annual rings		X		
Date miling the grooves		20.07.2020		
Check depth of grooves		X		
Date light grinding of the panel		21.07.2020	10:15	
Date bonding		21.07.2020		
Quantity resin/hardener		400	per panel [g/Platte]	15.6
Duration Mixing Resin/Hardener		Static mixer		
Duration Application Adhesive [s]		15		
Open/closed time		11:08	11:19	
Pressing force [N/mm²]		0.8		210
Press type		MJH/036		
Start Pressing		11:19		
Number of panels		2		
Date Cutting the panels to size		07.08.2020		

A.1.3 Batch 3

Table 24: Bonding details for Adhesive 1 and glue line thickness of 1.0 mm

Date		**09.03.2021**			
Editor		FH, PD			
Lab conditions	Temperature [°C]	20	rel. humidity [%]	65	
Weight proportion resin/hardener		Static mixer			
Glue line thickness [mm]		1			
Density wood [kg/m³]		775.19	1269.76	4 panels a 6mm und 4 panels a 5 mm	
Checking annual rings		X			
Date miling the grooves		09.03.2021			
Check depth of grooves		X			
Date light grinding of the panel		09.03.2021	10:15		
Date bonding		09.03.2021			
Quantity resin/hardener		400	per panel [g/Platte]	15.6	
Duration Mixing Resin/Hardener		Static mixer			
Duration Application Adhesive [s]		15			
Open/closed time		12:26	12:35		
Pressing force [N/mm²]		0.8			
Press type		MJH/036			
Start Pressing					
Number of panels		2			
Date Cutting the panels to size		06.04.2021			

Table 25: Bonding details for Adhesive 2 and glue line thickness of 1.0 mm

1.0 mm PUR

Date	**09.03.2021**			
Editor	FH, PD			
Lab conditions	20	rel. humidity [%]	65	
Weight proportion resin/hardener	Static mixer			
Glue line thickness [mm]	1			
Density wood [kg/m³]	775.19	1269.76	4 panels a 6mm und 4 panels a 5 mm	
Checking annual rings	X			
Date miling the grooves	09.03.2021			
Check depth of grooves	X			
Date light grinding of the panel	09.03.2021	10:15		
Date bonding	09.03.2021			
Quantity resin/hardener	400	per panel [g/Platte]	15.6	
Duration Mixing Resin/Hardener	Static mixer			
Duration Application Adhesive [s]	15			
Open/closed time	12:15	12:25		
Pressing force [N/mm²]	0.8			
Press type	MJH/036			
Start Pressing				
Number of panels	2			
Date Cutting the panels to size	06.04.2021			

A.2 Labeling of test specimens

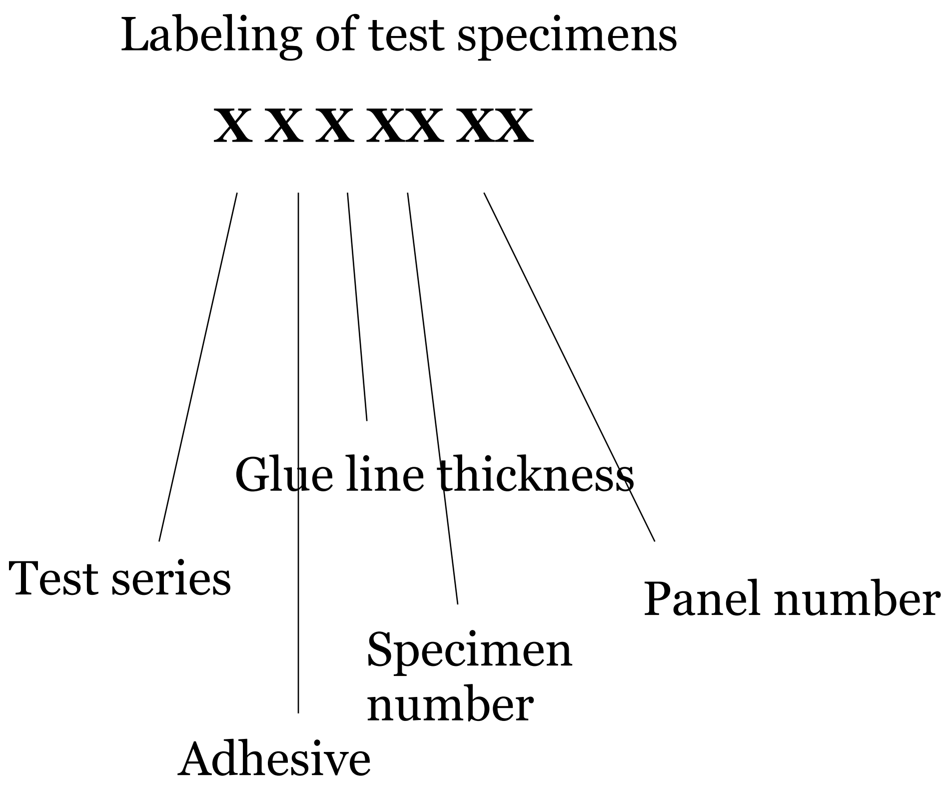


Table 26: Labeling of test specimens in test series 1

Tests		Adhesive		Glue line thickness [mm]		Specimen number	Panel number
1	20	1	EP	1	0.1	01	1-64
2	60	2	PUR	2	1.0	02	
3	70			3	3.0	03	
4	90_s					04	
5	90_f					05	
6	110					06	
7	0.4 F_{max}					07	
8	0.6 F_{max}					08	
#	Ersatz					09	
$	70_30					10	
€	70_60						
#	70_120						
9	0.4 F_130						

Table 27: Plate numbers for Adhesive 1 according to Batch

EP			
Batch 1	**Glue line thickness [mm]**	**Batch 2**	**Glue line thickness [mm]**
7-10	0.1	1-2	0.1
11-13	0.1 TE*	3-4	1.0
14-17	1.0	5-6	3.0
18-20	1.0 TE		
21-24	3.0	**Batch 3**	**Glue line thickness [mm]**
25-27	3.0 TE	55-58	1.0 TE
		59	1.0

*TE Panels with thermocouples

Table 28: Plate numbers for Adhesive 2 according to Batch

PUR			
Batch 1	**Glue line thickness [mm]**	**Batch 2**	**Glue line thickness [mm]**
34-37	0.1	28-29	0.1
38-40	0.1 TE	30-31	1.0
41-44	1.0	32-33	3.0
45-47	1.0 TE		
48-51	3.0	**Batch 3**	**Glue line thickness [mm]**
52-54	3.0 TE	60-63	1.0 TE
		64	1.0

*TE Panels with thermocouples

A.3 Test report

Failure mode

Adhesion	1
Cohesion	2
Timber	3
Mixed failure Adhesion, Timber	4
Mixed failure Cohesion, Timber	5
Mixed failure Adhesion, Cohesion	6

(blue)	Statistical anomaly	(red)	Broken before installation; Large bubble in glue line

Table 29: Test report for tests at elevated temperatures at 20 °C

Specimen number	Panel number	Test				Failure mode
		Testing speed [mm/min]	Temperature	Adhesive type	Glue line thickness [mm]	
11101	1	5	20	1	0.1	3
11102	1	5	20	1	0.1	3
11103	2	5	20	1	0.1	3
11104	7	5	20	1	0.1	3
11105	8	5	20	1	0.1	2
11106	9	5	20	1	0.1	4
11107	9	5	20	1	0.1	4
11108	10	5	20	1	0.1	3
11109	11	5	20	1	0.1	4
11110	12	5	20	1	0.1	4
11201	3	5	20	1	1.0	3
11202	3	5	20	1	1.0	3
11203	14	5	20	1	1.0	4
11204	14	5	20	1	1.0	3
11205	15	5	20	1	1.0	4
11206	16	5	20	1	1.0	4
11207	17	5	20	1	1.0	4
11208	18	5	20	1	1.0	4
11209	19	5	20	1	1.0	1
11210	19	5	20	1	1.0	4
11301	5	5	20	1	3.0	3
11302	5	5	20	1	3.0	3
11303	6	5	20	1	3.0	4
11304	21	5	20	1	3.0	3
11305	22	5	20	1	3.0	3
11306	23	5	20	1	3.0	3
11307	23	5	20	1	3.0	3
11308	24	5	20	1	3.0	3
11309	25	5	20	1	3.0	3
11310	26	5	20	1	3.0	3
12101	28	5	20	2	0.1	1
12102	28	5	20	2	0.1	1
12103	29	5	20	2	0.1	4
12104	34	5	20	2	0.1	1
12105	35	5	20	2	0.1	1
12106	36	5	20	2	0.1	1
12107	36	5	20	2	0.1	3
12108	37	5	20	2	0.1	4
12109	38	5	20	2	0.1	3
12110	39	5	20	2	0.1	1
12201	30	5	20	2	1.0	4
12202	30	5	20	2	1.0	1
12203	31	5	20	2	1.0	4
12204	41	5	20	2	1.0	1
12205	42	5	20	2	1.0	4
12206	43	5	20	2	1.0	4
12207	43	5	20	2	1.0	1
12208	45	5	20	2	1.0	1
12209	46	5	20	2	1.0	1
12210	46	5	20	2	1.0	1
12301	32	5	20	2	3.0	3
12302	32	5	20	2	3.0	3
12303	33	5	20	2	3.0	3
12304	48	5	20	2	3.0	3
12305	49	5	20	2	3.0	3
12306	50	5	20	2	3.0	3
12307	50	5	20	2	3.0	3
12308	51	5	20	2	3.0	3
12309	52	5	20	2	3.0	3
12310	53	5	20	2	3.0	3

Table 30: Test report for tests at elevated temperatures at 60 °C

Specimen number	Panel number	Test				Failure mode
		Testing speed [mm/min]	Temperature	Adhesive type	Glue line thickness [mm]	
21101	1	5	60	1	0.1	3
21102	1	5	60	1	0.1	5
21103	2	5	60	1	0.1	5
21104	7	5	60	1	0.1	5
21105	8	5	60	1	0.1	5
21106	9	5	60	1	0.1	2
21107	9	5	60	1	0.1	2
21108	10	5	60	1	0.1	2
21109	11	5	60	1	0.1	2
21110	12	5	60	1	0.1	2
21201	3	5	60	1	1.0	3
21202	3	5	60	1	1.0	4
21203	14	5	60	1	1.0	1
21204	15	5	60	1	1.0	4
21205	15	5	60	1	1.0	1
21206	16	5	60	1	1.0	1
21207	17	5	60	1	1.0	1
21208	18	5	60	1	1.0	4
21209	19	5	60	1	1.0	1
21210	20	5	60	1	1.0	4
21301	5	5	60	1	3.0	1
21302	5	5	60	1	3.0	1
21303	6	5	60	1	3.0	-
21304	21	5	60	1	3.0	3
21305	22	5	60	1	3.0	1
21306	23	5	60	1	3.0	-
21307	23	5	60	1	3.0	3
21308	24	5	60	1	3.0	1
21309	52	5	60	1	3.0	1
21310	26	5	60	1	3.0	1
22101	28	5	60	2	0.1	1
22102	28	5	60	2	0.1	1
22103	29	5	60	2	0.1	1
22104	34	5	60	2	0.1	1
22105	35	5	60	2	0.1	1
22106	36	5	60	2	0.1	1
22107	36	5	60	2	0.1	4
22108	37	5	60	2	0.1	1
22109	38	5	60	2	0.1	3
22110	39	5	60	2	0.1	1
22201	30	5	60	2	1.0	1
22202	30	5	60	2	1.0	1
22203	31	5	60	2	1.0	1
22204	41	5	60	2	1.0	1
22205	42	5	60	2	1.0	1
22206	43	5	60	2	1.0	1
22207	43	5	60	2	1.0	1
22208	45	5	60	2	1.0	4
22209	46	5	60	2	1.0	1
22210	47	5	60	2	1.0	1
22301	32	5	60	2	3.0	3
22302	32	5	60	2	3.0	3
22303	33	5	60	2	3.0	1
22304	48	5	60	2	3.0	3
22305	49	5	60	2	3.0	3
22306	50	5	60	2	3.0	4
22307	50	5	60	2	3.0	3
22308	51	5	60	2	3.0	3
22309	52	5	60	2	3.0	3
22310	53	5	60	2	3.0	3

Table 31: Test report for tests at elevated temperatures at 70 °C

Number	Panel number	Test				Failure mode
		Testing speed [mm/min]	Temperature	Adhesive type	Glue line thickness [mm]	
31101	1	5	70	1	0.1	5
31102	2	5	70	1	0.1	2
31103	2	5	70	1	0.1	2
31104	7	5	70	1	0.1	2
31105	8	5	70	1	0.1	2
31106	9	5	70	1	0.1	2
31107	10	5	70	1	0.1	2
31108	10	2.5	70	1	0.1	2
31109	11	2.5	70	1	0.1	2
31110	12	2.5	70	1	0.1	2
31201	3	2.5	70	1	1.0	-
31202	4	2.5	70	1	1.0	-
31203	14	2.5	70	1	1.0	1
31204	15	2.5	70	1	1.0	-
31205	15	2.5	70	1	1.0	-
31206	16	2.5	70	1	1.0	-
31207	17	2.5	70	1	1.0	-
31208	18	2.5	70	1	1.0	-
31209	19	2.5	70	1	1.0	1
31210	20	2.5	70	1	1.0	-
31301	5	5	70	1	3.0	-
31302	6	5	70	1	3.0	1
31303	6	5	70	1	3.0	-
31304	21	5	70	1	3.0	-
31305	22	5	70	1	3.0	-
31306	23	5	70	1	3.0	6
31307	24	5	70	1	3.0	1
31308	24	5	70	1	3.0	-
31309	25	5	70	1	3.0	-
31310	26	5	70	1	3.0	-
32101	28	2.5	70	2	0.1	1
32102	29	2.5	70	2	0.1	1
32103	29	2.5	70	2	0.1	1
32104	34	2.5	70	2	0.1	1
32105	35	2.5	70	2	0.1	1
32106	36	2.5	70	2	0.1	1
32107	37	2.5	70	2	0.1	1
32108	37	2.5	70	2	0.1	1
32109	38	2.5	70	2	0.1	3
32110	39	2.5	70	2	0.1	1
32201	30	2.5	70	2	1.0	1
32202	31	2.5	70	2	1.0	1
32203	31	2.5	70	2	1.0	1
32204	41	2.5	70	2	1.0	1
32205	42	2.5	70	2	1.0	1
32206	43	2.5	70	2	1.0	1
32207	44	2.5	70	2	1.0	1
32208	45	2.5	70	2	1.0	1
32209	46	2.5	70	2	1.0	1
32210	47	2.5	70	2	1.0	1
32301	32	2.5	70	2	3.0	4
32302	33	2.5	70	2	3.0	1
32303	33	2.5	70	2	3.0	1
32304	48	2.5	70	2	3.0	4
32305	49	2.5	70	2	3.0	1
32306	50	2.5	70	2	3.0	1
32307	51	2.5	70	2	3.0	1
32308	51	2.5	70	2	3.0	1
32309	52	2.5	70	2	3.0	1
32310	53	2.5	70	2	3.0	4

Table 32: Test report for tests at elevated temperatures at 90 °C with slow heating

Number	Panel number	Test				Failure mode
		Testing speed [mm/min]	Temperature	Adhesive type	Glue line thickness [mm]	
41101	1	2.5	20	1	0.1	3
41102	2	2.5	20	1	0.1	3
41103	2	2.5	20	1	0.1	3
41104	7	2.5	20	1	0.1	4
41105	8	2.5	20	1	0.1	4
41106	9	2.5	20	1	0.1	2
41107	10	2.5	20	1	0.1	1
41108	10	2.5	20	1	0.1	4
41109	11	2.5	20	1	0.1	2
41110	12	2.5	20	1	0.1	2
41201	3	2.5	20	1	1.0	3
41202	4	2.5	20	1	1.0	3
41203	14	2.5	20	1	1.0	4
41204	15	2.5	20	1	1.0	-
41205	16	2.5	20	1	1.0	-
41206	16	2.5	20	1	1.0	1
41207	17	2.5	20	1	1.0	-
41208	18	2.5	20	1	1.0	1
41209	19	2.5	20	1	1.0	1
41210	20	2.5	20	1	1.0	2
41301	5	2.5	20	1	3.0	1
41302	6	2.5	20	1	3.0	1
41303	6	2.5	20	1	3.0	1
41304	21	2.5	20	1	3.0	-
41305	22	2.5	20	1	3.0	-
41306	23	2.5	20	1	3.0	1
41307	24	2.5	20	1	3.0	6
41308	24	2.5	20	1	3.0	-
41309	25	2.5	20	1	3.0	-
41310	26	2.5	20	1	3.0	-
42101	28	2.5	20	2	0.1	1
42102	29	2.5	20	2	0.1	1
42103	29	2.5	20	2	0.1	4
42104	34	2.5	20	2	0.1	1
42105	35	2.5	20	2	0.1	1
42106	36	2.5	20	2	0.1	1
42107	37	2.5	20	2	0.1	1
42108	37	2.5	20	2	0.1	4
42109	38	2.5	20	2	0.1	4
42110	39	2.5	20	2	0.1	1
42201	30	2.5	20	2	1.0	4
42202	31	2.5	20	2	1.0	1
42203	31	2.5	20	2	1.0	1
42204	41	2.5	20	2	1.0	1
42205	42	2.5	20	2	1.0	4
42206	43	2.5	20	2	1.0	1
42207	44	2.5	20	2	1.0	1
42208	45	2.5	20	2	1.0	1
42209	46	2.5	20	2	1.0	1
42210	47	2.5	20	2	1.0	1
42301	32	2.5	20	2	3.0	3
42302	33	2.5	20	2	3.0	1
42303	33	2.5	20	2	3.0	1
42304	48	2.5	20	2	3.0	3
42305	49	2.5	20	2	3.0	1
42306	50	2.5	20	2	3.0	1
42307	51	2.5	20	2	3.0	1
42308	51	2.5	20	2	3.0	1
42309	52	2.5	20	2	3.0	1
42310	53	2.5	20	2	3.0	1

Table 33: Test report for tests at elevated temperatures at 90 °C with fast heating

Number	Panel number	Test				Failure mode
		Testing speed [mm/min]	Temperature	Adhesive type	Glue line thickness [mm]	
51101		2.5	20	1	0.1	2
51102		2.5	20	1	0.1	2
51103		2.5	20	1	0.1	2
51104		2.5	20	1	0.1	2
51105		2.5	20	1	0.1	2
51106		2.5	20	1	0.1	2
51107		2.5	20	1	0.1	2
51108		2.5	20	1	0.1	2
51109		2.5	20	1	0.1	2
51110		2.5	20	1	0.1	2
51201		2.5	20	1	1.0	6
51202		2.5	20	1	1.0	1
51203		2.5	20	1	1.0	6
51204		2.5	20	1	1.0	2
51205		2.5	20	1	1.0	2
51206		2.5	20	1	1.0	1
51207		2.5	20	1	1.0	6
51208		2.5	20	1	1.0	1
51209		2.5	20	1	1.0	6
51210		2.5	20	1	1.0	6
51301		2.5	20	1	3.0	1
51302		2.5	20	1	3.0	6
51303		2.5	20	1	3.0	1
51304		2.5	20	1	3.0	6
51305		2.5	20	1	3.0	6
51306		2.5	20	1	3.0	1
51307		2.5	20	1	3.0	6
51308		2.5	20	1	3.0	1
51309		2.5	20	1	3.0	6
51310		2.5	20	1	3.0	6
52101		2.5	20	2	0.1	1
52102		2.5	20	2	0.1	1
52103		2.5	20	2	0.1	4
52104		2.5	20	2	0.1	1
52105		2.5	20	2	0.1	2
52106		2.5	20	2	0.1	1
52107		2.5	20	2	0.1	1
52108		2.5	20	2	0.1	4
52109		2.5	20	2	0.1	4
52110		2.5	20	2	0.1	1
52201		2.5	20	2	1.0	1
52202		2.5	20	2	1.0	1
52203		2.5	20	2	1.0	1
52204		2.5	20	2	1.0	1
52205		2.5	20	2	1.0	1
52206		2.5	20	2	1.0	1
52207		2.5	20	2	1.0	1
52208		2.5	20	2	1.0	1
52209		2.5	20	2	1.0	1
52210		2.5	20	2	1.0	1
52301		2.5	20	2	3.0	1
52302		2.5	20	2	3.0	1
52303		2.5	20	2	3.0	1
52304		2.5	20	2	3.0	1
52305		2.5	20	2	3.0	1
52306		2.5	20	2	3.0	1
52307		2.5	20	2	3.0	1
52308		2.5	20	2	3.0	1
52309		2.5	20	2	3.0	1
52310		2.5	20	2	3.0	1

Table 34: Test report for tests at elevated temperatures at 110 °C

Number	Panel number	Test				Failure mode
		Testing speed [mm/min]	Temperature	Adhesive type	Glue line thickness [mm]	
61101	1	2.5	20	1	0.1	2
61102	2	2.5	20	1	0.1	2
61103	7	2.5	20	1	0.1	2
61104	7	2.5	20	1	0.1	2
61105	8	2.5	20	1	0.1	2
61106	9	2.5	20	1	0.1	2
61107	10	2.5	20	1	0.1	2
61108	11	2.5	20	1	0.1	2
61109	11	2.5	20	1	0.1	2
61110	12	2.5	20	1	0.1	2
61201	28	2.5	20	1	1.0	6
61202	29	2.5	20	1	1.0	6
61203	34	2.5	20	1	1.0	-
61204	34	2.5	20	1	1.0	6
61205	35	2.5	20	1	1.0	6
61206	36	2.5	20	1	1.0	6
61207	37	2.5	20	1	1.0	2
61208	38	2.5	20	1	1.0	6
61209	39	2.5	20	1	1.0	2
61210	39	2.5	20	1	1.0	6
61301	5	2.5	20	1	3.0	1
61302	6	2.5	20	1	3.0	6
61303	21	2.5	20	1	3.0	6
61304	21	2.5	20	1	3.0	6
61305	22	2.5	20	1	3.0	2
61306	23	2.5	20	1	3.0	6
61307	24	2.5	20	1	3.0	1
61308	25	2.5	20	1	3.0	6
61309	26	2.5	20	1	3.0	1
61310	26	2.5	20	1	3.0	6
62101	3	2.5	20	2	0.1	1
62102	4	2.5	20	2	0.1	1
62103	14	2.5	20	2	0.1	1
62104	15	2.5	20	2	0.1	1
62105	16	2.5	20	2	0.1	1
62106	17	2.5	20	2	0.1	1
62107	17	2.5	20	2	0.1	1
62108	18	2.5	20	2	0.1	1
62109	19	2.5	20	2	0.1	1
62110	20	2.5	20	2	0.1	1
62201	30	2.5	20	2	1.0	1
62202	31	2.5	20	2	1.0	1
62203	41	2.5	20	2	1.0	1
62204	41	2.5	20	2	1.0	1
62205	42	2.5	20	2	1.0	1
62206	43	2.5	20	2	1.0	1
62207	44	2.5	20	2	1.0	1
62208	45	2.5	20	2	1.0	1
62209	46	2.5	20	2	1.0	1
62210	47	2.5	20	2	1.0	1
62301	32	2.5	20	2	3.0	1
62302	33	2.5	20	2	3.0	1
62303	48	2.5	20	2	3.0	1
62304	48	2.5	20	2	3.0	1
62305	49	2.5	20	2	3.0	1
62306	50	2.5	20	2	3.0	1
62307	51	2.5	20	2	3.0	1
62308	52	2.5	20	2	3.0	1
62309	53	2.5	20	2	3.0	1
62310	53	2.5	20	2	3.0	1

Table 35: Test report for tests at elevated temperatures at 70 °C with 30 min storage time

Number	Panel number	Test				Failure mode
		Testing speed [mm/min]	Temperature	Adhesive type	Glue line thickness [mm]	
$1201	55	2.5	20	1	1.0	1
$1202	55	2.5	20	1	1.0	3
$1203	55	2.5	20	1	1.0	4
$1204	56	2.5	20	1	1.0	3
$1205	56	2.5	20	1	1.0	-
$1206	57	2.5	20	1	1.0	3
$1207	57	2.5	20	1	1.0	3
$1208	58	2.5	20	1	1.0	-
$1209	58	2.5	20	1	1.0	1
$1210	59	2.5	20	1	1.0	-
$2201	60	2.5	20	2	1.0	1
$2202	60	2.5	20	2	1.0	3
$2203	61	2.5	20	2	1.0	1
$2204	61	2.5	20	2	1.0	1
$2205	62	2.5	20	2	1.0	1
$2206	62	2.5	20	2	1.0	1
$2207	62	2.5	20	2	1.0	1
$2208	63	2.5	20	2	1.0	1
$2209	63	2.5	20	2	1.0	3
$2210	64	2.5	20	2	1.0	1

Table 36: Test report for tests at elevated temperatures at 70 °C with 60 min storage time

Number	Panel number	Test				Failure mode
		Testing speed [mm/min]	Temperature	Adhesive type	Glue line thickness [mm]	
€1201	55	2.5	20	1	1.0	3
€1202	55	2.5	20	1	1.0	3
€1203	56	2.5	20	1	1.0	-
€1204	56	2.5	20	1	1.0	3
€1205	57	2.5	20	1	1.0	3
€1206	57	2.5	20	1	1.0	3
€1207	58	2.5	20	1	1.0	-
€1208	58	2.5	20	1	1.0	3
€1209	58	2.5	20	1	1.0	-
€1210	59	2.5	20	1	1.0	4
€2201	60	2.5	20	2	1.0	1
€2202	60	2.5	20	2	1.0	3
€2203	61	2.5	20	2	1.0	1
€2204	61	2.5	20	2	1.0	3
€2205	62	2.5	20	2	1.0	1
€2206	62	2.5	20	2	1.0	1
€2207	63	2.5	20	2	1.0	3
€2208	63	2.5	20	2	1.0	3
€2209	64	2.5	20	2	1.0	1
€2210	64	2.5	20	2	1.0	-

Table 37: Test report for tests at elevated temperatures at 70 °C with 120 min storage time

Number	Panel number	Test				Failure mode
		Testing speed [mm/min]	Temperature	Adhesive type	Glue line thickness [mm]	
#1201	55	2.5	20	1	1.0	3
#1202	55	2.5	20	1	1.0	3
#1203	56	2.5	20	1	1.0	1
#1204	56	2.5	20	1	1.0	3
#1205	56	2.5	20	1	1.0	3
#1206	57	2.5	20	1	1.0	3
#1207	57	2.5	20	1	1.0	3
#1208	58	2.5	20	1	1.0	3
#1209	58	2.5	20	1	1.0	1
#1210	59	2.5	20	1	1.0	3
#2201	60	2.5	20	2	1.0	1
#2202	60	2.5	20	2	1.0	1
#2203	61	2.5	20	2	1.0	1
#2204	61	2.5	20	2	1.0	1
#2205	62	2.5	20	2	1.0	4
#2206	62	2.5	20	2	1.0	3
#2207	63	2.5	20	2	1.0	1
#2208	63	2.5	20	2	1.0	3
#2209	63	2.5	20	2	1.0	3
#2210	64	2.5	20	2	1.0	3

A.4 Testing times

Table 38: Heating times in configuration 1

Glue line thickness [mm]	Adhesive	Time [min]				
		60°C	70°C	90°C s	90°C f	110°C
0.1	1	05:20	06:30	65:00	10:00	70:00
	2	05:20	06:30	65:00	10:00	70:00
1.0	1	05:20	06:30	65:00	10:00	70:00
	2	05:20	06:30	65:00	10:00	70:00
3.0	1	06:00	07:30	65:00	12:00	70:00
	2	06:00	07:30	65:00	12:00	70:00

A.5 Wood fibre fraction

Statistical anomaly — Broken before installation; Large bubble in glue line

Table 39: Wood fiber fraction for Adhesive 1 with a glue line thickness of 0.1 mm

	20°C	40°C	60°C	70°C	90°C s	90°C f	110°C
	[%]	[%]	[%]	[%]	[%]	[%]	[%]
PK01	100		100		100	10	0
PK02	100		70		100	0	10
PK03	100		80	10	100	0	0
PK04	100		60	10	40	0	0
PK05	0		10	10	10	0	0
PK06	90		10		0	0	0
PK07	50		0	0	0		0
PK08	100		0	0	30	0	0
PK09	60		0				
PK10	10		0		0	0	0
Mean value	71.0		33.0	6.0	42.2	1.3	1.1

Table 40: Wood fibre fraction for Adhesive 1 with a glue line thickness of 1.0 mm

	20°C	40°C	60°C	70°C	70°C_30 min	70°C_60 min	70°C_120 min	90°C s	90°C f	110°C
	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]
PK01	100	100	100	0	0	80	90	100	0	0
PK02	100	100	50	0	100	100	90	100	0	0
PK03	50	70	10	0	75	0	10	70	0	0
PK04	90	100	50	0	100	100	100	0	0	0
PK05	60		10	0	0	90	100	0	0	0
PK06			10	0	90	100	90	0	0	
PK07	30		0	0	80	0	100	10	0	0
PK08	70		10	0	0	100	100	10	0	
PK09	0			0	0	0		10	0	0
PK10	90		50	0	10	80	90	0	0	0
Mean value	65.6	92.5	32.2	0.0	45.5	65.0	85.6	30.0	0.0	0.0

Table 41: Wood fiber fraction for Adhesive 1 with a glue line thickness of 3.0 mm

	20°C	40°C	60°C	70°C	90°C s	90°C f	110°C
	[%]	[%]	[%]	[%]	[%]	[%]	[%]
PK01	50	100	0	0	0	0	0
PK02	100	100	0	0	0	0	0
PK03	50	100	50	0	0	0	0
PK04	100		100	0	0	0	0
PK05	100		0	0	0	0	0
PK06	100		0	0	0	0	0
PK07	100		100	0	0	0	0
PK08	100		10	0	0	0	0
PK09	100		0	0	0	0	0
PK10	100		0	0	0		0
Mean value	90.0	100.0	26.0	0.0	0.0	0.0	0.0

Table 42: Wood fiber fraction for Adhesive 2 with a glue line thickness of 0.1 mm

	20°C	40°C	60°C	70°C	90°C s	90°C f	110°C
	[%]	[%]	[%]	[%]	[%]	[%]	[%]
PK01	0	80	0	0	0	0	
PK02	10	80	0	0	10	0	10
PK03	20	50	10	0	20	0	0
PK04	0		0	0	0	0	0
PK05	0		0	0	0	0	0
PK06	20		10	0	0	0	10
PK07	90		50	0	0	0	0
PK08	60		20	0	80	0	0
PK09	100		100	100	10	0	0
PK10	0		0	0	80	0	0
Mean value	30.0	70.0	19.0	10.0	20.0	0	2.2

Table 43: Wood fiber fraction for Adhesive 2 with a glue line thickness of 1.0 mm

	20°C	40°C	60°C	70°C	70°C_30 min	70°C_60 min	70°C_120 min	90°C s	90°C f	110°C
	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]
PK01	90	100	10	0	10	0		50	0	0
PK02		10	0	0	100	100	10	10	0	0
PK03	80	10	0		0	0	0	0	0	0
PK04	10	40	10		0	100	10	0	0	0
PK05	40		0	0	0		40	70	0	0
PK06	60		0	0	0	0	100	0	0	0
PK07	0		0	0	0	90	10	0	0	0
PK08	0		50	0	10	100	100	0	0	0
PK09	10		0	0	100	0	100	0	0	0
PK10	10		10	5	0		90	0	0	0
Mean value	33.3	40.0	8.0	0.6	22.0	48.8	51.1	13.0	0.0	0.0

Table 44: Wood fiber fraction for Adhesive 2 with a glue line thickness of 3.0 mm

	20°C	40°C	60°C	70°C	90°C s	90°C f	110°C
	[%]	[%]	[%]	[%]	[%]	[%]	[%]
PK01	100	100	100	10	100	0	0
PK02	100	100	100	0	0	0	0
PK03	100	100	0	0	0	0	0
PK04	100		100	80	100	0	0
PK05	100		100	0	0	0	0
PK06	100		50	0	0	0	0
PK07	100		100	0	0	0	0
PK08	100		100	0			0
PK09	100		100	10	0	0	0
PK10	100			20		0	0
Mean value	100	100	83.3	12.0	25.0	0.0	0.0

A.6 Stress-strain-curves

Adhesive 1

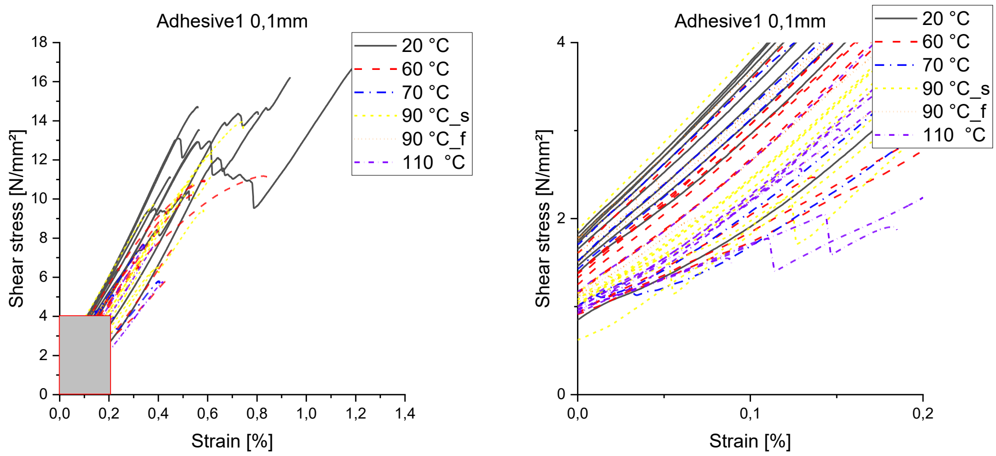


Figure 41: Stress-strain curves for Adhesive 1 with a glue line thickness of 0.1 mm

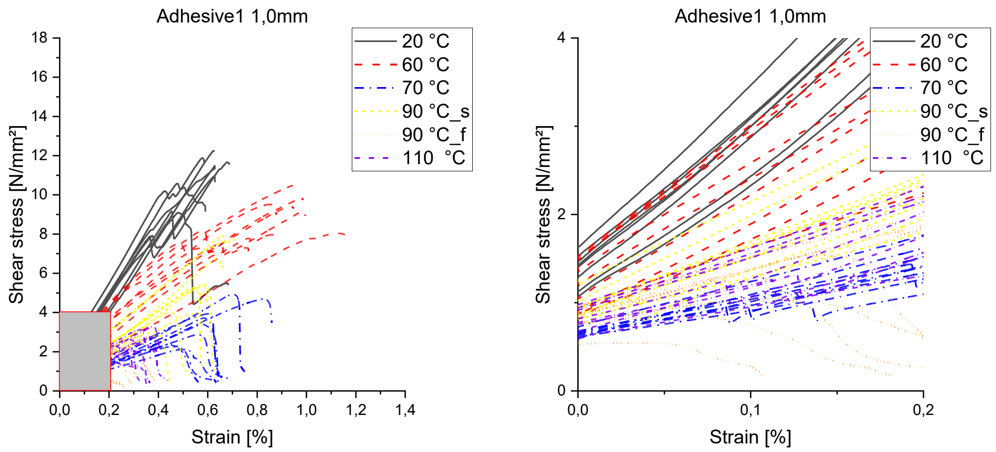


Figure 42: Stress-strain curves for Adhesive 1 with a glue line thickness of 1.0 mm

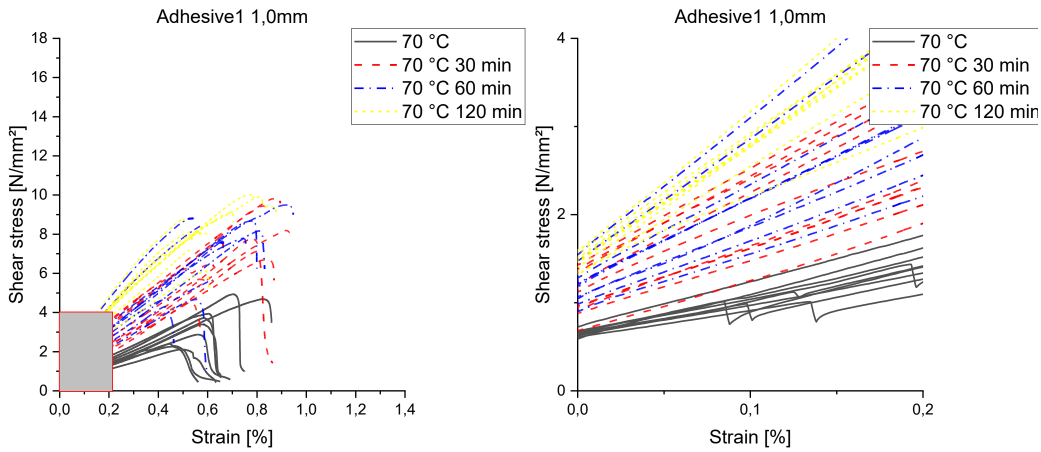


Figure 43: Stress-strain curves for Adhesive 1 with a glue line thickness of 1.0 mm and storage time

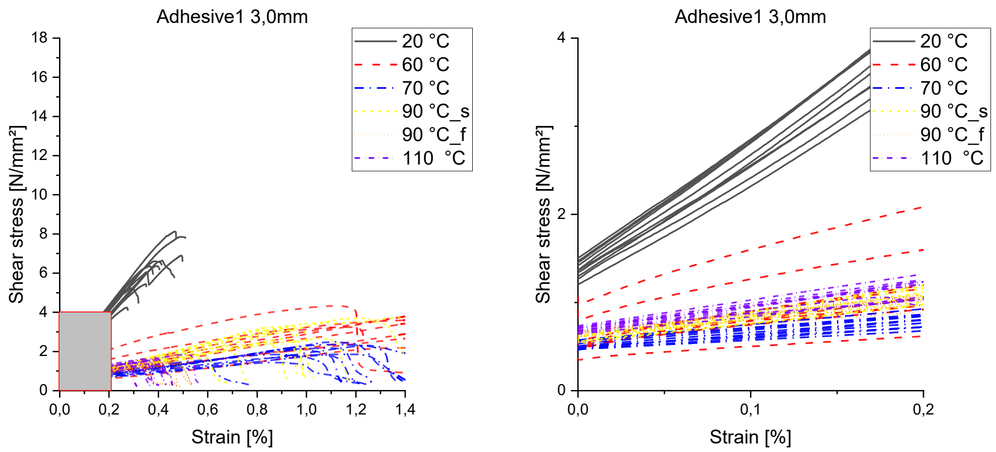


Figure 44: Stress-strain curves for Adhesive 1 with a glue line thickness of 3.0 mm

Adhesive 2

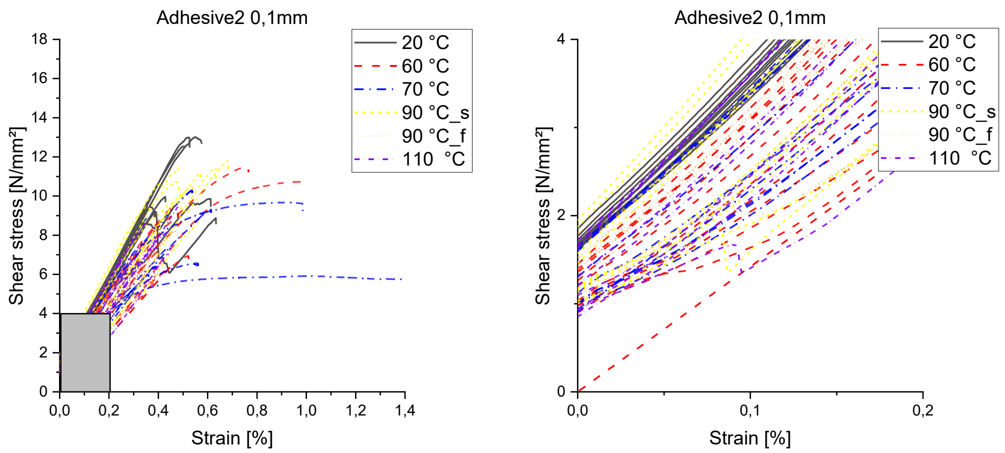


Figure 45: Stress-strain curves for Adhesive 2 with a glue line thickness of 0.1 mm

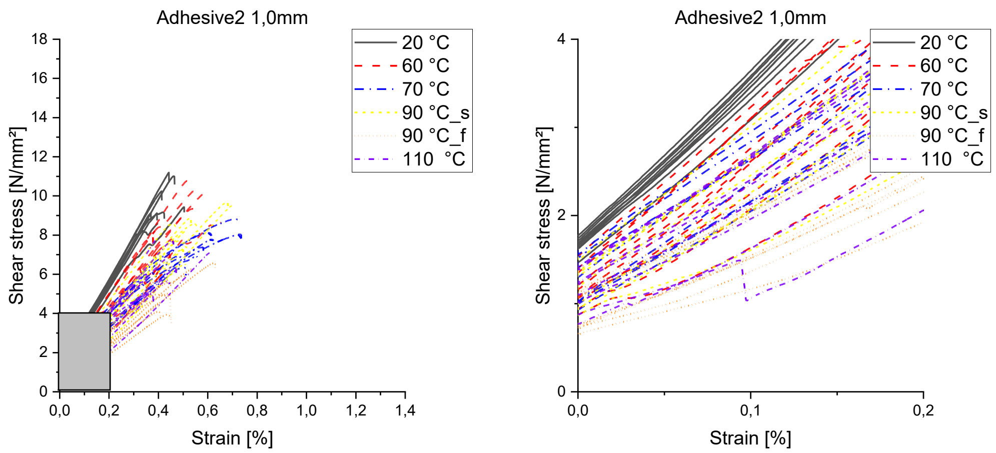


Figure 46: Stress-strain curves for Adhesive 2 with a glue line thickness of 1.0 mm

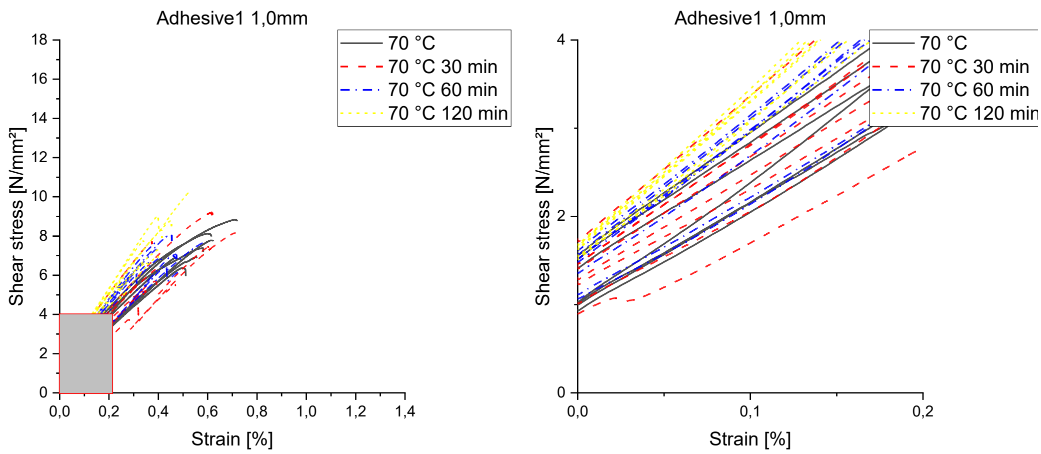


Figure 47: Stress-strain curves for Adhesive 2 with a glue line thickness of 1.0 mm and storage time

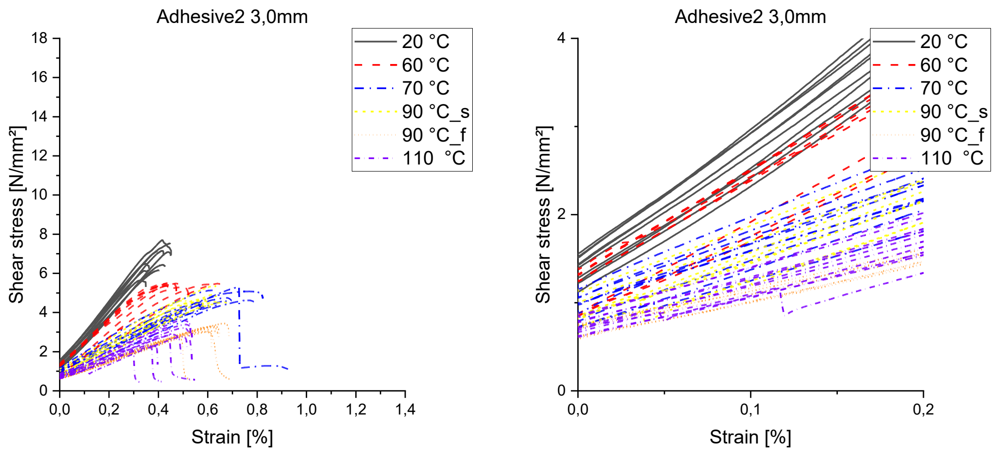


Figure 48: Stress-strain curves for Adhesive 2 with a glue line thickness of 3.0 mm

A.7 Deformation curves

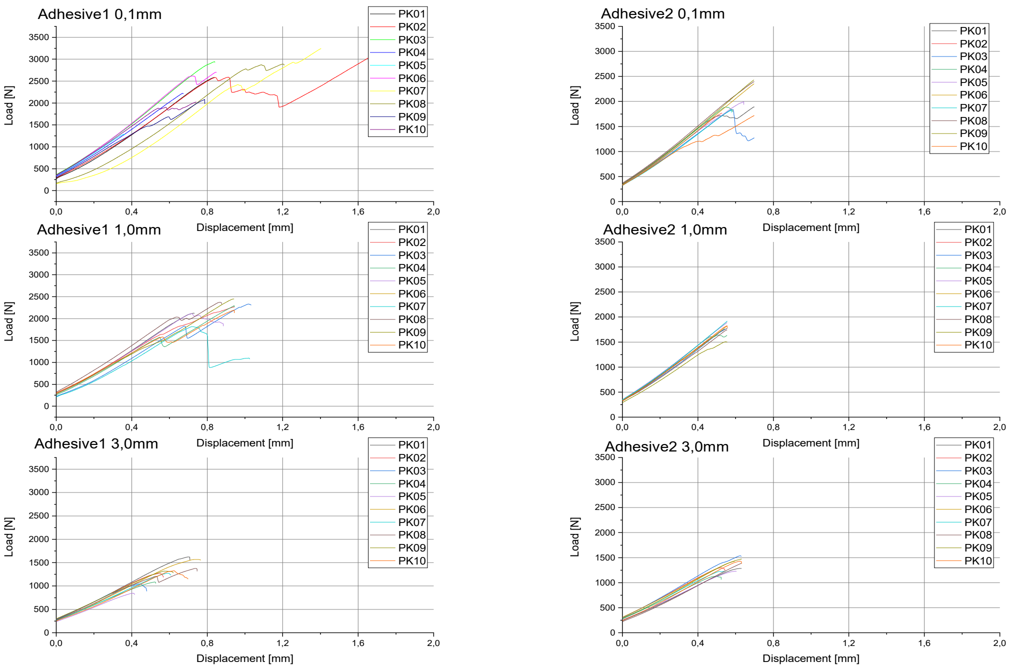


Figure 49: Deformation curves at 20 °C for tests at elevated temperatures

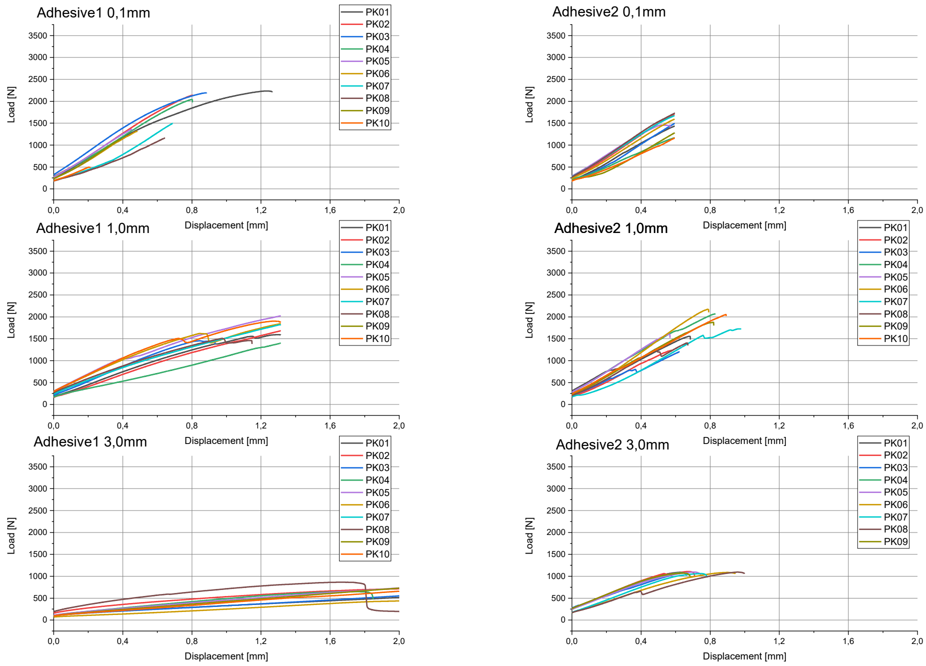


Figure 50: Deformation curves at 60 °C for tests at elevated temperatures

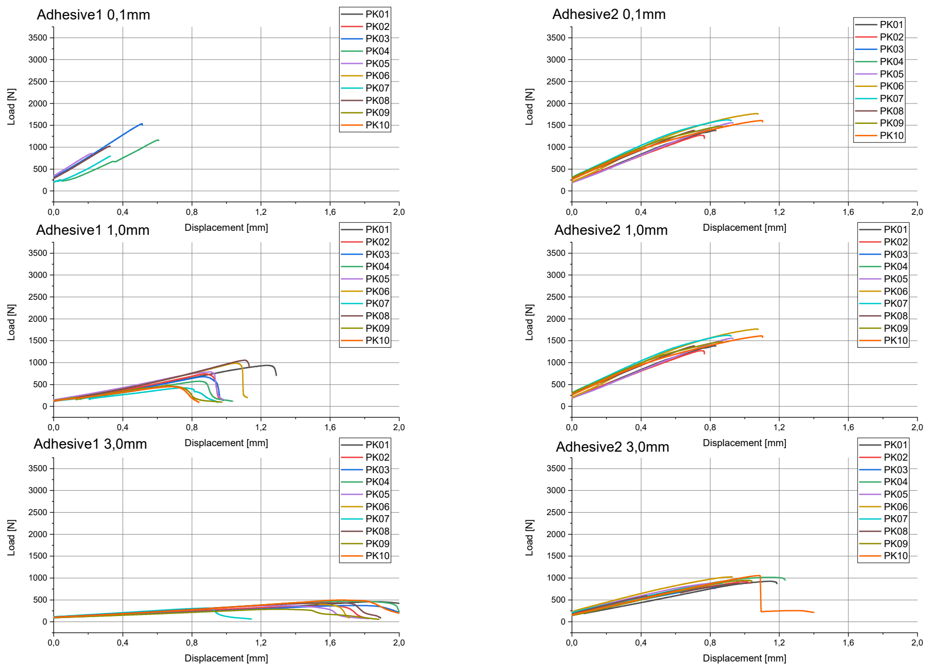


Figure 51: Deformation curves at 70 °C for tests at elevated temperatures

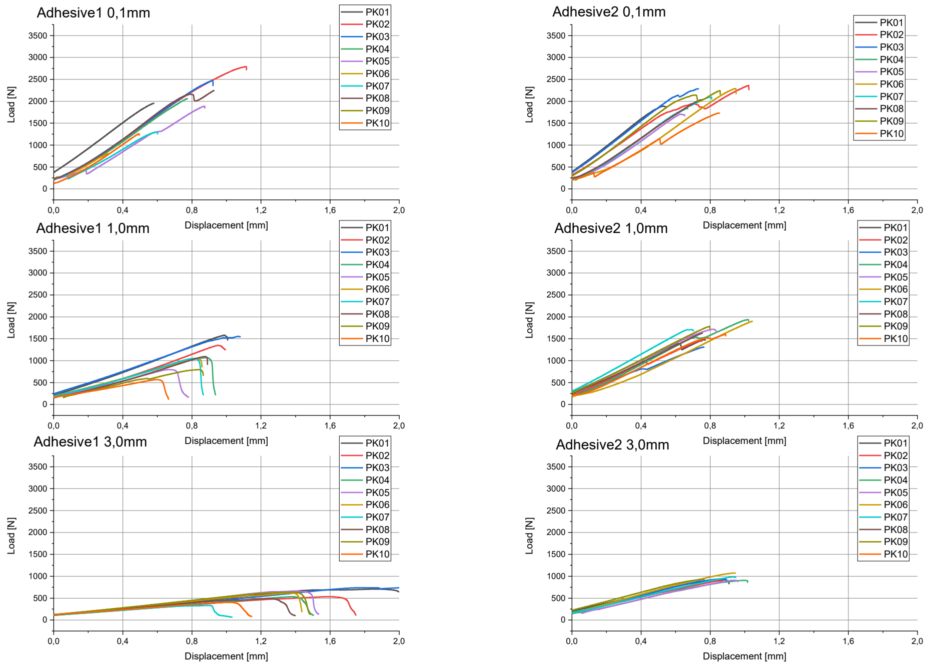


Figure 52: Deformation curves at 90 °C with slow heating for tests at elevated temperatures

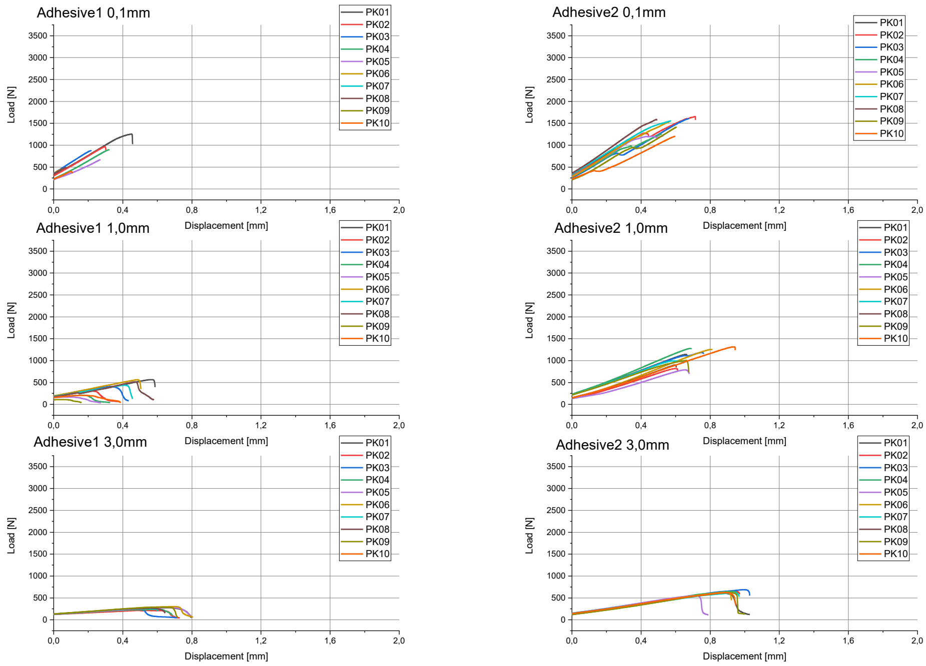


Figure 53: Deformation curves at 90 °C with fast heating for tests at elevated temperatures

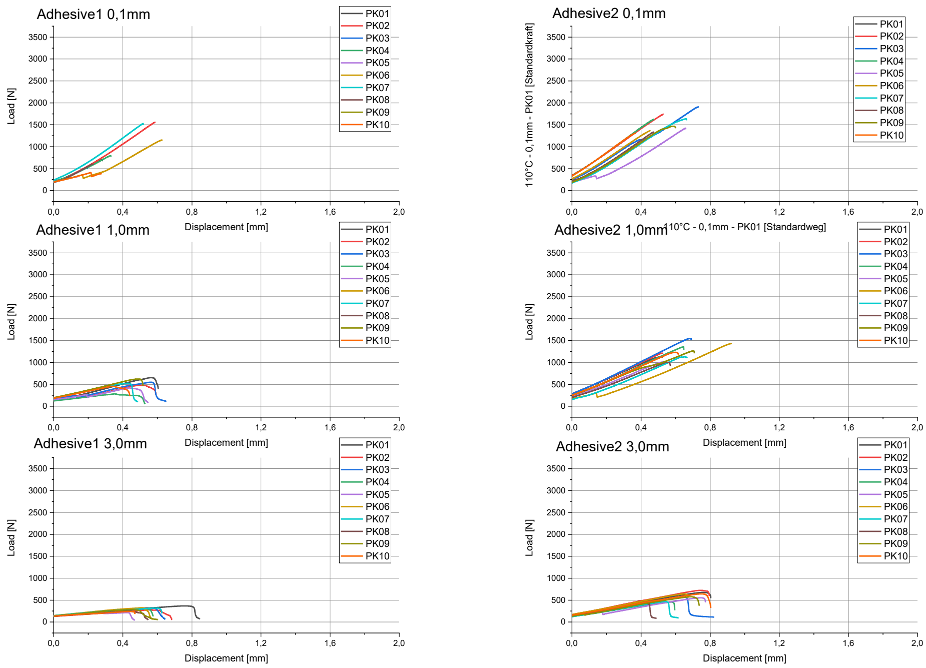


Figure 54: Deformation curves at 110 °C for tests at elevated temperatures

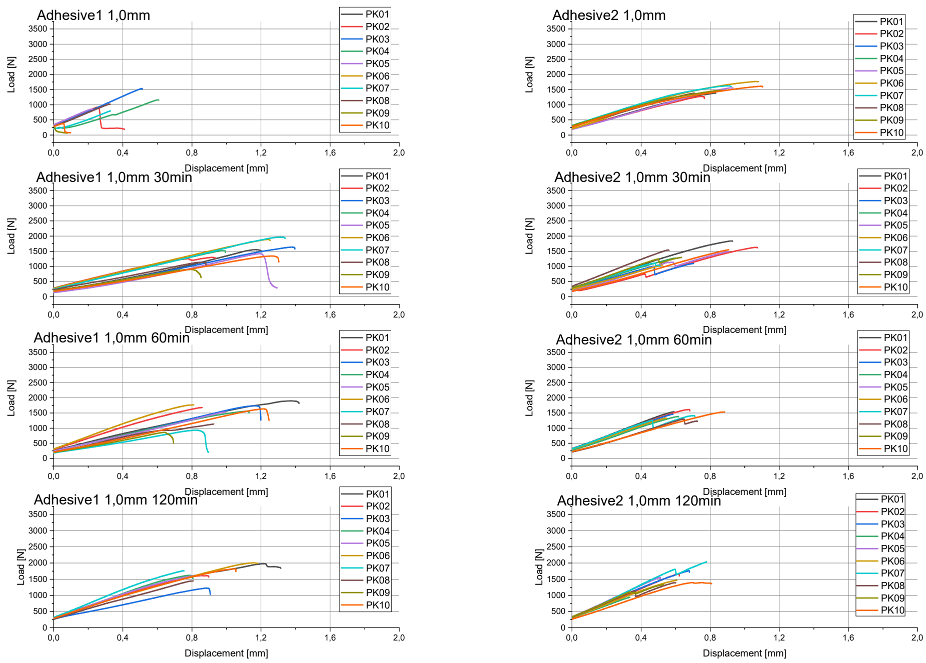


Figure 55: Deformation curves at 70 °C with storage time for tests at elevated temperatures

B Appendix B Test configuration 2

B.1 Test report

Failure mode

Adhesion	1
Cohesion	2
Timber	3
Mixed failure Adhesion, Timber	4
Mixed failure Cohesion, Timber	5
Mixed failure Adhesion, Cohesion	6

Statistical anomaly

Broken before target load is reached

Table 45: Test report for creep tests under thermal load with a level of $0.4 * F_{max}$

Number	Panel number	Test Temperature	Adhesive type	Glue line thickness [mm]	Load	Failure mode
71101	1	110	1	0.1	$0.4 * F_{max}$	2
71102	2	110	1	0.1	$0.4 * F_{max}$	2
71103	7	110	1	0.1	$0.4 * F_{max}$	2
71104	8	110	1	0.1	$0.4 * F_{max}$	2
71105	8	110	1	0.1	$0.4 * F_{max}$	2
71106	9	110	1	0.1	$0.4 * F_{max}$	2
71107	10	110	1	0.1	$0.4 * F_{max}$	2
71108	11	110	1	0.1	$0.4 * F_{max}$	2
71109	12	110	1	0.1	$0.4 * F_{max}$	2
71110	13	110	1	0.1	$0.4 * F_{max}$	2
71201	3	110	1	1.0	$0.4 * F_{max}$	1
71202	4	110	1	1.0	$0.4 * F_{max}$	1
71203	14	110	1	1.0	$0.4 * F_{max}$	1
71204	15	110	1	1.0	$0.4 * F_{max}$	1
71205	16	110	1	1.0	$0.4 * F_{max}$	1
71206	17	110	1	1.0	$0.4 * F_{max}$	1
71207	17	110	1	1.0	$0.4 * F_{max}$	1
71208	18	110	1	1.0	$0.4 * F_{max}$	1
71209	19	110	1	1.0	$0.4 * F_{max}$	1
71210	20	110	1	1.0	$0.4 * F_{max}$	1
71301	5	110	1	3.0	$0.4 * F_{max}$	1
71302	6	110	1	3.0	$0.4 * F_{max}$	1
71303	21	110	1	3.0	$0.4 * F_{max}$	1
71304	22	110	1	3.0	$0.4 * F_{max}$	3
71305	22	110	1	3.0	$0.4 * F_{max}$	1
71306	23	110	1	3.0	$0.4 * F_{max}$	1
71307	24	110	1	3.0	$0.4 * F_{max}$	1
71308	25	110	1	3.0	$0.4 * F_{max}$	3
71309	26	110	1	3.0	$0.4 * F_{max}$	1
71310	27	110	1	3.0	$0.4 * F_{max}$	3
72101	28	110	2	0.1	$0.4 * F_{max}$	1
72102	29	110	2	0.1	$0.4 * F_{max}$	1
72103	34	110	2	0.1	$0.4 * F_{max}$	1
72104	35	110	2	0.1	$0.4 * F_{max}$	1
72105	35	110	2	0.1	$0.4 * F_{max}$	1
72106	36	110	2	0.1	$0.4 * F_{max}$	1
72107	37	110	2	0.1	$0.4 * F_{max}$	1
72108	38	110	2	0.1	$0.4 * F_{max}$	1
72109	39	110	2	0.1	$0.4 * F_{max}$	1
72110	40	110	2	0.1	$0.4 * F_{max}$	1
72201*	30	110	2	1.0	$0.4 * F_{max}$	1
72202*	31	110	2	1.0	$0.4 * F_{max}$	1
72203*	41	110	2	1.0	$0.4 * F_{max}$	1
72204*	42	110	2	1.0	$0.4 * F_{max}$	1
72205*	42	110	2	1.0	$0.4 * F_{max}$	1
72206*	43	110	2	1.0,	$0.4 * F_{max}$	1
72207*	44	110	2	1.0	$0.4 * F_{max}$	1
72208*	45	110	2	1.0	$0.4 * F_{max}$	1
72209*	46	110	2	1.0	$0.4 * F_{max}$	1
72210*	47	110	2	1.0	$0.4 * F_{max}$	1
72301	32	110	2	3.0	$0.4 * F_{max}$	1
72302	33	110	2	3.0	$0.4 * F_{max}$	1
72303	48	110	2	3.0	$0.4 * F_{max}$	1
72304	49	110	2	3.0	$0.4 * F_{max}$	1
72305	49	110	2	3.0	$0.4 * F_{max}$	1
72306	50	110	2	3.0	$0.4 * F_{max}$	1
72307	51	110	2	3.0	$0.4 * F_{max}$	1
72308	52	110	2	3.0	$0.4 * F_{max}$	1
72309	53	110	2	3.0	$0.4 * F_{max}$	1
72310	54	110	2	3.0	$0.4 * F_{max}$	1

*Temperature from mean values of 0.1 mm

Table 46: Test report for creep tests under thermal load with a load level of 0.6 F_{max}

Number	Panel number	Test				Failure mode
		Temperature	Adhesive type	Glue line thickness [mm]	Number	
81101	1	110	1	0.1	$0.6 * F_{max}$	5
81102	2	110	1	0.1	$0.6 * F_{max}$	5
81103	7	110	1	0.1	$0.6 * F_{max}$	5
81104	8	110	1	0.1	$0.6 * F_{max}$	2
81105	8	110	1	0.1	$0.6 * F_{max}$	2
81106	9	110	1	0.1	$0.6 * F_{max}$	2
81107	10	110	1	0.1	$0.6 * F_{max}$	5
81108	11	110	1	0.1	$0.6 * F_{max}$	2
81109	12	110	1	0.1	$0.6 * F_{max}$	2
81110	13	110	1	0.1	$0.6 * F_{max}$	2
81201	3	110	1	1.0	$0.6 * F_{max}$	1
81202	14	110	1	1.0	$0.6 * F_{max}$	1
81203	14	110	1	1.0	$0.6 * F_{max}$	3
81204	15	110	1	1.0	$0.6 * F_{max}$	1
81205	16	110	1	1.0	$0.6 * F_{max}$	1
81206	17	110	1	1.0	$0.6 * F_{max}$	1
81207	18	110	1	1.0	$0.6 * F_{max}$	1
81208	18	110	1	1.0	$0.6 * F_{max}$	1
81209	19	110	1	1.0	$0.6 * F_{max}$	1
81210	20	110	1	1.0	$0.6 * F_{max}$	1
82101	28	110	2	0.1	$0.6 * F_{max}$	1
82102	29	110	2	0.1	$0.6 * F_{max}$	1
82103	34	110	2	0.1	$0.6 * F_{max}$	1
82104	35	110	2	0.1	$0.6 * F_{max}$	1
82105	35	110	2	0.1	$0.6 * F_{max}$	1
82106	36	110	2	0.1	$0.6 * F_{max}$	1
82107	37	110	2	0.1	$0.6 * F_{max}$	1
82108	38	110	2	0.1	$0.6 * F_{max}$	
82109	39	110	2	0.1	$0.6 * F_{max}$	1
82110	40	110	2	0.1	$0.6 * F_{max}$	1
82201	30	110	2	1.0	$0.6 * F_{max}$	1
82202	31	110	2	1.0	$0.6 * F_{max}$	1
82203	41	110	2	1.0	$0.6 * F_{max}$	1
82204	42	110	2	1.0	$0.6 * F_{max}$	1
82205	42	110	2	1.0	$0.6 * F_{max}$	1
82206	43	110	2	1.0	$0.6 * F_{max}$	1
82207	45	110	2	1.0	$0.6 * F_{max}$	1
82208	45	110	2	1.0	$0.6 * F_{max}$	1
82209	46	110	2	1.0	$0.6 * F_{max}$	1
82210	47	110	2	1.0	$0.6 * F_{max}$	1
82301	32	110	2	3.0	$0.6 * F_{max}$	
82302	33	110	2	3.0	$0.6 * F_{max}$	
82303	48	110	2	3.0	$0.6 * F_{max}$	3
82304	49	110	2	3.0	$0.6 * F_{max}$	3
82305	49	110	2	3.0	$0.6 * F_{max}$	1
82306	50	110	2	3.0	$0.6 * F_{max}$	3
82307	51	110	2	3.0	$0.6 * F_{max}$	1
82308	52	110	2	3.0	$0.6 * F_{max}$	1
82309	53	110	2	3.0	$0.6 * F_{max}$	1
82310	54	110	2	3.0	$0.6 * F_{max}$	1

Table 47: Test report for creep tests under thermal load with a load level of 0.2 * F_{max}

81301	**5**	**110**	**1**	**3.0**	**$0.2 * F_{max}$**	**1**
81302	6	110	1	3.0	$0.2 * F_{max}$	1
81303	21	110	1	3.0	$0.2 * F_{max}$	1
81304	22	110	1	3.0	$0.2 * F_{max}$	1
81305	22	110	1	3.0	$0.2 * F_{max}$	1
81306	23	110	1	3.0	$0.2 * F_{max}$	6
81307	24	110	1	3.0	$0.2 * F_{max}$	1
81308	25	110	1	3.0	$0.2 * F_{max}$	6
81309	26	110	1	3.0	$0.2 * F_{max}$	1
81310	27	110	1	3.0	$0.2 * F_{max}$	6

Table 48: Test report for creep tests under thermal load with a load level of 0.4 * F_{max} and a temperature of 130 °C

Number	Panel number	Test				Failure mode
		Temperature	Adhesive type	Glue line thickness [mm]	Number	
91201	55	130	1	1.0	0.4 * Fmax	1
91202	55	130	1	1.0	0.4 * Fmax	1
91203	56	130	1	1.0	0.4 * Fmax	1
91204	56	130	1	1.0	0.4 * Fmax	4
91205	57	130	1	1.0	0.4 * Fmax	1
91206	57	130	1	1.0	0.4 * Fmax	1
91207	58	130	1	1.0	0.4 * Fmax	1
91208	58	130	1	1.0	0.4 * Fmax	1
91209	58	130	1	1.0	0.4 * Fmax	1
91210	59	130	1	1.0	0.4 * Fmax	1
92201	60	130	2	1.0	0.4 * Fmax	1
92202	60	130	2	1.0	0.4 * Fmax	1
92203	61	130	2	1.0	0.4 * Fmax	1
92204	61	130	2	1.0	0.4 * Fmax	1
92205	62	130	2	1.0	0.4 * Fmax	1
92206	62	130	2	1.0	0.4 * Fmax	1
92207	63	130	2	1.0	0.4 * Fmax	1
92208	63	130	2	1.0	0.4 * Fmax	1
92209	64	130	2	1.0	0.4 * Fmax	1
92210	64	130	2	1.0	0.4 * Fmax	1

B.2 Stiffness

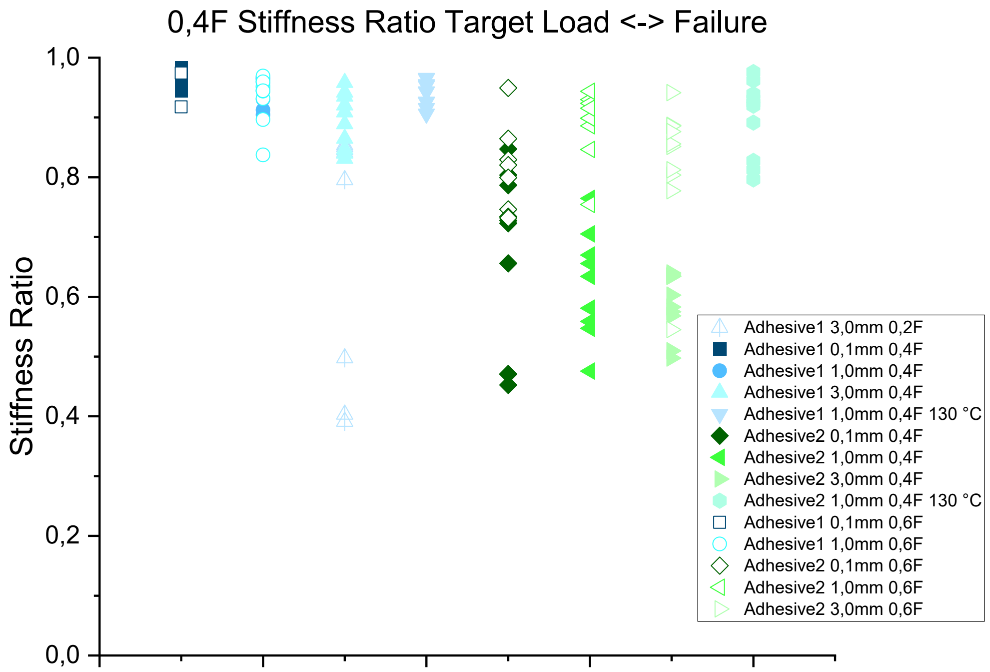


Figure 56: General overview of stiffness values of all test configurations

B.3 Failure temperature

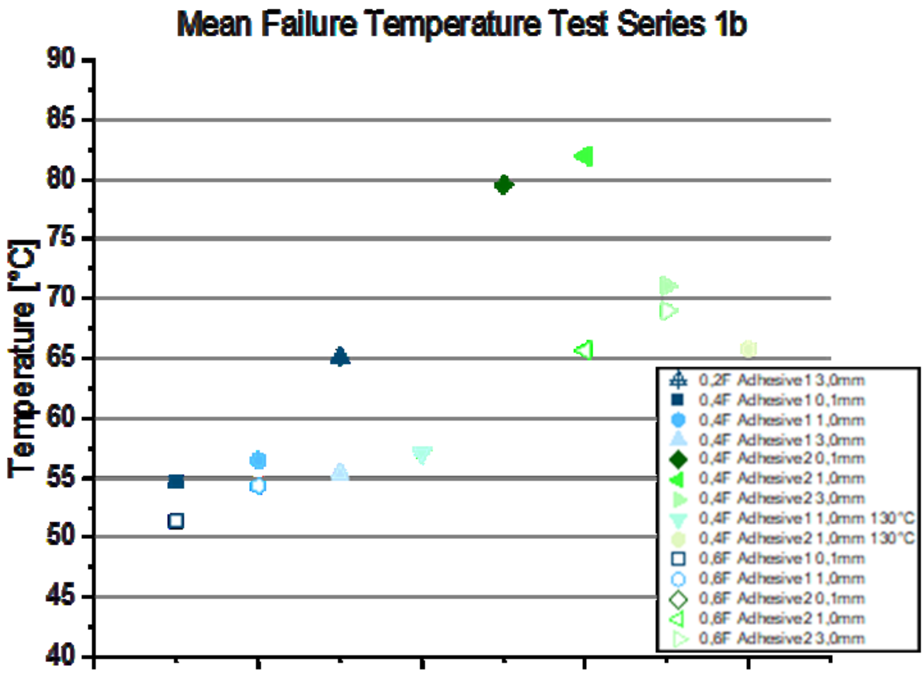


Figure 57: Overview of mean failure temperatures of all test configurations

Table 49: Failure temperatures for creep tests under thermal load with a load level of 0.2 Fmax

Failure temperature			
	Adhesive 1		
Specimen number	0.1mm	1.0mm	3.0mm
01			56.8
02			59.8
03			64
04			60.8
05			62.5
06			65.7
07			75.9
08			69.6
09			67.9
10			67.7

Table 50: Failure temperatures for creep tests under thermal load with a load level of 0.4 Fmax

Failure temperature								
	Adhesive 1		130°C		Adhesive 2		130 °C	
Specimen number	0.1mm	1.0mm	1.0mm	3.0mm	0.1mm	1.0mm	1.0mm	3.0mm
01	52.2	52.9	59.4	53	71.1	78.9	65	70
02	58.1	54.8	61	54.4	73.1	78.9	62.7	70.7
03	47.2	50.9	57	50.1	85		64.1	68.7
04	56.4		59.6	59.9	73.4	83.1	59.1	67.9
05	47.1	56.8	63.4	48.2	77.4	81.98	71	69.5
06	69.2		54.4	58.4	83.4		67	72.7
07	53.4	64.2	56.8	58.1	85.9	84.7	67	72
08	53.3	56	50.4	57	82.8	82.0	67.4	70.7
09		56.2	51.7	57.5	75.4	84.3	65	74.5
10		60	57	57.9	88.1		69.5	74.2

Table 51: Failure temperatures for creep tests under thermal load with a load level of 0.6 Fmax

Failure temperature						
	Adhesive 1			Adhesive 2		
Specimen number	0.1mm	1.0mm	3.0mm	0.1mm	1.0mm	3.0mm
01	57	52.5		69	60	60
02		65		60	61	64
03		48		43	65	60
04		62		67	70	73
05		66			68	76
06		48		57	75	68
07	54	48		68	63	74
08		57		55	62	77
09		50		66		
10		47			67	

B.4 Wood fiber fraction

Table 52: Wood fiber fraction for creep tests under thermal load with a glue line thickness of 0.1 mm

	Adhesive 1			Adhesive 2	
	0.2F	0.4F	0.6F	0.4F	0.6F
	[%]	[%]	[%]	[%]	[%]
PK01		10	30	0	-
PK02		0		-	0
PK03		0		0	0
PK04		0		10	0
PK05		0		10	0
PK06		0		0	0
PK07		0	60	20	0
PK08		0		10	-
PK09				-	0
PK10				10	0
Mean value		1.25	45	7.5	0
Standard deviation		3.5	21.2		7.1
Standard deviation %		283%	47%		94%

Table 53: Wood fiber fraction for creep tests under thermal load with a glue line thickness of 1.0 mm

	Adhesive 1			Adhesive 2		
	0.4F	0.6F	0.4F 130 °C	0.4F	0.4F 130°C	0.6F
	[%]	[%]	[%]	[%]	[%]	[%]
PK01	0	10	10	0	0	0
PK02	0	10	0	0	0	0
PK03	20	100	0	0	0	0
PK04		0	50	0	0	0
PK05	0	10	0	0	0	0
PK06		20	0	10	0	0
PK07	0	30	0	0	0	10
PK08	0	20	0	10	0	0
PK09	0	40	0	0	0	
PK10	0	10	0	0	0	0
Mean value	2.5	25	6	2	0	1.1
Standard deviation	7.1	28.8	15.8	4.2	0	3.3
Standard deviation %	283%	115%	263%	211%		300%

Table 54: Wood fiber fraction for creep tests under thermal load with a glue line thickness of 3.0 mm

	Adhesive 1		Adhesive 2	
	0.2F	0.4F	0.4F	0.6F
	[%]	[%]	[%]	[%]
PK01	0	0	0	-
PK02	0	0	10	-
PK03	0	0	0	100
PK04	0	90	10	100
PK05	0	0	0	0
PK06	0	0	0	100
PK07	0	30	0	0
PK08	0	80	0	0
PK09	0	0	0	0
PK10	0	80	0	0
Mean value	0	28	2	37,5
Standard deviation	0	39.4	4.2	51.8
Standard deviation %		141%	211%	138%