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ORIGINAL

Mechanical behaviour of finger joints at elevated temperatures

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Abstract Finger joints are commonly used to produce engineered wood products like glued laminated timber beams. Although comprehensive research has been conducted on the structural behaviour of finger joints at ambient temperature, there is very little information about the structural behaviour at elevated temperature. A comprehensive research project on the fire resistance of bonded timber elements is currently ongoing at the ETH Zurich. The aim of the research project is the development of simplified design models for the fire resistance of bonded structural timber elements taking into account the behaviour of the adhesive used at elevated temperature. The paper presents the results of a first series of tensile and bending tests on specimens with finger joints pre-heated in an oven. The tests were carried out with different adhesives that fulfil current approval criteria for the use in load-bearing timber components. The results showed substantial differences in temperature dependant strength reduction and failure between the different adhesives tested. Thus, the structural behaviour of finger joints at elevated temperature is strongly influenced by the behaviour of the adhesive used for bonding and may govern the fire design of engineered wood products like glued laminated timber beams.

Introduction

Traditionally, resorcinol–formaldehyde (RF) and phenol-resorcinol–formaldehyde (PRF) adhesives have been used for decades for bonding load-bearing timber

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components. These adhesives are characterised by their high strength and durability as well as moisture resistance. PRF resins are generally used as cold curing adhesives. More recently, new adhesives have entered the market: melamine-urea–formaldehyde (MUF) adhesives due to lower costs and shorter hardening times, and one-component polyurethane (PUR) adhesives, which are fast curing at ambient temperature, offering a broad range of application possibilities (no mixing) and are formaldehyde-free. PUR adhesives cure by reaction with water contained in the wood.

Finger joints are commonly used to produce engineered wood products like glued laminated timber beams. Although comprehensive research has been conducted on the structural behaviour of finger joints at ambient temperature (Larsen 1980; Heimeshoff and Glos 1980; Ayarkwa et al. 2000; Serrano 2000; Gonzàlez et al. 2004; Vassiliou et al. 2007; Özçifiçi and Yapici 2008; Papadopoulos 2008), there is very little information on the structural behaviour at elevated temperature. Fire tests performed in the past with glued laminated timber beams bonded with RF and PRF adhesives however never led to concerns about failure of the adhesive (Dorn and Egner 1961, 1967; Dreyer 1969). Nyman (1980) studied the influence of temperature and moisture on the strength of timber and bonded joints and found that the timber strength was more sensitive to an increase in temperature than the RF adhesive. A series of tensile tests aimed at the analysis of the temperature influence on the timber strength parallel-to-grain of finger jointed boards for glulam carried out by Nielsen and Olesen (1982) confirmed the test results by Nyman for elevated temperatures (160 and 230°C, respectively). However, they showed that the tensile strength of unjointed boards was higher than the tensile strength of finger joints tested at a temperature of 90°C. Källander and Lind (2001) analysed the strength properties of glued laminated beams before and after fire exposure. The results showed that the adhesive types tested (PUR, UF, PVA and EPI) had a small influence on the behaviour of the beams during and after fire exposure. No difference in the charring rate during fire and in the shear strength after fire was observed. It should be noted that the beams were not loaded during fire and a large proportion of the glue lines were not exposed to elevated temperatures. Recently, glued laminated timber beams with finger joints in the outer lamella on the fire-exposed tension side were tested by König et al. (2008). The finger joints were bonded with various structural PRF, MUF and PUR adhesives that fulfil current approval criteria for the use in load-bearing timber components. The tests showed no substantial difference in bending resistance at ambient temperature. In the fire situation, however, beams with PUR and MUF adhesives in the finger joints exhibited bending resistances of only 70–80% of the bending resistance of the beams with PRF-bonded finger joints. The results of a series of oven tests carried out by Frangi et al. (2004) to study the shear behaviour of different adhesives at elevated temperature demonstrated that the behaviour of PUR adhesives strongly depends on the type of adhesive. More recently, further investigation on the influence of temperature on the shear strength of glued wood joints showed large differences in thermal resistance and fracture behaviour between the adhesive systems tested (Clauß et al. 2011). The thermal behaviour of one-component polyurethane systems can be greatly varied by modifying their chemical structure.

One PUR adhesive tested showed excellent thermal stability similar to PRF. Test results based on one particular polyurethane adhesive are therefore not valid for other polyurethane adhesives.

In Europe, structural adhesives must comply with performance requirements given in EN 301 (2006) and EN 15425 (2008). With regard to performance at elevated temperature, the highest temperature in the tests according to these standards is 70°C, being held over 2 weeks under constant loading of the specimens. Therefore, the current European standards provide little or no information nor do they give a classification for adhesives at elevated temperature appropriate for fire design. In North America, as an alternative to costly full-scale testing for each structural application, a new standard ASTM D 7247 (2007) was published first in 2006, prescribing a method performing oven tests with pre-heated specimens with lap-shear joints and applying acceptance criteria that include temperatures considerably above 200°C. However, no link between these tests and the performance in fire has been demonstrated (König et al. 2008).

A comprehensive research project on the fire resistance of bonded timber elements (e.g. glued laminated timber beams, cross-laminated timber panels) is currently ongoing at the ETH Zurich. The aim of the research project is the development of simplified design models for the fire resistance of bonded structural timber elements taking into account the behaviour of the adhesive used at elevated temperature. As a basis for the structural fire resistance models, an extensive testing program and numerical analysis is planned. The combination of test results with specimens exposed to fire as well as pre-heated specimens in an oven should give the basis to establish a classification and test procedure for structural adhesives with respect to their performance in fire. The most common way of evaluating the strength of finger joints is probably through the flatwise bending of finger jointed laminations, as in practise a bending test is much easier to perform than a tensile test. However, since in a glulam beam the beam height is much greater than the thickness of the single laminations, the outer lamination is subjected to almost pure tension or pure compression (Serrano 2000). Thus, in the present study both testing methods were used. The paper presents the results of tensile and bending tests on specimens with finger joints pre-heated in an oven. The tests were carried out within the framework of two project works at master level at ETH Zurich. Results of fire tests with cross-laminated timber panels are presented and discussed in Frangi et al. (2009).

Materials and methods

Adhesives

Four different one-component polyurethane adhesives (P1–P4) and one melamine-urea–formaldehyde adhesive (M1) were studied. All adhesives fulfil current approval criteria for the use in load-bearing timber components according to EN 301 and EN 15425. All specimens with finger joints were prepared by the same certified manufacturer of glued laminated timber beams under the strict supervision of the manufacturer of the adhesives.

Tensile tests

The specimens for the tensile tests had dimensions of 800 × 140 × 40 mm^3. The geometry of the specimens with a detail of the finger joint is shown in Fig. 1. The specimens were produced using visually graded lamellas made of spruce (*Picea abies*). The average density of the specimens was (435 ± 31)kg/m^3 and the average moisture content was (12 ± 1)%. In order to obtain a reference value for the tensile strength, specimens without finger joints were also tested. The tensile tests were performed displacement-controlled with a velocity of about 0.02 mm/s using a Schenck universal machine. The specimen was fixed to the testing machine by two clamping steel plates at each end.

For the tensile tests at elevated temperature, the specimens were heated in an oven to the target constant temperature, transferred as quickly as possible to the testing machine and finally loaded reaching failure after approximately 1–2 min. The following target temperatures were analysed: 20, 60, 100 and 140°C. For each adhesive and temperature studied, 10 specimens were stored in the oven and heated until the target temperature was reached. The heating time varied between 1 and 2 h. In order to continuously monitor the temperature development, the first and the last specimen of each series of tensile tests at elevated temperature was equipped with 2 thermocouples (one on the surface and one in the centre of the specimen). Further, a reference specimen, equipped with eight thermocouples (four on the surface and four in the centre of the specimen) was also stored in the oven. As the reference specimen was permanently stored in the oven it completely dried. Thus, the temperature measured in the reference specimen was slightly higher than the temperature measured in the two additional specimens equipped with thermocouples. A typical heating cycle can be seen in Fig. 2. In order to be sure that the specimens did not cool down during transferring and testing, the finger joint region of the specimen was wrapped into glass fibre insulation that was stored in the oven as well. The whole testing procedure starting with opening the door of the oven and concluding with the failure of the specimen under tension took about four to 5 min. Preliminary tests showed that the temperature decrease of the specimen during the whole testing procedure was less than 5°C. No additional temperatures were measured while loading the specimens.

Four-point bending tests

The specimens for the bending tests were cut from the specimens that were not used for the tensile tests. Thus, for the bending tests the same wood material and

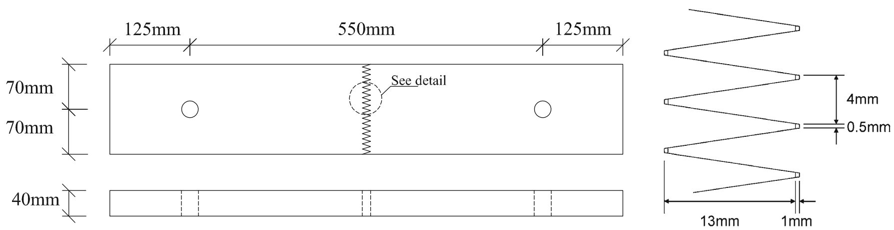


Fig. 1 Geometry of the test specimens (*left*) with detail of the finger joint (*right*)

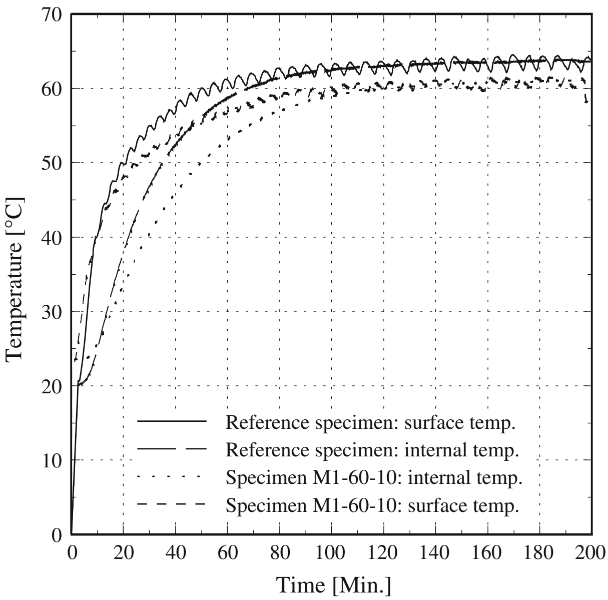


Fig. 2 Measured temperatures for the reference specimen as well as the specimen M1-60-10 (target temperature of 60°C; specimen no. 10)

adhesives were tested as for the tensile tests. From one specimen prepared for the tensile tests, it was possible to cut about 26 specimens for the bending tests. The specimens had dimensions of 420 × 19 × 13 mm^3 with the finger joint located in the middle of the specimen. Four-point bending tests according to ASTM 5572 (1995) were performed (Fig. 3). In order to study the influence of the temperature on the bending strength, 10–20 specimens for each adhesive and temperature studied were tempered in a drying chamber for about 1 h at 60, 100 and 140°C. Subsequently, they were tested using a universal testing machine (Zwick Z100). The temperature in the test laboratory was about 20°C, thus the temperature of the specimen could slightly decrease. The bending tests were performed displacement-controlled with a velocity of about 0.2 mm/s, reaching failure after approximately 1–2 min. Both, the failure load and the strain were experimentally determined. The strain was measured using a video-extensometer. Further, the bending modulus of elasticity was evaluated in the range between 10 and 40% of the failure load.

Tests results and discussion

Tensile tests

Three different failure types were observed during the tensile tests:

- Failure in the finger joint (Fig. 4, left)
- Tensile failure of timber outside the finger joint (Fig. 4, centre)
- Mixed-type failure (Fig. 4, right)

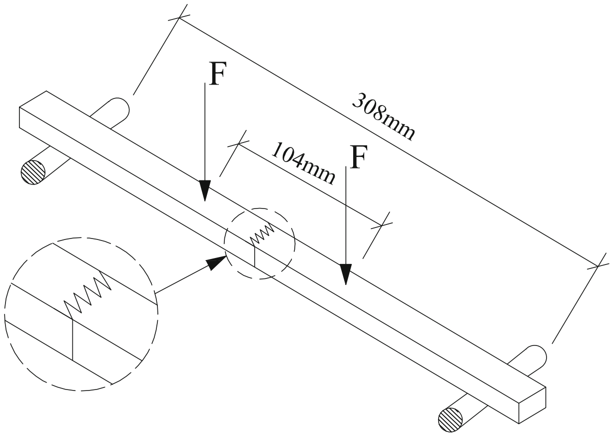


Fig. 3 Test set-up for the four-point bending tests

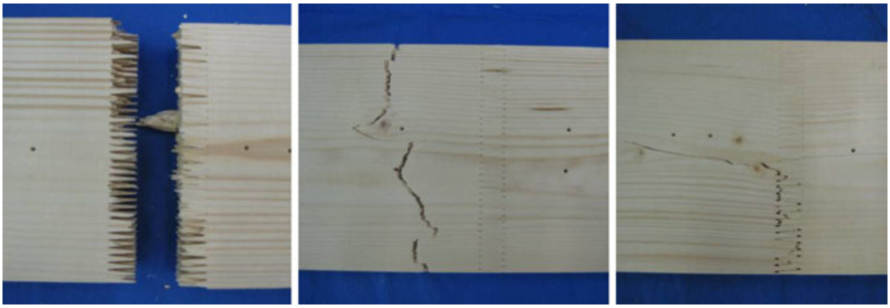


Fig. 4 Failure types observed during the tensile tests

A typical mixed-type failure usually started at a failure in the finger joint with a successive shear failure parallel to the timber grain. However, most of the test specimens failed in the finger joint. This failure type was analysed in more detail by taking into account the difference between wood failure and adhesive failure (i.e. failure of the adhesion between adhesive and timber). The evaluation of the wood failure percentage was visually estimated in 5% steps, i.e. the cross-section was divided into 20 zones, each corresponding to 5% of the whole cross-section (Fig. 5).

Figure 6 left shows the adhesive failure percentage in case of failure in the finger joint, while Fig. 6 right reports the average measured tensile strength (Table 1). At normal temperature, the specimens glued with PUR adhesives showed an adhesive failure percentage in the range of 55–65%, for the MUF adhesive it was around 35%. By increasing the temperature the adhesive failure percentage generally increased. At the temperature of 140°C, the specimens glued with PUR adhesives showed an adhesive failure percentage in the range of 90–95%, for the MUF adhesive it was around 65%.

Figure 7 shows the tensile strength measured for specimens P1 for the different target temperatures studied as a function of the density of the specimens that varied

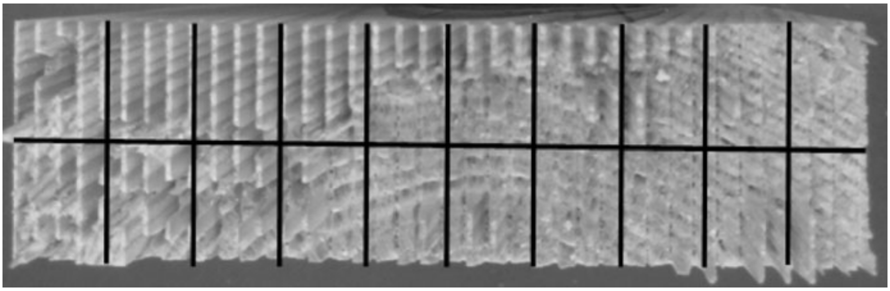


Fig. 5 Raster for visual evaluation of the failure type

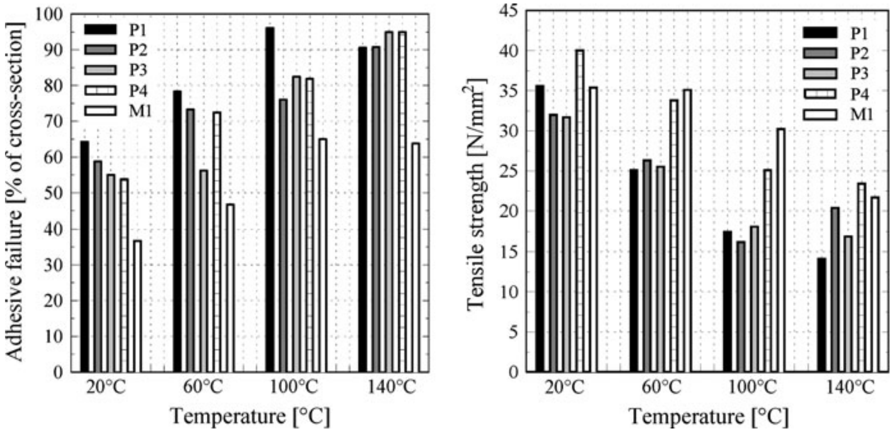


Fig. 6 Percentage of adhesive failure (*left*) and average tensile strength (*right*) as a function of the temperature for the different adhesives tested

between 390 and 510 kg/m^3. The tensile strength f_t was calculated based on the cross-sectional area according to the following equation:

$$f_t = \frac{F_u}{A} \quad (1)$$

with F_u: failure load; A: cross-sectional area ($A = 140 \times 40 = 5{,}600$ mm^2).

The influence of the temperature on the strength reduction can be clearly recognised. Further, a slight increase in the tensile strength by increasing density of the specimens tested at normal temperature was observed. The same effects were observed for all types of specimens tested.

Table 1 summarises the main statistical data (mean value $\bar{x}$, standard deviation s and coefficient of variation v) of all tensile tests including the reference tests performed without finger joints. The tensile strength measured at normal temperature (20°C) agrees well with results found in the literature (Larsen 1979; Heimeshoff and Glos 1980). For the finger joints glued with P1, P4 and M1, the tensile strength measured at normal temperature varied between 35 and 40 N/mm^2,

Table 1 Main statistical data (mean value $\bar{x}$, standard deviation s and coefficient of variation v) of the tensile strength for all tensile tests performed

Temp. (°C)	Tensile strength		Ref. spec.	Specimens glued with adhesive				
				P1	P2	P3	P4	M1
20	$\bar{x}$	[N/mm^2]	42.9	35.6	32.0	31.7	40.0	35.4
	s	[N/mm^2]	3.2	7.5	4.5	3.4	7.2	9.0
	v	[–]	0.07	0.21	0.14	0.11	0.28	0.26
60	$\bar{x}$	[N/mm^2]	35.4	25.1	26.3	25.5	33.8	35.1
	s	[N/mm^2]	4.3	5.0	2.6	4.0	3.7	6.8
	v	[–]	0.12	0.20	0.10	0.16	0.11	0.19
100	$\bar{x}$	[N/mm^2]	31.2	17.5	16.2	18.1	25.1	30.2
	s	[N/mm^2]	10.7	3.0	4.6	3.4	3.8	4.9
	v	[–]	0.34	0.17	0.28	0.19	0.15	0.16
140	$\bar{x}$	[N/mm^2]	25.4	14.1	20.4	16.9	23.4	21.7
	s	[N/mm^2]	2.2	3.2	3.0	2.3	2.7	5.5
	v	[–]	0.09	0.23	0.15	0.14	0.12	0.25

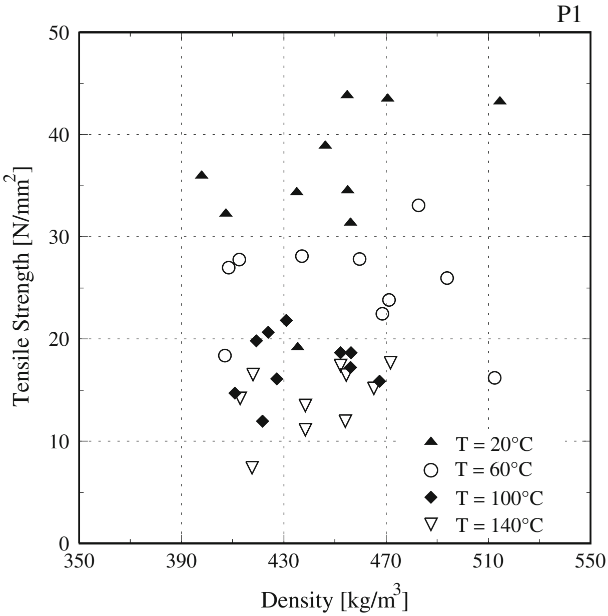


Fig. 7 Tensile strength for specimens P1 for the different target temperatures studied as a function of the density of the specimens

i.e. between 83 and 93% of the tensile strength measured from the reference specimens without finger joints. For the finger joints glued with P2 and P3, the tensile strength was comparatively slightly lower (about 74% of the tensile strength measured from the specimens without finger joints) and showed the lowest coefficients of variation, indicative of an influence of the adhesives on the structural performance of the finger joints.

Figure 8 shows the influence of the temperature on the tensile strength of the finger joints for the different adhesives tested. Following remarks can be drawn:

- Specimens glued with P1: a fairly linear decrease of the tensile strength is observed with increasing temperature. The residual tensile strength at 100°C (17.5 N/mm^2) corresponds to 49% of the tensile strength at normal temperature (35.6 N/mm^2).
- Specimens glued with P2: a fairly linear decrease of the tensile strength is observed at between 20 and 100°C. The residual tensile strength at 100°C (16.2 N/mm^2) corresponds to 51% of the tensile strength at normal temperature (32.0 N/mm^2). Thus, the temperature dependant relative reduction in strength was similar to the value observed for the specimens glued with P1. At 140°C, a recovery of the strength was observed. Ten additional tensile tests were carried out at 140°C confirming the results of the first ten tests performed. A possible reason might be found in the change of the adhesive's chemical structure (Clauß et al. 2011). Further, it should be considered that during the heating process a change in wood moisture content occurred. For the specimens heated at 100°C, the wood moisture decreased to about 7% and it dropped to about 2% for the specimens heated at 140°C (Table 2). Therefore, the increase in strength observed from 100 to 140°C might be explained by the reduction in wood moisture, which has a bigger effect on the strength than the increase of the temperature (Gerhards 1982; Glos and Henrici 1990).
- Specimens glued with P3: the tensile strength linearly decreases at between 20 and 100°C. The residual tensile strength at 100°C (18.1 N/mm^2) corresponds to 57% of the tensile strength at normal temperature (31.7 N/mm^2). Thus, the temperature dependant relative reduction in strength was slightly lower than the values observed for the specimens glued with P1 and P2. From 100 to 140°C, no significant reduction of strength was observed. A possible reason might be found in the reduction in wood moisture (Table 2).
- Specimens glued with P4: the tensile strength linearly decreases at between 20 and 100°C. The residual tensile strength at 100°C (25.1 N/mm^2) corresponds to 63% of the tensile strength at normal temperature (40.0 N/mm^2). From 100 to 140°C, no significant reduction of strength was observed. A possible reason might be found in the reduction in wood moisture (Table 2). The specimens glued with P4 reached the best results compared with the other PUR adhesives (P1, P2 and P3).
- Specimens glued with M1: at 60°C no decrease in tensile strength was observed; then a fairly linear decrease of the tensile strength was observed at between 60 and 140°C. The residual tensile strength at 100°C (30.2 N/mm^2) corresponds to 85% of the tensile strength at normal temperature (35.4 N/mm^2). The wood failure percentage (Fig. 6) and the coefficients of variation for the specimens M1 (Table 1) were generally higher than the values observed for the specimens glued with PUR, indicative of the influence of the wood material on the structural performance of the finger joints.

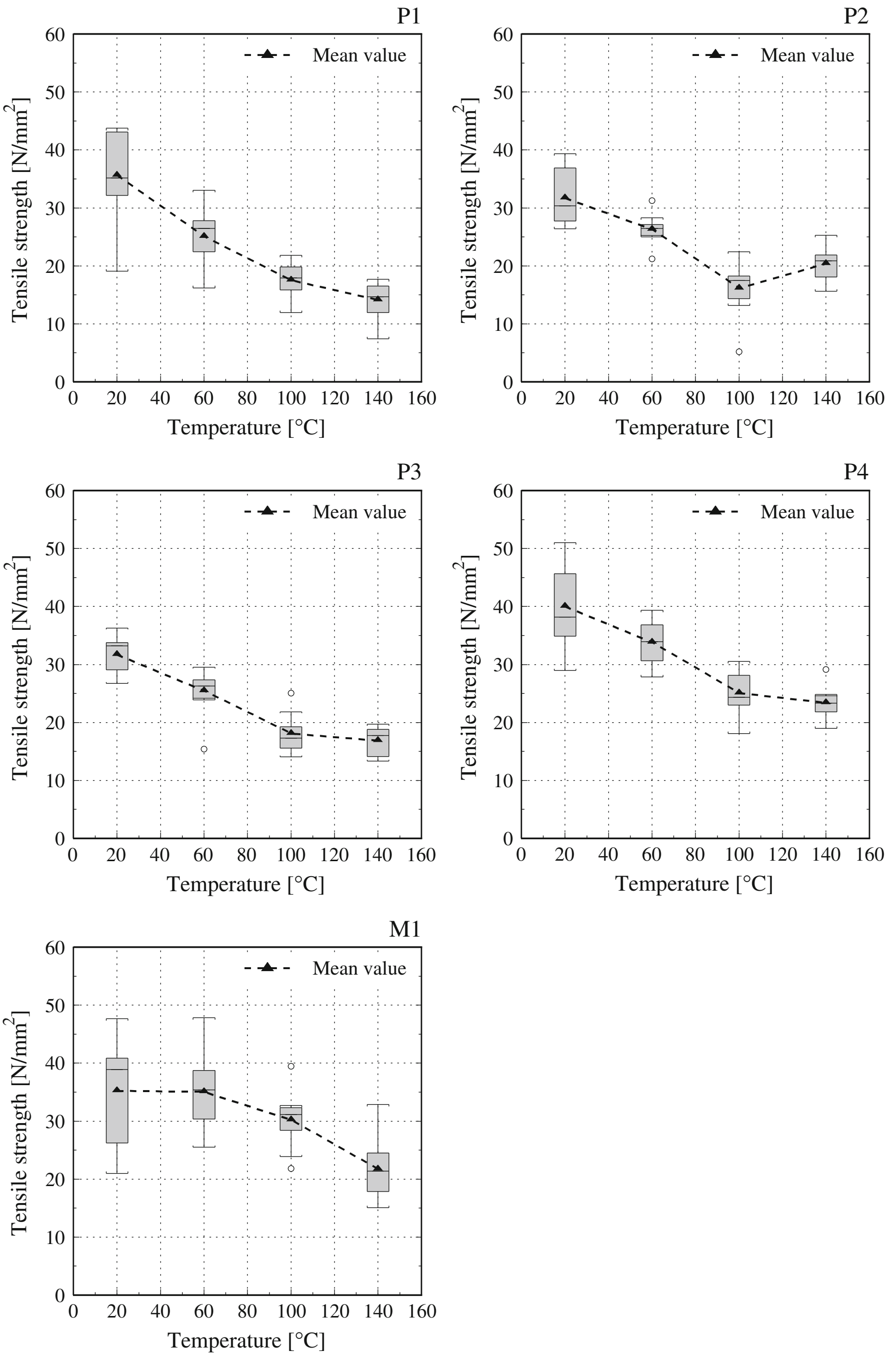
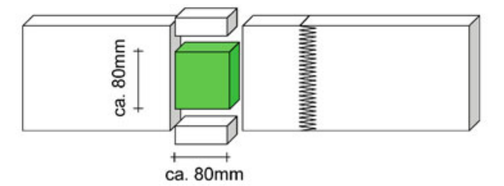


Fig. 8 Tensile strength as a function of temperature for all adhesives tested (*box* quartile of distribution; *whiskers* at most 1.5 × interquartile range; *points* outliers)

Table 2 Average wood moisture content measured according to ISO 3130 (1975) after the tensile tests

Temperature	Wood moisture content [%]				
	P1	P2	P3	P4	M1
20°C	12	12	12	13	12
100°C	7	7	8	8	7
140°C	2	2	3	3	3



For the heated specimens, the wood moisture content was measured close to the finger joint using a wood piece with dimensions of 40 × 80 × 80 mm^3 (see Figure)

Figure 9 shows a comparison between the average tensile strength measured for the different adhesives as a function of the temperature. Further, the results of the reference tests performed without finger joints (in Fig. 9 given as unjointed boards) as well as test results determined by Nielsen and Olesen (1982) are also reported. Following remarks can be drawn:

- As expected the reference specimens without finger joints showed the highest tensile strength at normal temperature as well as at elevated temperature
- In terms of absolute strength values (Fig. 9 left) the specimens glued with P1, P2 and P3 showed a similar performance at between 20 and 100°C, at 140°C however a recovery of strength was observed for the specimens P2. The specimens glued with M1 and P4 reached higher strength values than the specimens glued with P1, P2 and P3 within the whole temperature range tested. It is interesting to note the overall similar performance for the specimens glued with M1 and P4 and the good agreement with the test results determined by Nielsen and Olesen (1982)
- In terms of relative strength values (Fig. 9 right), the lowest temperature dependant reduction in strength was observed for the specimens M1 that reached a residual strength of about 62% at 140°C. The specimens P1 showed the greatest strength reduction within the whole temperature range tested and reached a residual strength of about 40% at 140°C.

Bending tests

In the case of the four-point bending tests, a visual evaluation of the failure type was carried out in a similar way as for the tensile tests, by dividing the cross-section into a number of small areas. It should be pointed out that in the upper part of the finger

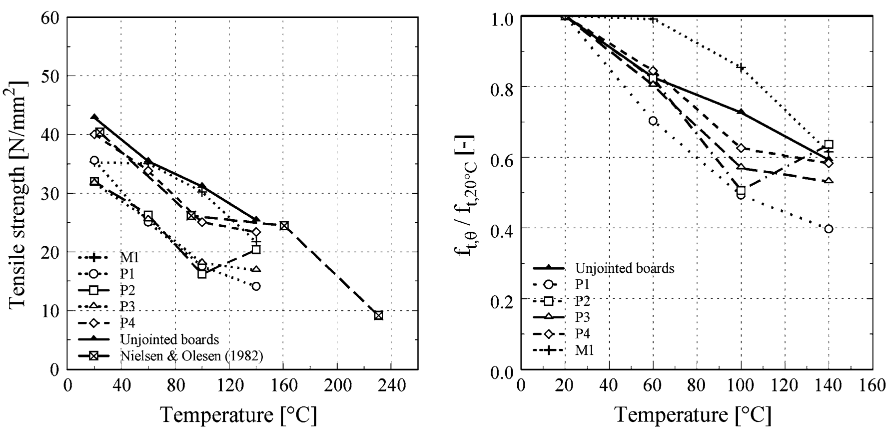


Fig. 9 Tensile strength as a function of temperature for all adhesives tested as well as for the reference tests performed without finger joints (in Figure given as unjointed boards) and the test results determined by Nielsen and Olesen (1982): absolute strength values (*left*) and relative strength values (*right*)

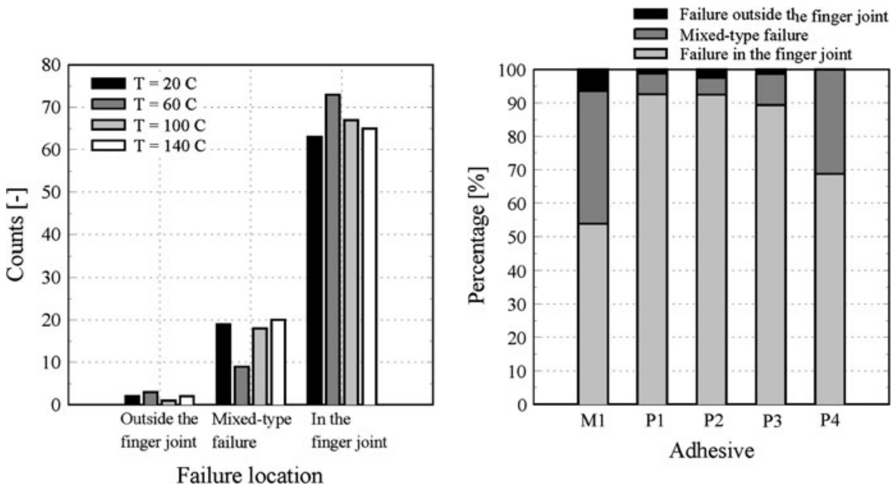


Fig. 10 Evaluation of the position of the failure

joints (i.e. in the compression zone due to bending moment) only wood failure was observed.

The position of the failure was visually evaluated as well. Three failure zones were defined: failure in the finger joint, failure outside the finger joint or a combination of both. The majority of the bending tests carried out showed failure in the finger joint (Fig. 10 left) and only a small part of the specimens partially failed outside the finger joint. Further, about the same frequency of the failure position was observed for the whole temperature range tested. The percentage distribution of the failure location is shown in Fig. 10 right. The amount of failure partly or completely outside the finger joint is much higher for the specimens M1 (45%) and P4 (30%) than for the specimens P1, P2 and P3, that showed about 90% of failure in the finger joint. These results are indicative of the influence of the adhesive P1, P2 and P3 on the structural performance of the finger joints and fit well with the observations gained from the tensile tests.

Table 3 summarises the main statistical data (mean value $\bar{x}$, standard deviation s and coefficient of variation v) of all bending tests. Figure 11 shows the influence of the temperature on the bending strength of the finger joints for the different adhesives tested. Following remarks can be drawn:

- Specimens glued with P1 showed the highest bending strength at normal temperature (64.8 N/mm^2), however the bending strength decreased considerably already at 60°C (47.8 N/mm^2, i.e. about 74% of the bending strength at normal temperature). A slight increase in the bending strength was observed at between 60 and 100°C. The residual bending strength at 140°C (41.8 N/mm^2) corresponds to 64% of the bending strength at normal temperature. The variation of the test results was significant (coefficient of variation between 17 and 28%) and increased as the temperature increases. The wood failure percentage for the

Table 3 Main statistical data (mean value $\bar{x}$, standard deviation s and coefficient of variation v) of the bending strength for all bending tests performed

Temp. (°C)	Bending strength		Specimens glued with adhesive				
			P1	P2	P3	P4	M1
20	$\bar{x}$	[N/mm^2]	64.8	56.3	50.2	56.8	61.3
	s	[N/mm^2]	11.4	7.2	10.1	6.1	8.4
	v	[–]	0.17	0.13	0.20	0.11	0.14
60	$\bar{x}$	[N/mm^2]	47.8	55.1	48.1	56.4	52.6
	s	[N/mm^2]	9.8	9.1	6.6	3.4	12.3
	v	[–]	0.20	0.16	0.14	0.06	0.23
100	$\bar{x}$	[N/mm^2]	50.9	51.3	49.7	55.1	56.6
	s	[N/mm^2]	12.3	8.0	7.8	6.5	7.7
	v	[–]	0.24	0.16	0.16	0.12	0.14
140	$\bar{x}$	[N/mm^2]	41.8	52.0	46.1	55.6	49.0
	s	[N/mm^2]	11.7	12.1	7.7	9.9	7.9
	v	[–]	0.28	0.23	0.17	0.18	0.16

specimens P1 was relatively low and a failure in the finger joint was predominantly observed.

- Specimens glued with P2, P3 and P4 in general showed a similar performance. No significant reduction of strength was observed by increasing temperature. The residual bending strength at 140°C corresponds to about 92% (P2 and P3) and 98% (P4) of the bending strength at normal temperature. The variation of the test results for the specimens P4 was quite low (coefficient of variation between 6 and 18%) and about 30% of the failure occurred partially or completely outside the finger joint.
- Specimens glued with M1 in general showed a similar behaviour to the specimens P1, however higher strength values were reached. The bending strength decreased at 60°C to about 86% of the bending strength at normal temperature, while a slight increase in the bending strength was observed at between 60 and 100°C. The residual bending strength at 140°C corresponds to 80% of the bending strength at normal temperature. The variation of the test results as well as the wood failure percentage was quite high (coefficient of variation between 14 and 23%; more than 70% wood failure). Further, about 45% of failure occurred partially or completely outside the finger joint.

Comparison of test methods

Figure 12 compares the tensile tests with the bending tests. It can be seen that the results of the tensile tests showed a much higher temperature dependant relative strength reduction than the results of the bending tests. Following factors play an important role on the structural behaviour of the finger joints and may explain the differences observed between the test methods:

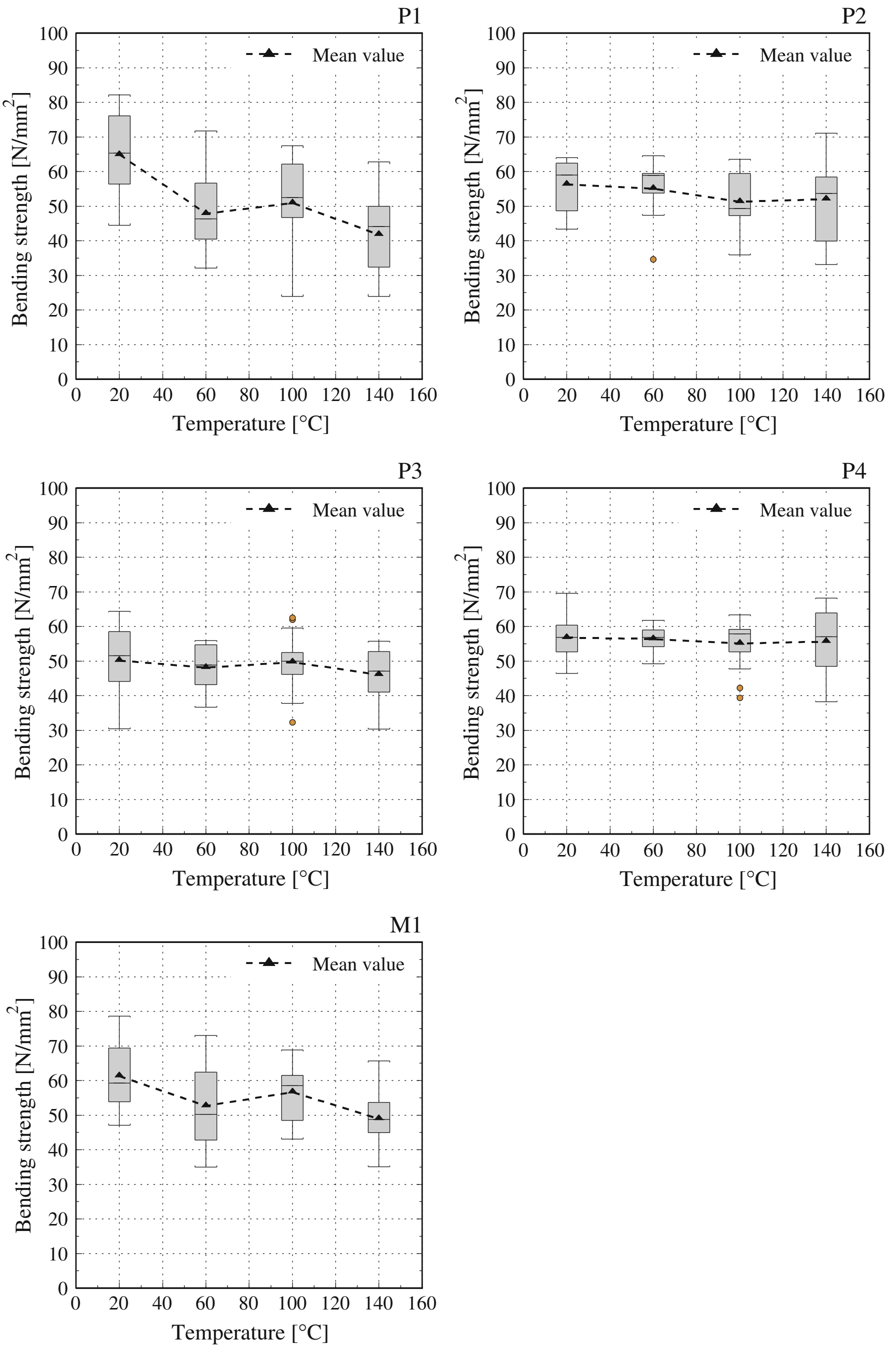


Fig. 11 Bending strength as a function of temperature for all adhesives tested (*box* quartile of distribution; *whiskers* at most 1.5 × interquartile range; *points* outliers)

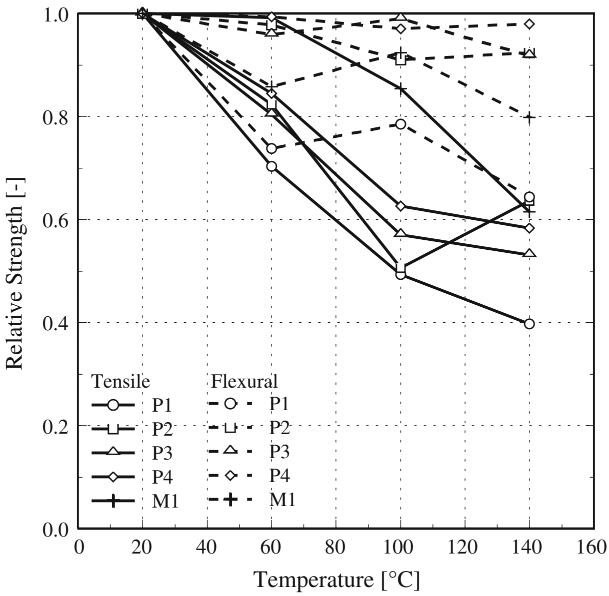


Fig. 12 Comparison between tensile and bending strength as a function of temperature for all adhesives tested

- Size effects: the specimens for the tensile tests (800 × 140 × 40 mm^3) were much larger than the specimens for the bending tests (420 × 19 × 13 mm^3)
- Influence of cooling before testing: because of the small size, the specimens for the bending tests might be more susceptible to cooling effects
- Change in the wood moisture content: because of the small size, the specimens for the bending tests were exposed with more intensity to drying effects
- Influence of moisture gradient: it can be expected that the moisture gradient in the specimens for the tensile tests was much larger than in the specimens for the bending tests, thus leading to higher moisture-induced stresses
- Influence of loading: for the bending tests only half of the finger joint was subjected to tension

Although both test methods identified the specimens with the highest temperature dependant strength reduction well (specimens P1), the bending tests performed do not seem adequate for the analysis of the behaviour of finger joints at elevated temperature.

Comparison with fire tests

Figure 13 shows the influence of the temperature on the tensile strength of timber according to EN 1995-1-2 (2004) based on results of fire tests conducted by König and Walleij (2000). For comparison, the results of the performed tensile tests at elevated temperature are reported as well. It is interesting to note that the results of the reference tests at elevated temperature are just slightly higher than the results of

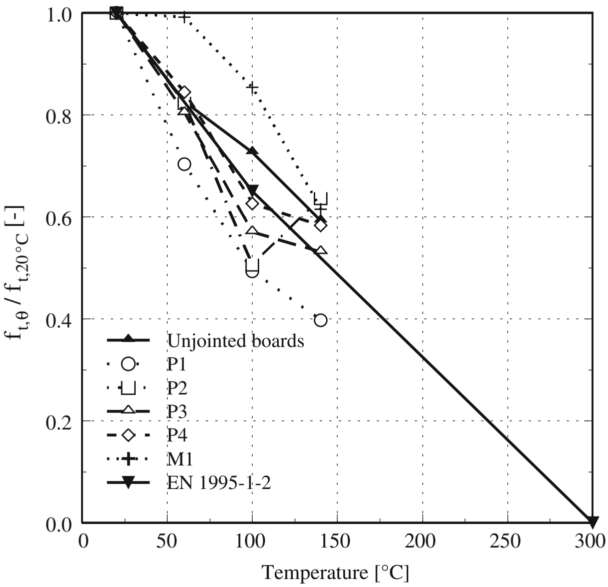


Fig. 13 Tensile strength as a function of temperature according to EN 1995-1-2 in comparison with the results of the tensile tests at elevated temperature

the fire tests, although it is known that oven tests at elevated temperature tend to give higher strength values in comparison to fire tests due to the influence of loading rate and change in wood moisture as well as the fact that the states of moisture and temperature in the fire situation are transient and not stationary as usual in the oven tests at elevated temperature (Frangi 2001; Mischler and Frangi 2001; König 2005). Further, from Fig. 13 it can be seen that the specimens P1, P2 and P3 showed a temperature dependant strength reduction higher than the strength reduction of timber. Thus, it may be expected that the behaviour of the adhesive at elevated temperature may influence the structural performance of the finger joints in fire.

König et al. (2008) recently investigated the fire behaviour of glued laminated timber beams with finger joints in the outer lamella on the fire-exposed tension side. The finger joints were bonded with various structural PRF, MUF and PUR adhesives. It is interesting to note that for the fire tests the same type of adhesive (P2) was used as for the tensile and bending tests at elevated temperature. The beams with PUR and MUF adhesives in the finger joints exhibited bending resistances of only 70–80% of the bending resistance of the beams with PRF-bonded finger joints. It can be assumed that the influence of PRF adhesive can be neglected and thus the temperature dependant bending resistance measured for the beams with PRF-bonded finger joints is mainly due to the temperature dependant reduction of wood strength. At failure, the residual part of the finger joints exhibited a temperature profile at between 50 and 300°C (König et al. 2008). As simplification a mean value of about 100°C can be assumed for the residual part of the finger joints. Based on the results of the tensile tests, the residual strength $f_{t,\mathrm{P2},100^\circ\mathrm{C}}$ at 100°C for the specimens glued with P2 was about 50%, while for the reference tests without finger joints the residual strength $f_{t,\mathrm{wood},100°\mathrm{C},\mathrm{test}}$ at 100°C was about 70% (Fig. 9 right). According to EN 1995-1-2, the residual strength $f_{t,\mathrm{wood},100°\mathrm{C},\mathrm{standard}}$ at 100°C can be estimated as about 65% (Fig. 13). The ratio between $f_{t,\mathrm{P2},100°\mathrm{C}}$ and $f_{t,\mathrm{wood},100°\mathrm{C},\mathrm{test}}$ as well as between $f_{t,\mathrm{P2},100°\mathrm{C}}$ and $f_{t,\mathrm{wood},100°\mathrm{C},\mathrm{standard}}$ therefore varies between 71 and 77% and fits very well with the observed reduction in bending resistance for the beams with PRF-bonded finger joints tested in fire by König et al. (2008). Additional fire tests are planned in order to verify the correlation between the tensile tests at elevated temperature and fire tests.

Conclusion

A series of tensile and bending tests with finger joints bonded with 5 different adhesives permitted the analysis of the influence of the adhesive on the structural behaviour of finger joints at elevated temperature. From the analysis of the test results, the following conclusions can be drawn:

- The results of the tensile tests showed a significant temperature dependant reduction in strength for the finger joints tested. Further, substantial differences in strength reduction and failure were observed between the different adhesives tested. E.g. the relative strength reduction at 100°C varied between 50 and 85% of the strength at normal temperature (20°C). Specimens bonded with three different adhesives showed a strength reduction higher than the expected strength reduction of timber in fire. Thus, it may be expected that the behaviour of the adhesive at elevated temperature may influence the fire performance of the finger joints.
- The results of the bending tests did not show significant temperature dependant reduction in strength for the finger joints tested. Thus, the bending tests do not seem appropriate for the analysis of the influence of the adhesive on the structural behaviour of finger joints at elevated temperature.
- The results of the tensile tests performed at elevated temperature seem to confirm the results of fire tests recently performed by König et al. (2008). Thus, the tensile tests may be suitable for the evaluation of the influence of the adhesive on the structural behaviour of finger joints in fire. Additional fire tests are planned in order to verify the correlation between the tensile tests at elevated temperature and fire tests.

The results of the tensile tests showed that the structural behaviour of finger joints at elevated temperature is influenced by the behaviour of the adhesive used for bonding. However, because of the random occurrence of weak zones (e.g. finger joints, knots and other defects) in commercial graded bonded structural timber elements, more experimental and numerical analysis will be performed in order to investigate to what extend fire safety is influenced by the performance of various adhesives.

For safe evaluation of the fire resistance of bonded structural timber elements, the behaviour of adhesives at high temperatures should be addressed in product and/or testing standards, providing a classification as a basis for the structural fire resistance models. The tensile tests performed may be considered as possible testing method for future standardization. Additional testing methods like the new Automated Bonding Evaluation System ABES (Wescott et al. 2007) will be assessed during the ongoing research project and the results will be presented in future publications.

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