Suitability of one-component polyurethane adhesives for timber structures - a review of 10 years' experience

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Suitability of one-component polyurethane adhesives for timber structures - the results of a 10-year test

Borimir Radovic, Claus Rothkopf *)

1. General

In Europe, the use of moisture-curing one-component polyurethane adhesives for the production of bonded load-bearing timber structures began in Switzerland already in the early 1970s. These projects were mainly pilot projects. In the 1980s, the interest in the use of one-component polyurethane adhesives for this type of application was also growing in Germany. Reasons for this were, among others, the light joints resulting from the intrinsic colour of these adhesives, their formaldehyde-free composition and processing advantages based on the fact that one-component polyurethane products, being one-component systems, are ready for use without prior mixing by the user.

As a consequence, initial activities were undertaken also in Germany to demonstrate the suitability of moisture-curing one-component polyurethane adhesives for the production of bonded load-bearing timber structures. In 1988, these activities finally resulted in the first actual order for the testing of a one-component polyurethane adhesive at the Otto-Graf-Institut, being the authorized German testing laboratory for adhesives for load-bearing timber structures.

Previous experience with this adhesive family in the production of bonded load-bearing timber structures in Switzerland as well as the corresponding test results available at the Otto-Graf-Institut were far from being sufficient to draw definitive conclusions with regard to the use of these adhesives for the production of bonded load-bearing timber structures. Therefore, extensive tests were required.

2. Testing of the first one-component polyurethane adhesives

2.1 Short-term tests

The testing of the first two moisture-curing one-component polyurethane adhesives (hereafter: Adhesive 1 and Adhesive 2) with respect to their suitability for use in the production of bonded load-bearing timber structures was based on the test standard for polycondensation adhesives for load-bearing timber structures valid at that time, DIN 68141:1969-10. In parallel, further short-term tests were performed to assess the following properties:

- Effect of bondline thickness, assembly time and climatic conditions on the bonding strength of the adhesive
- Suitability of the adhesive for the bonding of tongue-and-groove joints
- Tensile shear strength of the adhesive with various bondline thicknesses at high and low temperatures
- Resistance of the adhesive to a delamination test

A detailed description of the short-term tests and their results were published already in *Bauen mit Holz* 1/94.

2.2 Tests with respect to the long-term performance of the adhesives under permanent load

Because the long-term performance of the one-component polyurethane adhesives under load was largely unknown, tests to assess the performance of the two adhesives under permanent load were necessary in addition to the short-term tests. For this purpose, the following tests were performed.

2.2.1 Transverse tensile tests with beech wood specimens under permanent load in varying climatic conditions

Based on DIN 68141: 1969-10, section 2.5, transverse tensile test specimens made of beech wood were bonded with both adhesives. These specimens were installed in a room with transparent roof and walls (hereafter "the glass house") at the top of a flat-roof building, and subjected to a permanent load corresponding to a tensile stress perpendicularly to the bondline of 1 N/mm² for periods of up to 3 years. Groups of 10 specimens were removed after 3 (Adhesive 1 only), 6, 12 and 36 months and, after conditioning in standard climate 20°C/65 r.h., tested in a transverse tensile test up to maximum load. A detailed description of the test setup and the results for periods of up to one year under permanent load were published already in *Bauen mit Holz* 1/94 . The complete results after periods of up to three years under permanent load are shown in Table 1. The table also includes the results for transverse tensile test specimens of beech wood without adhesive joint, which had been tested in the glass house previously for effects of storage time, varying climatic conditions and permanent load on the transverse tensile strength.

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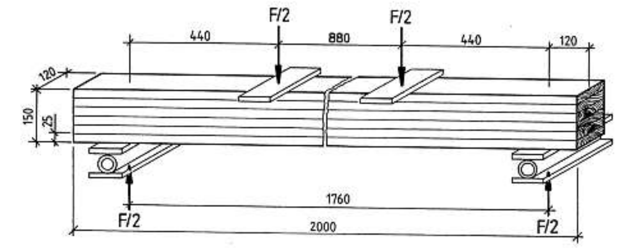

Fig. 1: Schematic test setup for bending test under permanent load.

The evaluation of the climate recordings indicates that the temperature in the glass house varied between a minimum of approx. –10 °C and a maximum of approx. +45 °C and the relative humidity ranged from a minimum of approx. 20% r.h. to a maximum of 100% r.h.. The daily differences in temperature and relative humidity ranged up to 30 K resp. 70%.

Table 1 illustrates that, under the prevalent test conditions, the transverse tensile strength of the specimens without adhesive joint decreases considerably over time. The decrease of the transverse tensile strength observed also in the bonded specimens is mainly based on this fact. This is also illustrated by the high proportion of wood failure observed in all test series. After a three years' loading period, the decrease of the transverse tensile strength of the specimens bonded with the two polyurethane adhesives is even smaller than the decrease in strength of the specimens without adhesive joint. It should be noted, however, that the bonded and non-bonded specimen groups were produced with beech wood from different lots. This makes it very likely that the observed differences were due to unequal wood quality of the specimen groups.

2.2.2 10-year bending test with glued laminated timber beams under permanent load

A total of six glued laminated timber beams were built, two each with the two adhesives under test and two reference beams with a well-established PRF adhesive being approved for the bonding of load-bearing timber structures. These beams were stored under permanent load (m = 2800 kg) in a laterally open storage hall.

Fig. 1 schematically shows the test setup of the glued laminated timber beams loaded in the four-point bending test, Fig. 2 shows a test jig with one of the beams in the long-term test. The test setup results in a maximum bending stress of approx. 14 N/mm² and a maximum shear stress of approx. 1.2 N/mm², which, according to DIN 1052, corresponds to the maximum permissible bending and shear stress level for glulam in strength class BS 14. Since the permanent load has been applied, the time-dependent increase of deflection of the beams has been measured at regular intervals.

The performance of these tests and the results of the first three years were also reported earlier in *Bauen mit Holz* 1/94 and 2/97. In the meantime, the results after 10 years under permanent load are available, which are summarized below.

The climate recordings from the test setup show that during the test period elapsed so far, the temperature in the laterally open storage hall ranged from a minimum of –11 °C to a maximum of +32 °C, depending on the time of day and the season. The relative humidity varied between a minimum of 15% r.h. and a

	Transverse tensile test specimens with adhesive 1					Transverse tensile test specimens with adhesive 2					Transverse tensile test specimens without adhesive joint		
	Transverse tensile strength		Failure type [1)]		Residual strength in %, relative to unloaded test	Transverse tensile strength		Failure type [1)]		Residual strength in %, relative to unloaded test	Transverse tensile strength		Residual strength in %, relative to unloaded test
Type of storage before the test	Range N/mm²	Mean N/mm²	H %	F %		Range N/mm²	Mean N/mm²	H %	F %		Range N/mm²	Mean N/mm²	
5 weeks unloaded in standard climate 20/65	7.16 ... 11.24	10.08	62	38/39	100	6.38 ... 8.54	7.60	75	25/74	100	8.28 ... 11.12	9.42	100
3 months in glass house with 1.0 N/mm² permanent load	8.30 ... 11.56	9.96	85	15/67	98.8	-	-	-	-	-	-	-	-
6 months in glass house with 1.0 N/mm² permanent load	8.36 ... 9.87	9.12	89	11/41	90.5	6.08 ... 8.22	6.95	77	23/81	91.4	-	-	-
1 year in glass house with 1.0 N/mm² permanent load	8.51 ... 10.64	9.59	92	8/13	95.1	5.25 ... 8.12	6.41	92	8/75	84.3	3.64 ... 8.24	6.28	66.7
3 years in glass house with 1.0 N/mm² permanent load	6.82 ... 8.42	7.75	93	7/36	76.9	3.22 ... 5.84	4.70	86	14/92	61.8	3.27 ... 5.44	4.67	49.6

Table 1: Results of the tests with transverse tensile test specimens under permanent load, made of beech wood.

1) H = wood failure outside the bond-line, F = failure in the bond-line with indication of surface covered by wood fibres in % (number behind slash)

Fig. 2: Test jig with one of the beams, loaded with m= 2800 kg

maximum of 100% r.h. during the test period. The prevalent climatic conditions produced the wood moisture development shown in Diagram 1, when measuring the wood moisture content in the middle of the length of the beam in a reference sample made of glulam with the same cross-section as the test specimens and 1.5 m in length.

From the initial deflections f_0 determined at the beginning of the loading and the deflections f_t determined at time t, the ratios f_t/f_0 of the beams were calculated. The ratios determined in this way describe the time-dependent increase of deflection, i.e. the creep deformation of the test beams.

Beam No.	1	2	3	4	5	6
Adhesive used	Adhesive 1	Adhesive 1	Adhesive 2	Adhesive 2	PRF-adhesive	PRF-adhesive
Initial deflection f_0 in mm	4.4	5.0	5.0	4.6	4.6	4.8
$f_{(52\ weeks)}/f_0$	1.52	1.40	1.34	1.37	1.41	1.35
$f_{(104\ weeks)}/f_0$	1.59	1.50	1.40	1.39	1.48	1.46
$f_{(156\ weeks)}/f_0$	1.64	1.52	1.44	1.43	1.52	1.48
$f_{(208\ weeks)}/f_0$	1.68	1.58	1.46	1.48	1.56	1.50
$f_{(262\ weeks)}/f_0$	1.73	1.64	1.50	1.54	1.59	1.52
$f_{(310\ weeks)}/f_0$	1.75	1.68	1.52	1.57	1.61	1.56
$f_{(362\ weeks)}/f_0$	1.80	1.70	1.56	1.59	1.61	1.56
$f_{(415\ weeks)}/f_0$	1.80	1.69	1.55	1.53	1.63	1.56
$f_{(467\ weeks)}/f_0$	1.81	1.71	1.55	1.54	1.64	1.56
$f_{(523\ weeks)}/f_0$	1.82	1.70	1.56	1.54	1.64	1.56

Table 2: Ratios ft/f0 , depending on the test duration.

Diagram 1: Wood moisture content of a reference sample during the test period.

Table 2 shows the ratio f_t/f_0 for each of the tested beams, depending on the test duration. Using the ratio f_t/f_0 , the value for the deformation factor k_{def} was determined for each beam with $k_{def} = f_t/f_0 - 1$. Diagram 2 graphically illustrates this value for the six beams over the test period of ten years elapsed so far.

As shown in diagram 2, the values for the deformation factors k_{def} after a loading period of so far ten years are 0.82 and 0.70 for the two beams bonded with Adhesive 1, 0.56 and 0.54 for the two beams bonded with Adhesive 2, and 0.64 and 0.56 for the two beams bonded with the PRF adhesive.

In the draft of the new standard DIN 1052, a deformation factor k_{def} of 0.8 is set for glulam for the calculation of the final deformation for use in service class 2 conditions and under permanent load. After a loading period of ten years, five of the six beams are significantly below this value, one of the two beams bonded with Adhesive 1 is insignificantly higher than this value with $k_{def} = 0.82$.

Based on the measured deflections, the yearly deflection increase, expressed as percentage, was calculated for the six beams in relation to the total deflection increase within ten years. This is shown in Table 3.

Diagram 2: Deformation factors k_{def} of the beams during a test period of 10 years.

Beam No.	Adhesive	Yearly deflection increase in percent									
		1st year	2nd year	3rd year	4th year	5th year	6th year	7th year	8th year	9th year	10th year
1	Adhesive 1	63.9	8.3	5.6	5.6	5.6	2.8	5.6	0	1.4	1.4
2	Adhesive 1	57.1	14.3	2.9	8.6	8.6	5.7	2.9	-1.4	2.9	-1.4
3	Adhesive 2	60.7	10.7	7.1	3.6	7.1	3.6	7.1	-1.8	0	1.8
4	Adhesive 2	68.0	4.0	8.0	8.0	12.0	4.0	4.0	-10.0	2.0	0.0
5	PRF	64.4	10.2	6.8	6.8	3.4	3.4	0	3.4	1.7	0
6	PRF	63	18.5	3.7	3.7	3.7	7.4	0	0	0	0

Table 3: Yearly deflection increase of the beams, expressed as percentage, in relation to the total deflection increase over ten years.

Adhesive type	Phenol-resorcinol resins [2]	Melamine resins MF/MUF[2]	One component PUR adhesives[2),4)]	Urea resins UF[3]	Building code approvals for adhesives (special applications)	Total
Number of adhesives tested [1]	46	13	9	9	3	80

Table 4: Number of adhesives tested successfully, separated into adhesive types (as at Jan. 22, 2003).
1) Tested resins, some resins are tested and approved with several hardeners or several hardener proportions
2) For use in indoor and outdoor conditions
3) For use in indoor conditions
4) Maximum bond-line thickness 0.3 mm.

Diagram 2 shows a slightly higher deflection as well as a somewhat greater weather-related oscillation of the deflection for the beams bonded with Adhesive 1. However, as shown in Table 3, the increase in deflection of all the tested beams has practically come to a stop in the last three years.

3. Industrial use of one-component polyurethane adhesives for the bonding of load-bearing timber structures in Germany

In the meantime, other one-component polyurethane adhesives have been tested successfully with regard to their suitability for the production of bonded load-bearing timber structures. The share of one-component polyurethane adhesives among the adhesives used in the production of bonded load-bearing timber structures in Germany has clearly increased.

Table 4 shows the current number of adhesives which have been tested successfully with regard to their suitability for the production of bonded load-bearing timber structures as at January 22, 2003. At present, a total of 80 adhesives have been approved, whereof 46 are PRF adhesives, 13 are melamine based adhesives, 9 are UF adhesives, 9 are one-component polyurethane adhesives and 3 are adhesives according to two general building code approvals for special applications (one melamine based adhesive and two EPI adhesives). Regarding these figures it should be noted that at present some of the PRF adhesives are used not at all or only with relatively small volume.

Table 5 shows the number of adhesive types in use, depending on the product to be manufactured, for all 170 companies authorized to bond load-bearing timber structures. The figures are based on the information available at the Otto-Graf-Institut as at January 2003. For each of the product groups it is specified which type of adhesive the companies use for finger-joint and/or lamination bonding. Because some of the manufacturers produce products from several product groups and use several adhesive types, the total number of manufacturers and adhesives differs from the number given in the list of companies with certification to bond load-bearing timber structures according to DIN 1052.

The numbers stated do not include information on the manufacturers' production volumes of load-bearing timber structures or the quantities of the adhesives in use. Therefore, the figures can serve only as a guideline, but nevertheless two things are significant: Firstly, the large number of PRF adhesives tested and approved does no longer correspond to their frequency in use. In the last few years, PRF adhesives have been replaced to a large

Type of product		Glulam based on certificate A		Glulam based on certificate B		Duo and trio beams according to Z-9.1-440		Finger-jointed solid wood according to DIN 68140-1	Others	
Number of manufacturers[1]		81		35		24		52	21	
Bonding of		Finger-jointing	lamination	Finger-jointing	lamination	Finger-jointing	lamination	Finger-jointing	Finger-jointing	lamination
Number of adhesives in use[2]	PRF	6	42	2	7	0	1	2	6	2
	MUF/MF	72	69	22	18	10	11	22	8	11
	UF	1	18	1	1	0	1	0	1	1
	PUR	10	10	10	13	14	15	32	2	5
total		89	139	35	39	24	28	56	17	19

Table 5: Number of adhesives in use at companies with certificate to bond load-bearing timber structures according to DIN 1052, depending on the type of product.

1) Some of the manufacturers produce several types of products, therefore the number of manufacturers is greater than the number of companies with certificate to bond load-bearing timber structures
2) Figures based on information from the manufacturers available at the Otto-Graf-Institut, as at January 2003.

extent by the melamine adhesives, some of which are recently also used with separate application of resin and hardener in lamination bonding. Only the companies producing glulam with a certificate A are still using PRF adhesives to a significant degree. Secondly, the frequent use of one-component polyurethane adhesives in the production of finger-jointed solid wood and duo/trio beams is remarkable, whereas PRF adhesives and UF adhesives are almost totally absent in the production of these two product groups.

4. Summary

The results of the tests with glued laminated timber beams under permanent load, running for more than ten years now, show that structural elements bonded with one-component polyurethane adhesives perform satisfactorily under long-term load with the maximum allowable design load. The industrial use of one-component polyurethane adhesives in Germany, lasting for eight years now, has also shown positive results and no cases of adhesive-based damage have become known, provided that the manufacturers' processing instructions were complied with.

When one-component polyurethane adhesives are used, it is important to take into account the special properties of these adhesives, especially the foaming behaviour and the moisture reactivity. It should also be noted that there may exist big differences between individual brands of one-component polyurethane adhesives as to their properties. This was for example the reason that one of the one-component polyurethane adhesives, tested successfully by the Otto-Graf-Institut, was not able to succeed on the market because of its working properties. In Germany, all tested and approved one-component polyurethane adhesives may on principle be used only up to a maximum bondline thickness of 0.3 mm.

In the last few years, the use of one-component polyurethane adhesives for the production of bonded load-bearing timber structures started as well in other European countries. Based on the existing experience, the preparation of a CEN-standard for the testing of this adhesive family has been initiated meanwhile. It is to be expected that such a future test-standard will be more comprehensive than the current standard DIN EN 301/302 for phenolic and amino plastic adhesives, and that tests with respect to the long-term performance of these adhesives will certainly be required.

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