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Strength properties of wood adhesives after exposure to fire

NORDTEST Project No. 1482-00

SP Report 2001:35
Building Technology
Borås 2001

Norsk Treteknisk Institutt
Norwegian Institute of Wood Technology

Abstract

Nordtest and SP Swedish National Testing and Research Institute (SP) have financed a study to draft a common Nordic test method to classify wood adhesives for structural purposes according to strength properties after fire exposure.

The study has been planned and carried out in cooperation between SP and Norwegian Institute of Wood Technology (NTI) with participation of Otto Graf Institute in Germany (FMPA).

Glulam beams produced with six different adhesives have been exposed to fire. Temperature distribution during the fire exposure test, weight loss and charring rate have been determined. Shear strength of glulines and wood have been determined and delamination tests have been carried out on samples exposed to fire and samples not exposed to fire. Short term shear strength and creep rupture tests at elevated temperature have been carried out on samples with wood adhesives used in the test. Preliminary calculations of temperature distributions during fire in wooden members protected against direct fire exposure by gypsum board have been made.

The results of the study on beams not protected by gypsum indicate that a wood adhesive that has shown favourable results in a creep rupture test at elevated temperature (80 °C) also will perform well during and after direct fire exposure. A static load test at elevated temperature can be used as an efficient and cheap method as an alternative to fire exposure tests of glued products for structural use.

The results of the preliminary calculations on temperature distributions during fire exposure of gypsum protected smaller wood members indicate that under certain circumstances, the temperature can reach and stay at temperatures above 120 °C for a longer period of time. An additional test at higher temperature could be needed for adhesives intended for such structures.

Key words: wood adhesives structural applications fire exposure internal temperature distribution charring rate strength properties delamination creep rupture test method

SP Sveriges Provnings- och Forskningsinstitut
SP Rapport 2001:35
ISBN 91-7848-883-4
ISSN 0284-5172
Borås 2001

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SP Report 2001:35

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Preface

This project has been aimed at drafting a common Nordic test method to classify wood adhesives for structural purposes regarding the strength properties after fire exposure.

The project has been financed by Nordtest and SP Swedish National Testing and Research Institute (SP). The study has been planned in cooperation between SP Swedish national Testing and Research Institute and Norwegian Institute of Wood Technology (NTI).

The existing standards and approval procedures in Europe do not cover new adhesive types such as PolyUretane (PU) and Emulsified Polymer Isocyanate (EPI) adhesives. These new adhesives can show tendencies for deformation under sustained load and can also be influenced by high temperatures, both by thermoplastic behaviour and chemical degradation, characteristics that the established adhesives do not have. There is a need to develop test methods and approval procedures for these new adhesive types. Methods to determine the effect of fire exposure on glulines made with these new adhesive have previously not been developed.

The primary aim of the study has been to establish a test method for adhesives regarding properties after fire exposure. A comparative study of properties of glulines made with different adhesives before and after fire exposure. The results of the comparative study have been related to results from creep deformation and creep rupture tests at elevated temperature.

The study has not primarily been aimed at test methods for adhesives used in small structural members protected against direct fire exposure. Such structures can be made with Engineered Wood Products such as I-beams made with massive wood flanges and hardboard web protected by gypsum boards. Preliminary calculations of temperature distributions within wood protected against direct fire exposure by gypsum boards have been made in addition to the fire exposure tests.

In the comparative study charring rates, internal wood temperatures and open glulines after fire exposure have been determined. It should be noted that the study has not been designed to determine charring rates for glulam beams in general.

Summary

Nordtest and SP Swedish National Testing and Research Institute (SP) has financed a study to draft a common Nordic test method to classify wood adhesives for structural purposes according to strength properties after fire exposure. The study has been planned and carried out in cooperation between SP and Norwegian Institute of Wood Technology (NTI). Otto Graf Institute in Germany (FMPA) has contributed in a round robin test with creep deformation and creep rupture testing of PU adhesives.

Glulam beams produced with six different adhesives have been exposed to fire in a comparative study. Temperature distribution during the fire exposure test and charring rate have been determined. Shear strength of glulines and wood have been determined and delamination tests have been carried out on samples exposed to fire and samples not exposed to fire. Short term shear strength and static load tests at elevated temperature have been carried out on wood adhesives used in the test. Preliminary calculations on temperature distributions in wood members protected by gypsum boards have been made.

The results of the study show no significant difference in charring rate between beams produced with different adhesives, not even between Type II Urea Formaldehyde UF adhesives and thermoplastic Poly Vinyl Acetate PVA adhesives. This result is explained by the internal temperature of the glulam beams that remains low throughout the fire exposure test, not exceeding 50 °C at the centre of the beams after 45 minutes fire exposure. However, if the openings in glulines in the glulam beams inside of the charred zone are measured and the remaining solid beam cross section is determined, the thermoplastic PVA adhesives show a significantly larger loss of solid beam width than the other adhesives.

The shear strength of all gluline samples shows a significant reduction after fire exposure. The average reduction is 12 %. The reduction in shear strength is greater for samples taken close to the charred zone as compared to samples taken in the centre of the beams. However, when the reduction in shear strength is calculated for the samples for individual adhesives, only five show significant reduction. The reduction of the shear strength after fire exposure can to a certain degree be explained by reduced strength of the wood material. The wood material close to the charred zone shows a significant reduction of shear strength while the interior material does not.

The delamination tests show a reduced delamination rate after fire exposure for all adhesives in the test, the glulines perform better after fire exposure. A possible explanation of the result is a reduced hygroscopicity of the wood after fire exposure.

The results of the study indicate that a wood adhesive that has shown favourable results in a creep rupture test at elevated temperature also will perform well during and after direct fire exposure. A static load test at elevated temperature can be used as an efficient and cheap method as an alternative to fire exposure tests of glued products for structural use.

The results of the preliminary calculations on temperature distributions during fire exposure of gypsum protected smaller wood members indicate that under certain circumstances, the temperature can reach and stay at temperatures above 120 °C for a longer period of time. An additional test at higher temperature could be needed for adhesives intended for such structures.

1 Background, aim of project

Phenolic and aminoplastic adhesives dominate in the production of laminated and fingerjointed structural wood components. These adhesives have been used for a long period of time and experiences have shown that the adhesives have favourable properties regarding durability, fire, creep and creep rupture. Test procedures, product standards and approval procedures have been developed for and adapted to these adhesives.

The existing standards do not cover new adhesive types such as PolyUretane (PU). These new adhesives can show tendencies for deformation under sustained load and can also be influenced by high temperatures, both by thermoplastic behaviour and chemical degradation, characteristics that the established adhesives do not have. There is a need to develop test methods and approval procedures for these new adhesive types.

Methods to determine creep tendencies and long term durability of adhesives are being developed within the framework of CEN, in the working group CEN/TC193 /SC1/WG4 New adhesives. Methods to determine the effect of fire exposure on glulines made with these new adhesive have previously not been developed.

The primary aim of the study has been to establish a test method for adhesives regarding properties after fire exposure. A comparative study of properties of glulines made with different adhesives before and after fire exposure. The results of the comparative study have been related to results from creep deformation and creep rupture tests at elevated temperature.

In the comparative study charring rates, internal wood temperatures and open glulines after fire exposure have been determined. However, the study has not been designed to determine charring rates for glulam beams in general.

2 Material and methods

Twelve glulam beams have been produced by NTI and cross sections for tests of gluline properties have been removed. The beams have been exposed to fire at Norwegian Fire Research Laboratory (SINTEF). Internal wood temperature, remaining cross sections, beam weight and open glulines after fire exposure have been determined. Charring rates have been determined by NTI.

Samples for determining shear strength and resistance to delamination have been produced from beams not exposed to fire and exposed to fire by SP. Shear strength for glulines and wood and gluline resistance to delamination have been determined by SP. Creep deformation and creep rupture tests have been made by FMPA, NTI and SP. Analysis of the results has been made by SP.

2.1 Adhesives in test

Six adhesives have been used to produce glulam beams for fire exposure tests; two PVA adhesives not approved for structural applications and four structural adhesives. The adhesives have been chosen to cover the whole range from thermoplastic adhesives that cannot be used for structural purposes to aminoplastic adhesives that show no thermoplastic behaviour. See Table 1.

Table 1. Adhesives used in fire exposure test.

Adhesive	Adhesive class	Comment
PVA D3	EN 204 class D3 exterior not exposed to weather	One component, thermoplastic, not for structural applications-
PVA D4	EN 204 class D4 exterior surface coated	Two component, thermoplastic, not for structural applications.
PU 1	EN 301 Type II	30 min curing one component PU adhesive
PU 2	EN 301 Type II	3 h curing one component PU adhesive
EPI	EN 204 class D4, exterior surface coated JAS 111	Adhesive type used for structural applications in Japan, but as of today not approved for structural applications in Europe.
UF	EN 301 Type II / DIN 68 141	

2.2 Wood material

Glulam beams for fire exposure tests were produced by Norwegian spruce (Picea Abies) wood. Lamellae of where produced from wood that had been pre sorted by stress grading in order to reduce variations in material properties between beams. The average density of the lamellae was 455 kg/m3 (12m/12v) with minimum density 418 kg/m^3 and maximum density 484 kg / m^3, see appendix 1.

Lamellae had been stored at 20 °C / 65 % RH for several months in order to reach an equilibrium Moisture Content (MC) of 12 %. Lamellae dimension after planing was 40 mm x 150 mm x 1400 mm.

2.3 Production of glulam beams

The glulam beams were produced at Norwegian Institute of Technology (NTI) Each of the six adhesives was used to produce two glulam beams with 6 lamellae. The lamellae were selected to achieve a minimum 200 mm zone free of knots in the centre of the fire exposed area.

Five thermocouples were installed in the glulines of each sample beam, see Figure 1.

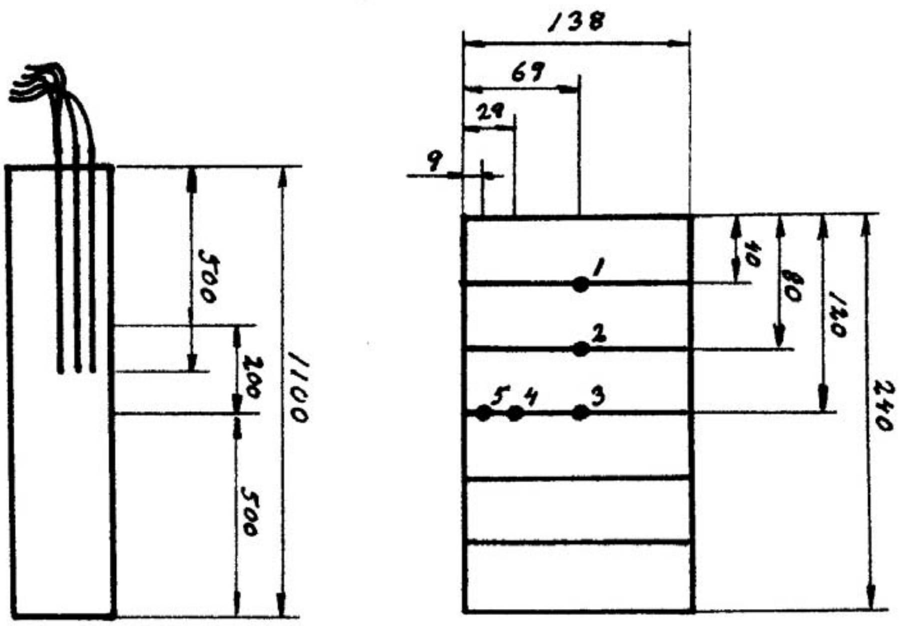

Figure 1. Placement of thermocouples in glulam beams. No knots were allowed in the lamellae in the area 500 mm - 700 mm from the bottom of the furnace. The thermocouples were placed in the centre of the zone without knots. The production method of the beams had the effect that the exact position of thermocouples could vary. Thermocouples are in the following labelled after approximate distance from surface: No 5 = 10 mm; No 4 = 30 mm; No 2 and No 3 = 70 mm and No 1 = 40 mm.

The beams were cured at ambient room temperature approximately 20 °C. Gluline pressure was 0,8 N/mm2.

Sample cross sections were taken from the beams for delamination test and shear test of glulines not exposed to fire. Final beam dimension was 140 mm x 240 mm x 1100 mm.

2.4 Fire exposure test

Fire exposure tests were carried out at Norwegian Fire Research Laboratory (SINTEF). The glulam beams were exposed to fire during 45 minutes in a 1 m^3 furnace. Six beams were used in each fire exposure test, see Figure 2. Temperature in the furnace followed standard time - temperature curve described in ISO 834 (similar to EN 1363-1). Pressure in the furnace was set to 10 Pa at 100 mm below top cover. Temperatures in the furnace and in the beams were recorded during the tests by means of thermo couples. As the fire exposure was terminated, the beams were lifted out of the furnace and cooled down with water. Loose charcoal was removed from the beams.

Figure 2. Sample glulam beams installed in furnace.

2.4.1 Measurements on beams after fire exposure

Sample beams were weighed and cut approximately 0.3 m from the bottom and from the top of the oven. Remaining cross section of solid wood, charring rate and open glulines in the solid wood adjacent to the charred zone were determined adjacent to the cut surfaces.

The area of the remaining solid beam was determined by means of tracing the perimeter of the cross section on a film, cutting out the profile and weighing the profile.

Charring rate was determined by measurement of average solid beam width in the centre 100 mm of two cross sections of each beam, see Figure 3. Charring rate was calculated as:

Charring rate = (original beam width - average remaining width) / (2 * 45) [mm/min]

Figure 3. Surfaces for measurement of remaining solid beam area cut approximately 0.3 m from the bottom end of the beams. The arrows indicate the front of the furnace.

Open glulines in the solid wood were determined by means of measurement of the depth of cracks in the glulines with a feeler gauge.

2.4.2 Shear strength of glulines and wood

Short term compression shear strength was determined for six samples from each cross sections of the beams taken before and after fire exposure. Shear tests were conducted according to American standard ASTM D 905 with reduced sample size.

Shear test samples were first taken from the cross sections that had been exposed to fire. From each remaining gluline of the beams one sample was taken close to the charred surface, immediately adjacent to the end of the open gluline. A second sample was taken from the centre section of the gluline.

Shear test samples were then taken from the cross sections not exposed to fire. Each sample was as far possible taken from the same position in the beam cross section as the ones from the fire exposed samples in order to create matched pairs.

A total of 144 gluline samples and 96 wood lamellae samples were produced. Samples damaged during production and samples containing knots in the tested area were removed. In total 136 gluline samples were tested, resulting in 65 matched pairs of samples exposed to and not exposed to fire. Totally 82 wood samples were tested, resulting in 39 matched pairs.

2.4.3 Delamination tests of beams

Delamination tests on samples taken from the beams before and after fire exposure were made according to European standard EN 302-2 with low temperature cycle as well as EN 391:1995, method B (higher temperature). The reason for the double tests was that the initial test according to EN 302-2 failed to show expected delaminations and the delamination test was repeated according to EN 391:1995 at a higher temperature.

Initial delamination tests of beams not exposed to fire were made on the full cross section of the beams, 140 mm x 240 mm. Delamination tests on beams exposed to fire were made on rectangular pieces cut from the remaining cross section of the beams.

The results of a delamination test can be expected to be influenced by the geometry of the tested cross sections, a small cross section showing lower delaminations than a larger cross section. To compare the delamination results of beams exposed to fire and not exposed to fire a similar cross section should be used. The test according to EN 391:1995 was made on three types of samples:

1) full cross sections of the beams not exposed to fire,
2) rectangular pieces cut from the remaining cross sections of the beams exposed to fire
3) rectangular pieces from beams not exposed to fire cot from positions corresponding to the pieces from the fire exposed beams.

2.4.4 Creep deformation and creep rupture tests

Creep deformation and creep rupture tests have been made on four of the adhesives in the fire exposure test, one PVA D4 adhesive, two PU adhesives and one EPI adhesive. Creep tests were made according to European varieties of ASTM D 3535 - 92 (European 3535) and ASTM D 4680 - 92 (European 4680). The test methods were chosen as they are being evaluated by standardisation group CEN / TC193 / SC1 / WG4 New adhesives.

The European 3535 method measures creep deformation in 6 test samples with 12 glulines subject to compression shear. The glulines are subject to constant load corresponding to nominally 3 N/mm^2 shear stress in a 6 week series of climates: two weeks in each climate 80 °C / dry followed by 20 °C / 85 % RH and 50 °C / 75 % RH.

Samples are loaded in cold conditions before the test rigs are placed in the climatic chamber. If noticeable deformation or gluline failure occurs in any sample, the adhesive is considered to have failed the test.

The European 4680 method measures time to failure for 50 test samples with one gluline each. The test is carried out in two constant climates: 50 °C / 75 % RH and 80 °C / dry.

The test samples at 50 °C are subject to constant loads corresponding to 4 nominal shear stress levels between 4 N/mm^2 and 10 N/mm^2. Median time to failure at each load level is determined and the shear stress corresponding to 10 000 h median failure time is calculated. At 80 °C the test samples are subject to a constant load corresponding to nominal shear stress level 3 N/mm^2.

Test samples are pre heated before load is applied. If the calculated shear stress at 50 °C corresponding to 10 000 h median time to failure is below 3 N/mm^2, or if the median time to failure at 80 °C is below 1 000 h the adhesive is considered to have failed the test.

2.4.5 Calculations of temperatures within protected beams

Preliminary calculations of temperatures during fire exposure within beams protected by thin gypsum boards where made by Heimo Tuovinen at SP. Calculations where made with beams subject to standard fire temperature curve on two sides, see Appendix 4.

Calculations where made with wood MC 6 % and 15 %. All moisture evaporates between 100 °C and 120 °C. Heat of evaporation 6780 J/kg K at MC 6 % and 16900 J/kg K at MC 15 %. Beam thickness 50 mm, 100 mm and 200 mm. Beams covered by gypsym board with thickness 0 mm, 6 mm and 12 mm. The gypsum board remains in place throughout the fire exposure in the calculations.

3 Results

3.1 Temperature within wood during fire exposure

The temperature in the centre of the glulam beams remained low throughout the fire exposure test, the temperature did not increase above approximately 50 °C, see Figure 4.

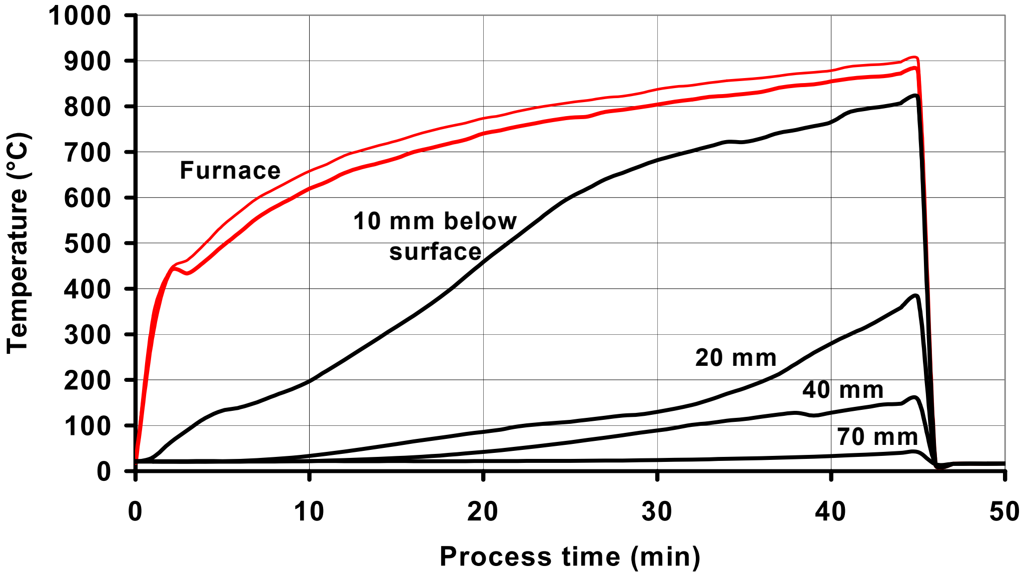

Figure 4. Average temperatures for six beams at different wood positions inside the glulam beams during the first fire exposure test. Temperatures in the test chamber marked as "Furnace".

3.2 Charring rate

The charring rates did not vary significantly between beams made with different adhesives, see Figure 5.

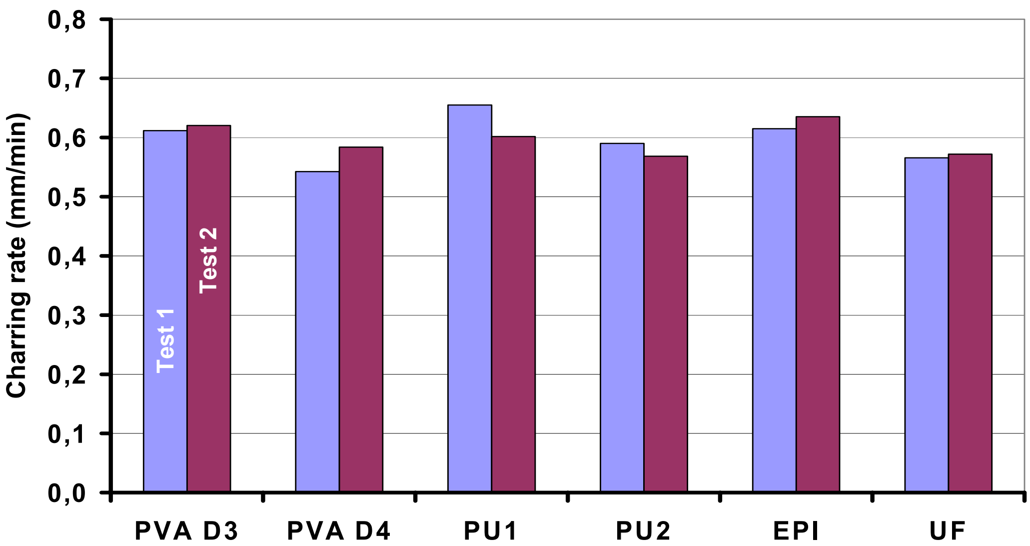

Figure 5. Average charring rate for each beam during fire exposure test. Charring rate determined at two positions of each beam; approximately 0.3 m and 0.8 m from the bottom.

The charring rate was higher during the second fire exposure test. Due to the small dimensions of the test chamber, the charring rate varies between different positions. The average charring rate was 18 % higher in the lower part of the chamber than in the upper part. There seems to be a difference also between beam positions, however, the number of tests are not sufficient to establish the magnitude of the variations. Figure 6 show the average charring rate for each beam position.

Figure 6. Average charring rate for each beam position in test chamber.

The possible effect of the beam position on the charring rate show above would increase the differences seen between the adhesives in the test. Hence, if it would be possible to adjust the measured charring rate for each beam in the test for beam position, the differences between adhesives would be reduced. However, with the limited data available for statistical evaluation, this has not been done.

3.3 Weight loss of beams

The relative density loss of the beams during the fire exposure varied between 57 % and 66 %. Density was calculated as kg/m wet weight for original beam dimension and remaining solid cross section of beam in the centre 0.7 m section after charcoal removal. Figure 7 shows the relative density loss for each beam in the test.

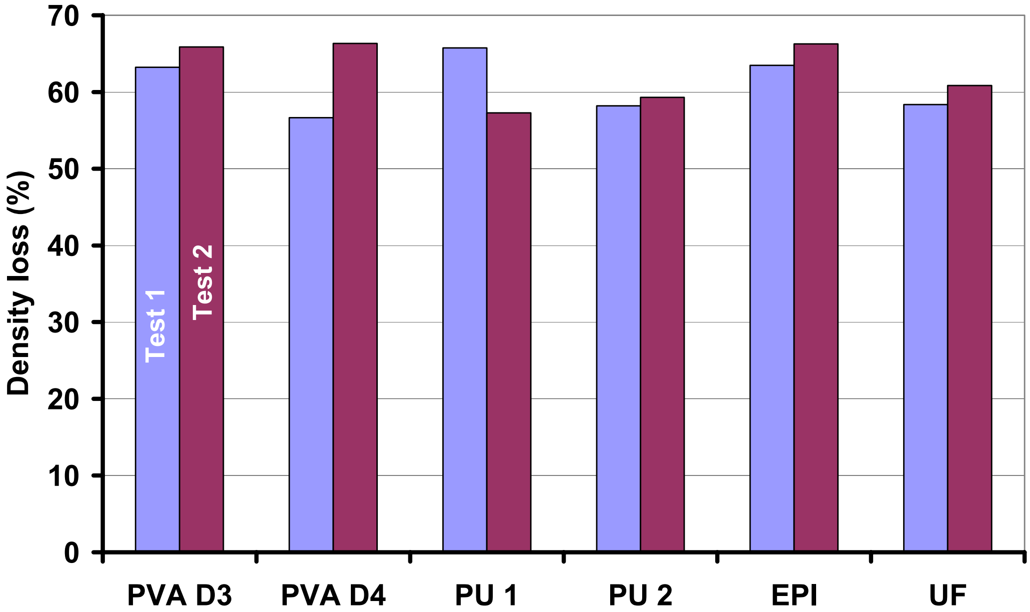

Figure 7. Density loss during fire exposure. Density calculated as kg/m wet weight for original beam dimension and remaining solid cross section in the centre 0.7 m section of beam after charcoal removal.

3.4 Open glulines and remaining cross section

Openings in glulines in the apparently solid wood after removal of loose charcoal were measured with feeler gauges. The gluline openings in the thermoplastic PVA adhesives were significantly deeper than the gluline openings in the other adhesives, resulting in a smaller remaining solid beam width, see Figure 8.

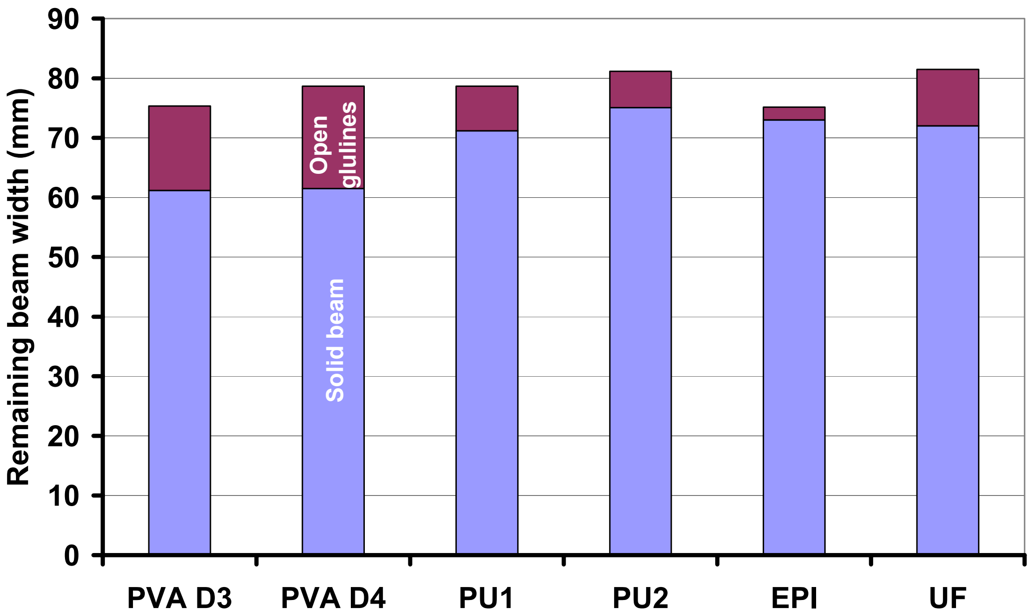

Figure 8. Average remaining beam width after removal of loose charcoal. Total beam width equals solid beam section together with beam sections with open glulines.

3.5 Shear strength before and after fire exposure

3.5.1 Shear strength of glulines

All adhesives show reduced average shear strength of the glulines after fire exposure as compared to glulines not exposed to fire. The standard deviation of gluline shear strength increase after fire exposure. The reduction in shear strength after fire exposure is significant to 99 % for the total population of matched pairs of samples. See Figure 9.

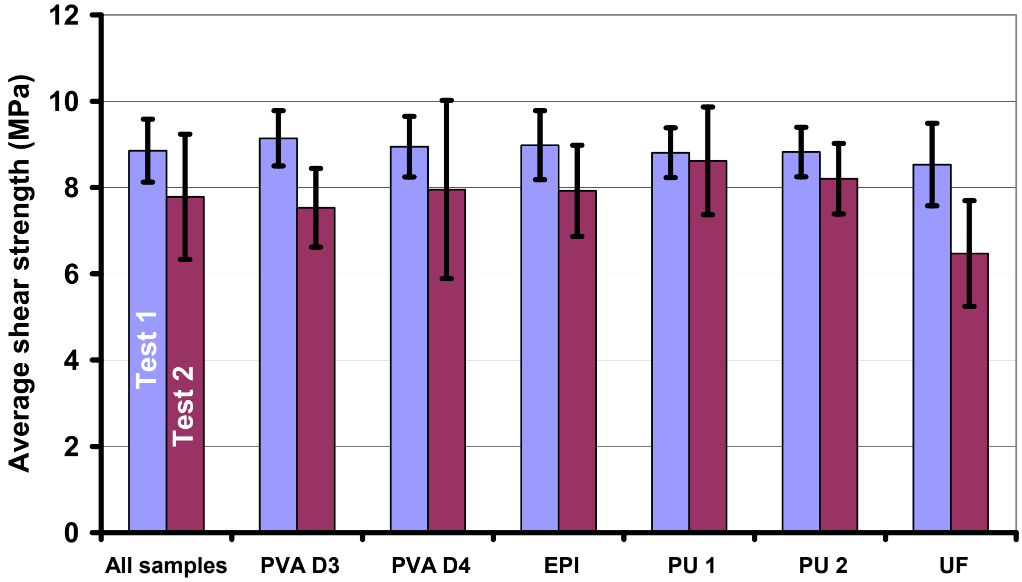

Figure 9. Average shear strength of samples from glulines not exposed to fire and exposed to fire. Standard deviation marked by bars.

The relative reduction in average shear strength is greater close to the charred zone than in the interior of the beams, see Figure 10 and Table 2. However, this is not statistically significant on 95 % level for the total population of matched pair samples.

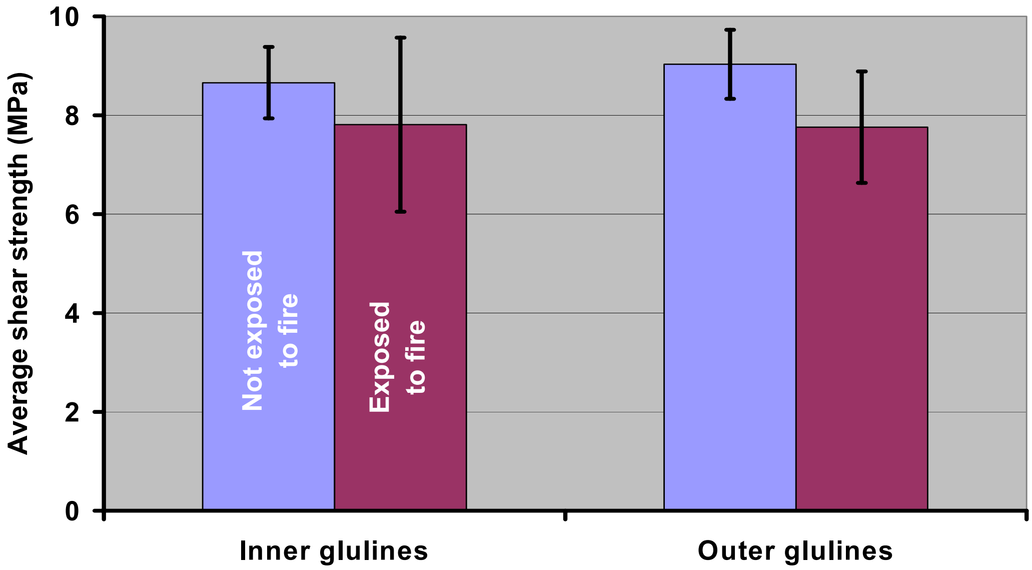

Figure 10. Average shear strength of gluline samples taken close to the charred zone (Outer glulines) and in the interior of the beam (Inner glulines). The standard deviation for each group of samples are marked by bars.

The average shear strength of the glulines not exposed to fire is higher in the surface samples as compared to the internal samples. After fire exposure, this difference has been eliminated. The average shear strength has been reduced more close to the surface than in the interior to the beam, se Table 3.

Table 3. Results of shear tests of glulines not exposed to fire and exposed to fire.

Adhesive type	Average shear strength for glulines not exposed to fire		Average shear strength for glulines exposed to fire		Reduction in average shear strength after fire exposure	
	surface sample (N/mm2)	internal sample (N/mm2)	surface sample (N/mm2)	internal sample (N/mm2)	surface sample (%)	internal sample (%)
PVA D3	9.24	8.97	7.41	7.73	19.8	13.8
PVA D4	9.27	8.62	7.65	8.25	17.5	4.3
PU 1	8.94	8.67	8.82	8.42	1.3	2.9
PU 2	8.99	8.58	8.23	8.17	8.5	4.8
EPI	9.14	8.85	8.08	7.79	11.6	12.0
UF	8.67	8.40	6.36	6.58	26.6	21.7
All samples	9.03	8.66	7.76	7.81	14.1	9.8

3.5.2 Shear strength of wood

The shear strength of the outer parts of the lamellae close to the charred zone was reduced during fire exposure. The reduction in shear strength of the outer parts of the wood is significant at 95 % confidence interval. The interior parts of the lamellae were not effected, see Figure 10.

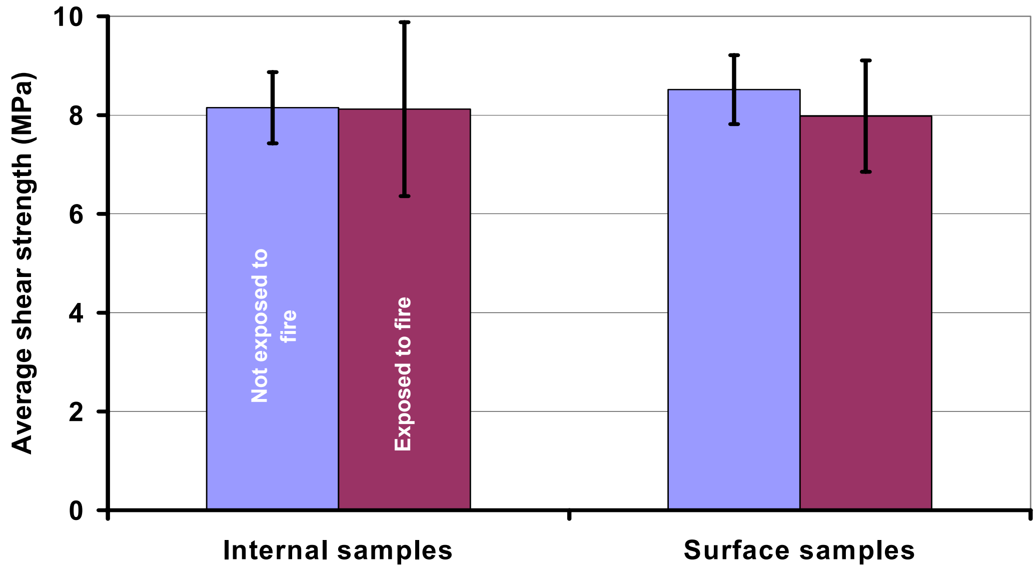

Figure 10. Average shear strength of wood samples taken from the interior of the beams and close to the charred zone. Standard deviations of each set of samples are marked with bars.

3.5.3 Radial checking in wood close to charred surface

Both gluline samples and solid wood samples cut close to the charred surface of the wood showed radial checking, possibly caused by drying. See Figure 11.

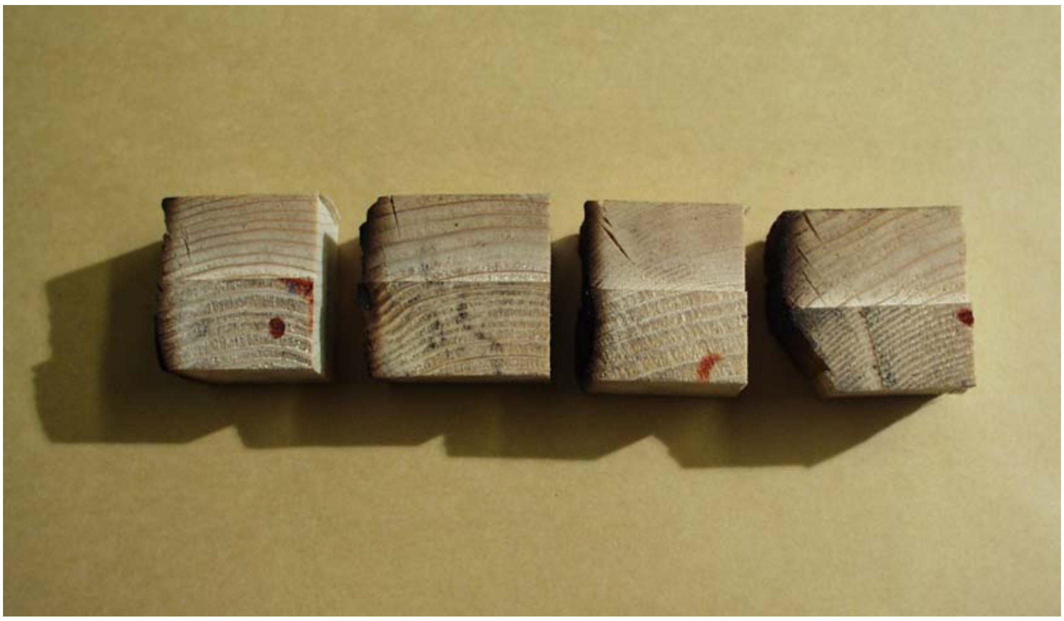

Figure 11. Radial checking in wood samples cut close to the charred surface of beams exposed to fire.

3.6 Delamination test before and after fire exposure

Delaminations after treatment according to EN 391 method B were lower for fire exposed samples than for samples that not hade been exposed to fire, for all adhesives in the study, see Table 4.

Table 4. Results of delamination tests according to EN 391 Method B before and after fire exposure. Samples not exposed to fire were tested with the original beam cross section and also with a reduced cross section corresponding to the samples exposed to fire.

Adhesive type	Delaminations in samples not exposed to fire		Delaminations in samples exposed to fire
	original cross section (% open glulines)	reduced cross section (% open glulines)	reduced cross section (% open glulines)
PVA D3	86.1	73.4	58.0
PVA D4	69.1	90.7	72.7
PU 1	1.6	3.3	0.0
PU 2	2.2	1.5	0.0
EPI	1.3	1.5	0.0
UF	12.9	2.8	0.0

3.7 Creep deformation and creep rupture tests

Both the European 3535 method and European 4680 method differentiate between the thermoplastic PVA adhesives and the adhesives designed for structural purposes. Samples glued with the PVA adhesive have no possibility to pass the requirements.

3.7.1 Creep tests according to European 3535

The European 3535 method can be used both as a creep deformation and a creep rupture method. If failure or significant creep deformation occur during the six week exposure period, the samples have failed. Table 5 shows time to failure data for PVA D4, PU1, PU2 and EPI adhesives after tests at NTI, SP and FMPA. All failures except one have occurred in the first climate 80 °C / dry.

Table 5. Results from creep rupture testing according to European 3535 (deformation data of samples not failed are not shown).

Adhesive : sample nr	Time to failure after test at NTI (h)	SP (h)	FMPA (h)	Comment
PVA D4:1	--	0.7	--	Only tested at SP
PVA D4:2	--	0.3	--	
PU1:1	0.5	3.7	0.5	
PU1:2	1.0	8.8	0.5	
PU1:3	5.0	0.5	1.1	
PU1:4	--	0.3	--	
PU2:1	ok	424.1*)	1.1	
PU2:2	2.0	211.2	1.3	
PU2:3	ok	0.63	ok	
PU2:4	--	37.1	--	
EPI:1	--	ok	--	Only tested at SP
EPI:2	--	ok	--	
EPI:3	--	ok	--	
EPI:4	--	ok	--	

*) failed in second climate 50 °C / 75 % RH

The test samples were loaded pre heated to 80 °C at SP and cold at FMPA and NTI,

The proposed requirement in European 3535 is to pass a six week climatic cycle at 3 N/mm^2 static shear stress:

Climate 1: 14 days at 80 °C / dry
Climate 2: 14 days at 50 °C / 75 % RH
Climate 3: 14 days 20 °C / 85 % RH.

The order of the climatic cycle has been changed from originally 1-2-3 in tests made at SP to 1-3-2 in tests made at a later stage at FMPA and NTI.

3.7.2 Creep tests according to European 4680

The creep rupture tests according to the European 4680 method made at 50 °C and 80 °C clearly differentiate between the thermoplastic PVA D4 adhesive and the adhesives developed for structural applications. The PVA D4 adhesive shows expected times to failure approximately 1/1000 of the requirements, see Figure 12 and Table 6.

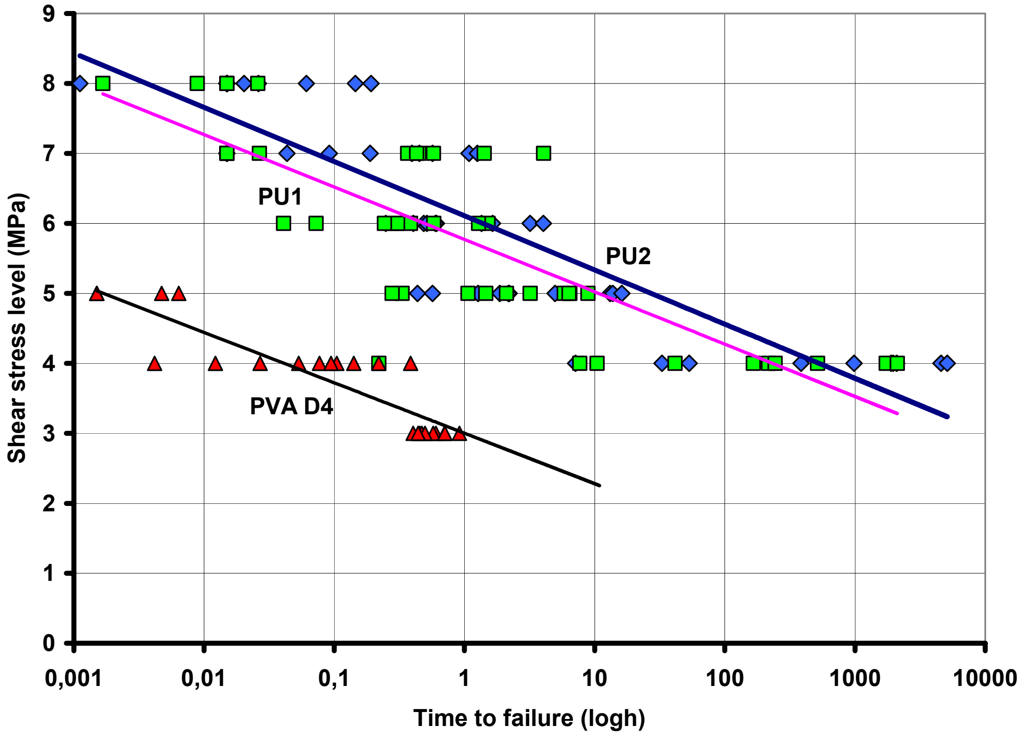

Figure 12. Creep rupture tests according to European 4680 method of PU1, PU2 and PVA D4 adhesives. Climate 50 °C / 75 % RH. PVA D4 adhesive show expected times to failure within 10 h at 3 N/mm2 stress level, as compared to required 10 000 h.

Table 6. Time to failure at 3 N/mm2 shear stress and 80 °C temperature. Nordic requirement 1000 h median time to failure.

Adhesive type	Time to failure median (h)	min (h)	max (h)	Comment
PVA D4	0.8	0,01	2.1	
PU 1	2 269	734	3 655	
PU 2	1 891	1 260	2 698	
EPI	--	--	--	No failures after 8600 h

3.8 Temperatures within protected beams

The results of the preliminary calculations of temperatures in gypsum- covered beams indicate that the moisture of the wood has a great influence of the temperature. Figure 13 and Figure 14 show the calculated temperature distribution in a 50 mm wide beam covered with 6 mm gypsum board at MC 6 % and 15 % respectively.

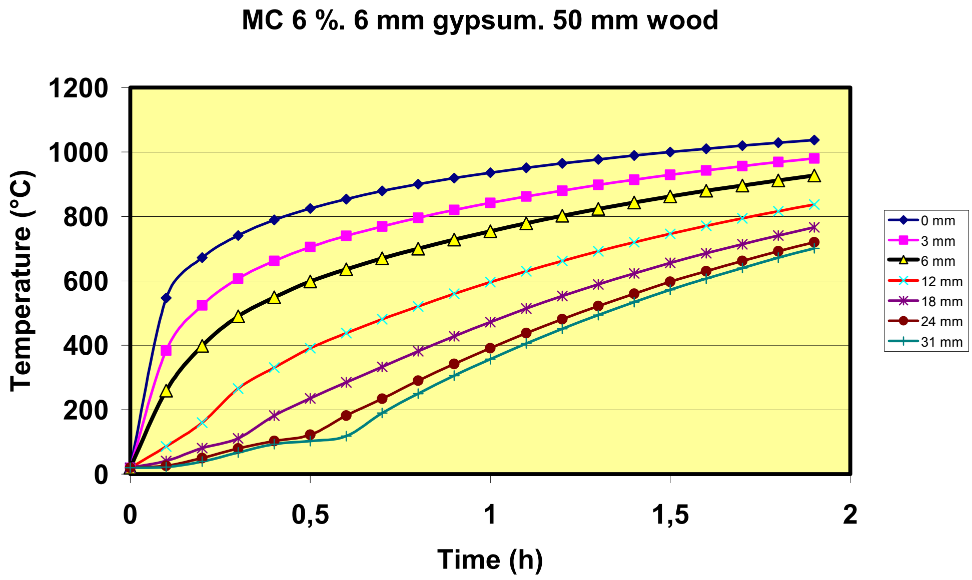

Figure 13. Calculated temperature in a 50 mm wide beam covered by 6 mm gypsum board at MC 15 %. Fire exposure standard fire on both sides of the beam. Borderline gypsum - wood at 6 mm.

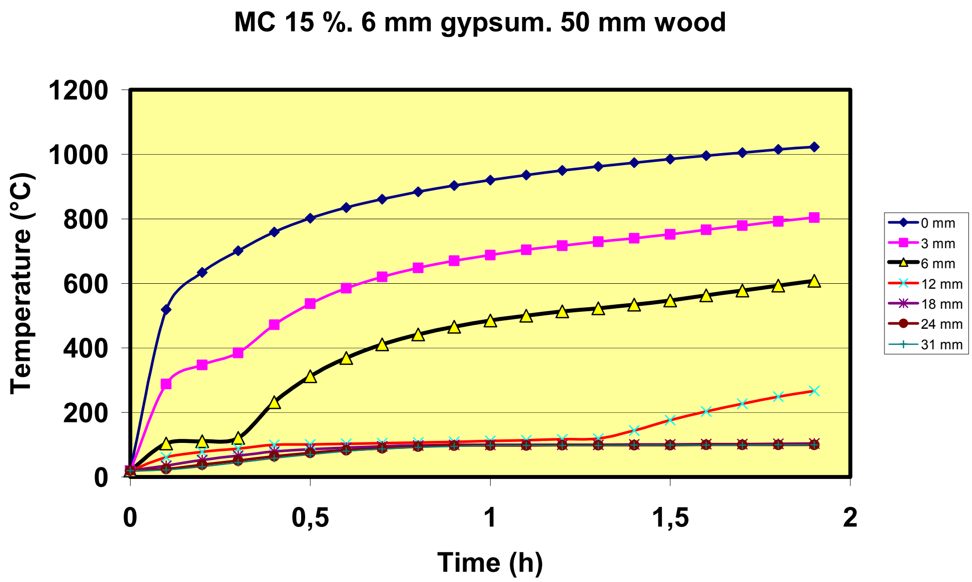

Figure 14. Calculated temperature in a 50 mm wide beam covered by 6 mm gypsum board at MC 15 %. Fire exposure standard fire on both sides of the beam. Borderline gypsum - wood at 6 mm.

The results indicate that at MC 6 %, the temperature in the centre of the beam increase from 120 °C to 350 °C in approximately 25 minutes. At MC 15 %, the temperature in the centre does not reach above 100 °C during the period of the calculation, 1.9 h. At 6 mm depth of the wood, temperature does not reach 120 °C until after 1.3 h.

4 Discussion

No difference in charring rate between the different adhesives in the test has been shown, not even between the thermoplastic PVA adhesives and the other adhesives. This perhaps unexpected result is explained by the temperature distribution in the beams.

The thermoplastic PVA adhesives show larger gluline openings inside the charred zone than the other adhesives. However, no significant increase in charring rate of the beams due to the greater gluline openings in the PVA glulines has been determined.

4.1 Temperature within the fire exposed beams

The temperature in the centre of the beams remains low throughout the entire fire exposure test. The temperature in the centre of the beams at the end of the fire exposure varies between 37 °C and 50 °C for the 12 beams tested. Several earlier studies have shown similar patterns of low internal wood temperatures during fire exposure tests, such as [Dorn and Egner, 1962, Haksever, 1982 and Broo, 1998].

The low internal wood temperature has the effect that for all beams, a large proportion of the glulines will never be exposed to high temperature. Also a thermoplastic adhesive can thus perform well during fire in a beam.

The volume of wood that is subject to temperatures above 100 °C is limited to the zone closest to the charred surface and will in a relatively short time be destroyed by the fire. The time from that the temperature in the wood increase above 100 °C until it reaches 300 °C is in this test roughly 10 - 20 minutes. With a charring rate of approximately 0.6 mm / minute, this corresponds to a 6 - 12 mm wide zone of the wood being heat affected. This has the effect that in a beam, only a limited proportion of the remaining glulines after fire exposure will actually have been subject to higher temperatures, and then only for a short period of time.

The combination of the limited volume that is exposed to high temperature and a short exposure time will reduce the risk of chemical breakdown of adhesives to the volume of the beam where the wood itself is damaged. Also an adhesive that can be expected to be damaged by higher temperatures, such as UF adhesives, will perform well during and after fire exposure.

A thermoplastic adhesive will soften in the hot zone of the beam close to the charred surface. The softening of the adhesive in combination with stresses introduced in the wood, such as perpendicular stresses due to shrinking, will cause the glulines to open. This is seen in the test results and leads to a reduced remaining solid cross section of the beam for the thermoplastic adhesives. However, the greater openings in the thermoplastic PVA glulines have not lead to a significant increase in charring rate of the beams.

It is possible that a significant difference between the thermoplastic PVA adhesives and the adhesives designed for structural applications would have been detected with a larger number of test samples. A second possibility is that open glulines perhaps have little effect on the charring rate due to the limited supply of oxygen inside the open gluline and a cooling effect of water evaporating from the interior of the wood.

4.2 Temperature within gypsum covered beams

The preliminary temperature calculations indicate that at MC level 6 %, the smaller size beams will behave fairly similarly to beams subject to direct fire exposure. The period during which the temperature is within the range where there is risk that the adhesive is subject to degradation but the wood still is intact is very short. At MC 6 % there should then not be needed a specific heat exposure test of the adhesive due to the short duration of the heat exposure.

At MC level 15 %, the temperature within the beams seems to remain low for a very long time due to the cooling effect from the heat of evaporation. Thus at MC 15 % the low internal temperature of the wood could indicate that there is no need for a heat exposure test of the adhesive.

However, the results above show that there can be a MC level between 6 % and 15 % where the wood temperature can remain within the dangerous levels for a prolonged time. If so, this could mean that there is a need for a specific heat resistance test aimed at adhesives for fire protected or covered structural members.

4.3 Charring rates

No significant difference in charring rate have been detected between the beams made with different adhesives in the test. Not even between thermoplastic PVA adhesives and structural adhesives. This indicates that the adhesive type have little or no effect on the charring rates of the beams.

The charring rates measured in this study are at approximately the same levels or below charring rates of earlier studies. Dorn and Egner show charring rates for 160 mm wide beams of 0,56 mm/min after 30 minutes fire exposure and 0.66 mm/min after 60 minutes exposure [Dorn and Egner, 1961]. Haksever use 0.8 mm/min [Haksever, 1982].

The charring rates may have been influenced by the small dimensions of the furnace and the possibly low oxygen content in the furnace. However, since the charring rates measured are at approximately the same level as earlier studies, this should not have affected the comparative study of the adhesives.

Also, the charring rates are not reduced with a stronger adhesive. Fire exposure tests made at SP with beams glued with PU 2 of this study and PRF showed no difference in charring rate between the two adhesives [Kemmsies, 1998]. This supports the conclusion that the adhesive type have little effect on the charring rates.

4.4 Shear strength of glulines and wood

The average shear strength of the <u>gluline samples</u> is reduced after fire exposure of the beams. The average reduction is greater for samples cut close to the charred surface as compared to samples taken from the interior of the beams.

The average shear strength of the <u>wood samples</u> is only reduced for the samples cut close to the charred surface, not for the interior samples.

The original shear strength of the samples, the samples not exposed to fire, is higher closer to the surface of the beam than in the centre part of the beam. This is probably due to a higher density of the wood in the lamellae taken farther away from the pith in the logs. After fire exposure, the difference in shear strength has been reduced and the wood samples cut close to the charred zone show similar shear strength as the interior samples. The average shear strength of the interior samples have not been reduced, see Figure 10.

The greater reduction in shear strength for the samples cut from the beam close to the charred surface can have been influenced by the radial checking shown in Figure 11. Another possible explanation is reduced wood strength due to hydrolysis of the wood. The interior parts of the beams have been subject to neither high temperatures nor excessive drying and are not affected.

The greater loss in shear strength for the gluline samples cut close to the charred surface can possibly be explained by the reduced shear strength of the wood. However, since the interior parts of the beams have not been exposed to high temperatures and the wood in the interior parts of the beams does not show a reduced shear strength, the entire loss of gluline strength cannot be explained by damage to the wood. The damage to the glulines from the interior parts of the beams cannot be explained by the results in this study.

The UF adhesive shows a lower initial shear strength in comparison to the other adhesives, as well as a greater reduction in shear strength after fire exposure for the samples taken close to the charred zone. This can be expected since UF is a less ductile, more brittle, adhesive than the others.

It is possible that the adhesive has suffered from hydrolysis in the zone close to the charred surface. However, it is unlikely that a short period of exposure to high temperature during a fire will lead to severe degradation of the adhesive in the gluline. Studies by Bally and by Fox on full size beams damaged during fires show no or limited reductions of shear strength [Fox, 1974 and Bally, 1971]. A study by ATO Findley and Sagot have shown that also UF adhesives of class D4 can withstand high temperatures for several hours [Elbez, 1999]. This could indicate that the reduced shear strength of the gluline close to the charred zone is dependent on the wood properties, possibly in combination with a physical degradation of the wood- adhesive interface.

4.5 Improved delaminations

The results of the delamination test do not indicate a reduced resistance to moisture after fire exposure, on the contrary the fire exposed glulines performed better in the test. The delamination test showed reduced openings in the glulines tested after fire exposure as compared to glulines not exposed to fire for all adhesives in the test.

There can be several possible explanations for this result. The most likely are related to the changes in wood properties close to the charred surface:

- The wood closest to the charred surface will most likely show a reduced hygroscopicity due to beginning hydrolysis of the material which in turn can reduce the swelling and shrinking during the test.
- Reduced tensile strength of the wood close to the charred surface due to hydrolysis of the wood can reduce the tensile stresses on the glulines.
- Internal radial cracks in the wood close to the charred surface reduce the stresses across the glulines.

A less probable explanation is post curing of the adhesives during the fire exposure test. This is less probable since all adhesives show the same trend.

4.6 Static load test alternative to fire exposure

The temperatures in the centre part of the beams are lower during the fire exposure tests than during the creep deformation and creep rupture tests according to European 3535 and European 4680, temperatures below 50 °C in the beams as compared to 80 °C during the creep tests.

The wood is destroyed relatively fast after the temperature has increased above 100 °C. After a fire exposure, only a limited proportion of the beams have actually been exposed to higher temperatures.

A study by ATO Findley / Sagot made with UF D4, UF Type II, MUF Type II and PRF Type I adhesives indicate that the gluline will regain shear strength after cooling down after fire exposure and that a significant permanent decrease in gluline shear strength for Type I and Type II adhesives does not occur until several hours of exposure at 80 °C [Elbez, 1999].

The fire exposure test lasted only 45 minutes of which the period when the wood is actually above 100 °C is only 10-20 minutes. This can be compared to the proposed test periods of European 3535 with 336 h each at 80 °C, 20 °C and 50 °C; and the test period of European 4680 of more than 1000 h at 80 °C.

The higher temperatures and longer test periods of the creep tests add up to much more severe tests conditions than an actual fire exposure test. It is most unlikely that an adhesive that has passed either the European 3535 or European 4680 creep test will fail in a fire exposure tests. Creep tests at elevated temperatures can thus be used as an effective alternative to fire exposure tests for adhesives for structural purposes.

The results are valid under the condition that the material or the design of the structure protects the gluline from high temperatures. In this study the fire exposure tests were made on glulam beams not protected against direct fire where the combined effects of the insulating charcoal layer and the heat of evaporation of the wood moisture reduce the temperature increase in the early stages of the fire. Only the glulines closest to the charcoal layer are actually exposed to high temperature and will relatively quickly be destroyed.

If on the other hand the glulines structure would be made up with wood members protected against direct fire by a relatively thin gypsum board or fire resistant lacquer layer, the temperature could perhaps reach levels where the adhesive is damaged without the wood being destroyed. An additional test made at higher temperatures than 80 °C could then be needed for adhesives intended to be used for fire protected structural wood members.

4.7 Sources of errors

4.7.1 Beams not subject to static load

The fire exposure tests were made with beams not subjected to static load. This may have influenced the results, the thermoplastic adhesives can be expected to show less favourable results if subjected to load.

However, the internal temperature of the beams has remained low throughout the fire exposure tests and the test period has only lasted only 45 minutes. The glulines in the remaining cold solid beam cores could have been able to carry the load throughout the tests. A test made with loaded beams could then be expected to show greater variation between the adhesives.

4.7.2 Small test furnace

The furnace in which the fire exposure test was made was small, with a test volume limited to 1 m^3. The small test chamber in combination with a high amount of wood in the furnace may have influenced the results:

- varying temperatures between different parts of the furnace due to samples placed close to walls and each others
- lower temperatures in the measured points of the furnace than the standard curve, although within the limits of the standard. The temperatures were measured in the top half of the furnace with thermocouples that can be influenced by heat radiation.
- possibly a low oxygen content in the chamber. The oxygen content was not measured during the test, but the low wood temperatures in combination with the differences in charring rate between the higher parts and lower parts of the beams could indicate a shortage in oxygen.

When the results of this study are compared to an earlier study made with a larger furnace, both internal wood temperatures and charring rates were similar [Broo, 1998]. This indicate that if the small furnace has influenced the temperature levels and charring rates, the effect is limited, and that the possible influence on the comparative test between the adhesive types is acceptable.

4.7.3 Limited number of samples

The relatively small number of tests samples has made it difficult to achieve significant differences between various parameters. With a greater number of samples, a complete statistical evaluation of the material could have been made.

4.7.4 Short fire exposure

The fire exposure was relatively short, 45 minutes. Thermal breakdown of adhesives could be expected if the fire exposure had been longer. A longer period of elevated temperature in the wood could possibly occur if the wood was protected against direct fire exposure, as in the preliminary temperature calculations.

4.7.5 Moisture content of beams

The moisture content of the beams was 12 % during the fire exposure test, the normal MC level used for tests of wood. However, in a dry indoor environment the MC level of wood can be as low as 4-5 % during wintertime. Since the heat of evaporation has a significant effect on the temperature distribution, a test made at a lower MC level could show different results.

A lower MC level would probably result in a faster fire process, a faster temperature increase as well as faster charring. A fire exposure test at a lower MC level could then be expected to result in shorter exposure of the adhesive to high temperature.

5 Conclusions

Although minor differences in behaviour have been measured between the adhesives in this study, the overall impression is that the adhesive types have had a remarkably small influence on the behaviour of the beams during the fire exposure tests.

No difference in charring rate between the beams made with different adhesives has been detected.

Also thermoplastic adhesives have shown reasonably good properties during the fire exposure. Although the remaining solid cross section of the beams after the fire exposure tests is smaller than for the other adhesives in the test, the difference has not lead to an increase of the measured charring rate.

The average shear strength of the glulines inside the charred surface has been reduced 12.1 % as compared to samples not exposed to fire. The reduction is greater close to the charred surface than in the interior.

The resistance to delamination has increased for all adhesives in the test after fire exposure.

The study has shown low temperatures inside the beams, the temperature in the centre of the beams have not exceeded 50 °C after 45 minutes fire exposure. The zone subject to high temperature has been shown to be narrow, and the time that the wood and glulines are subject to high temperature short. Hence the influence of high temperature on the glulines has been limited in this study.

The low internal temperatures in the beam in combination with the short period of time the glulines are subject to higher temperatures indicate that a direct fire exposure test is less severe to a gluline than a creep test at 80 °C temperature. The thermoplastic PVA adhesives that functioned fairly well during the fire exposure test have no possibility to pass a creep test at 80 °C.

A creep rupture test or a creep deformation test made at 80 °C is an efficient alternative to direct fire exposure tests of structural adhesives.

The results of the preliminary calculations on temperature distributions during fire exposure of gypsum protected smaller wood members indicate that under certain circumstances, the temperature can reach and stay at temperatures above 120 °C for a longer period of time. An additional test at higher temperature could be needed for adhesives intended for such structures. SP recommends that the need for such a test should be evaluated.

6 Literature

6.1 Standards

American standard ASTM D 3535-92 Standard test method for resistance to deformation under static loading for structural wood laminating adhesives used under exterior (wet use) exposure conditions.

American standard ASTM D 4680- 98 Standard test method for creep and time to failure of adhesives in static shear by compression loading (wood-to-wood).

American standard ASTM D 905-98 Standard test method for strength properties of adhesive bonds in shear by compression loading.

European standard EN 204 : 1991 Evaluation of non -structural adhesives for jointing of wood and derived timber products.

European standard EN 301: 1992 Adhesives, phenolic and aminoplastic, for load-bearing timber structures: Classification and performance requirements.

European standard EN 302 - 2: 1992 Adhesives for load-bearing timber structures- Test methods - Part 2: determination of resistance to delamination (laboratory method).

European standard EN 391: 1995 Glued laminated timber - Delamination test of glue lines.

European standard draft prEN 1365-3 Fire resistance tests for loadbearing elements - Part 3: beams. October 1998.

European standard EN 1365:3 Fire resistance test for load bearing elements - Part 3: beams. The tests according to this standard should be made with beams under load.

International standard ISO 834-1975 Fire test - Fire resistance tests - elements of building construction.

6.2 Other sources

Bally: Beschreibung des angekolten Trägers und Resultate von Schversuchen. EMPA report 13996/1. Dübendorf, 1971.

Broo, Helén: Fire test of glue-laminated wooden beams. Report 98R1,3071. SP Swedish National Testing and Research Institute. Borås, 1998. Cited by courtesy of Collano AG, Sempach Station, Switzerland.

Dorn, Hans and Egner, Karl: Brandversuche mit geleimten Holzbauteilen (Hetzer-Balken) Holz-Zentralblatt nr 28, March 6 1961. Stuttgart, 1961.

Elbez, Gerard: Analysis of behaviour of glues to fire exposure and to prolonged heat exposures. CTBA Pôle- Construction Bordeaux, 1999.

Fox, Selwyn P.: Residual strength of fire-damaged laminated beams. p 48-50. FPJ vol. 24 No 1. 1974.

Haksever, A.: Brandverhalten von Brettschichtverleimten Holzstützen und Holzbalken. Bauingenieur no 57 p.19-26. Springer-Verlag, 1982.

Kemmsies, Martin: Comparison of bondlines in glulam beams bonded with a PRF (phenol-resorcinol-formaldehyde) and Collano HB 110 (one -component polyurethane) after 30 resp. 60 minutes fire exposure. SP Report 97B2,2063-1. SP Swedish National Testing and Research Institute. Borås, 1998. Cited by courtesy of Collano AG, Sempach Station, Switzerland.

Källander, B., Kemmsies, M. and Johansson, C-J. ASTM D 4680-92 - Standard test method for creep and time-to-failure of adhesives in static shear by compression loading. Experiences from use of the method on 3 adhesives. Document presented at CEN/TC193/SC1/WG4 meeting. Borås, April 11-12. SP Swedish National Testing and Research Institute. Borås, 2000.

Lau, P.W.C., Van Zeeland, I. and White, R.: Modelling the char behaviour of structural timber. Proceedings, Fire and materials '98 conference, p 123-135. San Antonio, February 23-24, 1998.

Lind, Per: ASTM D3535-90 - NTI version. Proposal for test cycle and test method when using the standards test jig and test piece. Document presented at CEN/TC193/SC1/WG4 meeting. Borås, April 11-12. Norwegian Institute of Wood Technology. Oslo, 2000.

White, Robert H: Charring rate of composite timber products. Proceedings. Wood and Fire Safety 2000, p. 353-363. ISBN 80-228-0774-5. High Tatras, May 14-19, 2000.