BONDED GLULAM-STEEL ROD CONNECTIONS WITH LONG ANCHORAGE LENGTH

GEKLEBTE BRETTSCHICHTHOLZ-STAHLSTANGENVERBINDUNGEN MIT GROSSEN VERANKERUNGSLÄNGEN

ASSEMBLAGES DE GOUJONS COLLES EN BOIS LAMELLE-COLLE AVEC GRANDE LANGUEUR D'ANCRAGE

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SUMMARY

It is reported on a comparative evaluation of several literature known design equations for glued-in rods in timber structures and a respective validating test series. It is focused on threaded rods with a rather high slenderness ratio ($\lambda = 30$) bonded into glulam parallel to fiber with either Epoxy or 2component Polyurethane adhesives. The literature review revealed partly very inconsistent assumptions on the influence of adhesive type, effective rod diameter, wood density and especially anchorage length.

The test results confirmed those design equations accounting for a bond strength decrease with increasing anchorage length especially in the range of longer ($\lambda > 10...15$) embedments. Contrary, an extreme discrepancy was obtained with respect to the proposal in European Prestandard prEN 1995-2 delivering roughly two times higher values.

The study revealed an obvious demand for clarification in order to use the utmost promising connector ''glued-in rod'' for a reliable designable connections in timber engineering.

ZUSAMMENFASSUNG

Es wird über einen Vergleich verschiedener literaturbekannter Bemessungsgleichungen für in Holz eingeklebte Stahlstangen und eine diesbezüglich validierende Versuchsreihe berichtet. Das Hauptaugenmerk liegt auf Gewindestangen mit einem vergleichsweise hohen Schlankheitsgrad ($\lambda = 30$), die faserparallel in Brettschichtholz unter Verwendung von Epoxid oder einem 2Komponenten-Polyurethanklebstoff eingeklebt sind. Die Literatur zeigte teilweise sehr inkonsistente Auffassungen über den Einfluß der Klebstoffart, des effektiven Stangendurchmessers, der Rohdichte des Holzes und insbesondere der Verankerungslänge auf.

Die Versuchsergebnisse bestätigten diejenigen Bemessungsansätze, die eine Abnahme der Bindefestigkeit mit zunehmender Einbindetiefe speziell im Bereich größerer Verankerungslängen ($\lambda > 10 \ldots 15$) unterstellen. Im Gegensatz hierzu ergab sich ein extremer Unterschied zwischen den Versuchsergebnissen und dem Bemessungsansatz in der Europäischen Vornorm prEN 1995-2, der rund zweifach höhere Werte erbringt.

Die Studie offenbarte einen offensichtlichen Klärungsbedarf, um das äußerst vielversprechende Verbindungsmittel „eingeklebte Stahlstange“ für verläßlich bemessbare Verbindungen im Ingenieur-Holzbau einzusetzen.

RESUME

Une étude comparative de plusieurs équations de dimensionnement données en litérature pour des goujons collés utilisés en structures bois est présentée et complétée par des essais de validations. L'étude se limite aux tiges filetées ayant relativement grand élancement ($\lambda = 30$), collées dans du lamellé-collé parallèlement au fil du bois par des colles Epoxy ou Polyuréthane a 2 composants. La recherche bibliographique fait apparaître partiellement des hypothèses incohérentes concernant l'influence du type de colle, du diamètre effectif du boulon, de la densité du bois et particulièrement de la longueur d'ancrage.

Les résultats expérimentaux ont validé ces équations de dimensionnement montrant que la résistance du collage décroît lorsque la longueur d'ancrage croît, particulièrement pour les grandes longueurs de collage ($\lambda > 10 \ldots 15$). Cependant, ces résultats sont deux fois inférieurs aux valeurs proposées par la prénorme européenne prENV 1995-2.

Il existe donc un besoin manifeste de clarification afin de pouvoir utiliser cet assemblage prometteur par „goujons collés“ comme une technique fiable d'assemblage des structures bois.

KEYWORDS: glued-in steel rods, metric thread, glulam, axial resistance, bond strength, influence of anchorage length, rod slenderness ratio

1. INTRODUCTION

Glued-in rods embedded in solid timber or glulam provide an excellent method for transferring high concentrated loads into wooden members. In some foreign countries glued-in rods have been perceived and partly employed for engineered structural connections in recent years. In Germany, the primary emphasis in the use of glued-in rods until today consists in repair, upgrading and preventive reinforcement of large sized glulam members subjected to high resp. excessive stresses perpendicular to the grain.

In the frame of a recently finished research project on portal frame corners based on glued-in steel plates resp. threaded rods [Aicher et al., 1997] the necessity arose to quantify the ultimate axial load carrying capacity resp. the bond strength of glulam-steel rod connections especially with rather long anchorage lengths. The reason for long anchorage lengths lies in the joint capacity maximization with a limited number of steel rods which, in view of sensible spacings in a cross-section, can not be increased deliberately. The literature review revealed partly rather inconsistant design proposals, resulting in a conciderable span for bond strengths resp. axial withdrawl resistances. This then led to a small validating test series with the specifically regarded adhesives.

2. LITERATURE REVIEW

The first systematic tests with glued-in rods in glulam in this country are reported in [MÖHLER AND HEMMER, 1981a, b]; the investigations were confined to threaded rods and Phenolic-Resorcinol adhesive. A deepened continuation of these tests took place in three successive investigations [EHLBECK AND SIEBERT, 1987; EHLBECK ET AL., 1991; BLAß ET AL., 1996]. The first part comprised practical gluing methods and bond stress investigations in axial loading. Apart from threaded rods, tests were performed with special wood screws and deformed reinforcing bars with threaded ribs; as adhesives Phenolic-Resorcinol and a 2component Polyurethane were used. In the second part, additionally incorporating an Epoxy adhesive, the influence of long term loading and the effect of climate with and without load was investigated, including strain measurements along the rod. Related design proposals for short term and climate loading were presented in [GEROLD, 1992, 1993]. The third part of the Karlsruhe project aimed primarily at reinforcement of notched and bent members; further, a design proposal for rods embedded perpendicular to the grain was given.

An interesting contribution regarding the embedment of threaded rods and deformed reinforcing bars in oversized holes up to 1,7times of the rod diameter by means of a highly filled Epoxy was given in [MÜLLER AND VON ROTH, 1991].

Very substantial foreign experimental and theoretical contributions are described i.a. in [BERNASCONI, 1996; RIBERHOLT, 1986, 1988; BUCHANAN ET AL., 1990; BUCHANAN AND BARBER, 1996; HOLLINSKY, 1992; JOHANSSON, 1995; JOHANSSON ET AL., 1996; KANGAS, 1993, 1994; LAW AND YTTRUP, 1989]. The most comprehensive experimental investigations regarding axially loaded threaded rods bonded parallel to fiber in glulam were performed by [RIBERHOLT, 1986]; as adhesives 2component Polyurethane and an Epoxy were used. The bond strength investigations comprised i. a. the effect of corrosive media on zinked and uncoated rods and influences of climate and long term loading. Extensive research on deformed reinforcing bars glued with rather large glueline thickness of 2 - 2,5 mm inclined (30° - 90°) to grain direction by means of Epoxy and Polyurethane adhesives is discussed in [KANGAS, 1993, 1994]; a reduced effective anchorage length due to impact of welding temperatures (jointing of steel plates) was introduced. The influences of elevated temperatures (40 - 90°C) on epoxied rod connections in glulam and the fire performance of full sized tension members exposed to standard fire conditions was studies by [BUCHANAN AND BARBER, 1996]; expressed strength decreases above approximately 50°C were obtained with the used Epoxies.

Design proposals are stated in [RIBERHOLT, 1988; KANGAS, 1993; JOHANSSON, 1995]. First results of nonlinear Finite Element computations on axially loaded bolts in timber accounting for the different shapes of strain softening curves of Epoxies and Polyurethanes were presented in [JOHANSSON ET AL., 1996].

3. PROPOSED DESIGN EQUATIONS

Following, some literature known design equations for glued-in rods in glulam are given. It is focussed on axially loaded threaded rods, glued-in parallel to grain. The compilation incorporates results of some major contributions, however may not be perceived as a fully comprehensive literature review. Quantitative evaluations of the literature equations are discussed altogether with the empiric results of the validating test series in chap. 5.

3.1 Investigations and design proposal by MÖHLER AND HEMMER

Based on investigations with glued-in threaded rods with Phenolic-Resorcinol adhesive [MÖHLER AND HEMMER, 1981a] the following equations were proposed in [MÖHLER AND HEMMER, 1981b] for the mean axial withdrawl resistance resp. bond strength (l_a = anchorage length, $d_{nom} = d_a$ = nominal resp. outer rod diameter):

$$F_{ax,mean} = \pi\, d_a\, \ell_a\, f_{v,mean} \qquad \lambda_a = \ell_a/d_a \leq 20 \qquad (1a)$$

where

$$f_{v,mean} = 5\ \mathrm{N/mm^2} \qquad d_a \leq 24\ \mathrm{mm}\,, \qquad (1b)$$

$$f_{v,mean} = 5 - 0{,}2668\,(d_a - 24)\ \mathrm{N/mm^2} \qquad 24\ \mathrm{mm} < d_a \leq 30\ \mathrm{mm}\,. \qquad (1c)$$

For permissible design resistances resp. bond stresses a global safety factor of 4 was proposed; historically bound, no proposal was given for characteristic resistance resp. strength values.

3.2 Investigations and design proposal by RIBERHOLT

According to a re-evaluation of earlier investigations [RIBERHOLT, 1986], comprising i. a. Epoxy and Polyurethane adhesives, the following fracture mechanics related equations and material parameters were proposed in [RIBERHOLT, 1988] for mean and characteristic axial resistances:

$$\left.\begin{aligned} F_{ax,\,mean} &= f_{ws,\,mean}\; d\, \rho_{sp}\, \sqrt{\ell_a}\;, \\ F_{ax,k} &= f_{ws,k}\; d\, \rho_k\, \sqrt{\ell_a} \end{aligned}\right\} \quad l_a \geq 200\ \text{mm} \qquad \begin{aligned} &(2a)\\ &(2b) \end{aligned}$$

where

$$d = \max\left(d_a, d_h\right)\,,$$

$$\left.\begin{aligned} f_{ws,\,mean} &= 784 \text{ and } 627\ \frac{N}{\sqrt{mm^3}}\;, \\ f_{ws,k} &= 650 \text{ and } 520\ \frac{N}{\sqrt{mm^3}}\;. \end{aligned}\right\} \quad \text{for PU and Epoxy, respectively}$$

Quantities d (d_h = hole diameter), ℓ_a are to be inserted in mm units and densities ρ_{sp}, ρ_k dimensionless with the scalars for g/cm^3. A peculiarity, bound to the revaluation of former results and sometimes not recognised correctly in literature, concerns the different definitions of densities in eqs. (2a, b). Whereas characteristic density ρ_k in eq. (2b) as usual refers to 12 % MC, the specific density in eq. (2a) is related to oven dry mass but volume in humid ($\approx$12%) condition.

For anchorage lengths l_a < 200 mm, a constant resistance resp. bond strength conforming to l_a = 200 mm is specified.

3.3 Investigations and design proposal by EHLBECK ET AL. resp. by GEROLD

Based on investigations with Phenolic-Resorcinol, Polyurethane and Epoxy adhesives in [EHLBECK AND SIEBERT, 1987; EHLBECK ET AL., 1991] the following design equations for mean axial resistances resp. bond strengths were proposed in [GEROLD, 1992; 1993], here given without an additional term accounting for climate induced stresses:

$$F_{ax,\,mean} = \pi\, d_a\, \ell_a \left(\frac{\rho}{\rho_k = 380}\right)^c f_{v,\,mean,\,cor}\ , \tag{3a}$$

$$f_{v,\,mean,\,cor} = f_{v,\,mean,\,b}\,(1 - k_s\,\lambda_a)\,k_d \tag{3b}$$

where

$f_{v,\,mean,\,b} = 7{,}5\ \mathrm{N/mm^2},\quad k_s = 0{,}019\,[-],\quad c = 1\,[-]$ for PU,

$f_{v,\,mean,\,b} = 12{,}6\ \mathrm{N/mm^2},\quad k_s = 0{,}042\,[-],\quad c = 0{,}55\,[-]$ for Epoxy.

Quantity k_d in case of metric thread may be assumed as one; $f_{v,\,mean,\,cor}$ represents the mean bond strength referring to a characteristic density of $\rho_k = 380\ \mathrm{kg/m^3}$. For the derivation of characteristic axial resistance resp. bond strength, $f_{v,\,mean,\,b}$ has to be replaced by the characteristic value, given in the reference solely for Phenolic-Resorcinol adhesive, there as 75% of the respective mean value.

3.4 Investigations and design proposal by KANGAS

Based on evaluations of experiments with deformed reinforcing bars (d_{nom} = 20 mm) bonded in glulam by means of Epoxies or 2component

Polyurethanes using a rather large hole diameter of 25 mm, the following proposal is given in [KANGAS, 1994] for angles of 30° - 90° between rod and graing direction.

$$F_{ax,k} = \pi \, d_h \, \ell_{a,ef} \, f_{v,k} \tag{4a}$$

where

$$\ell_{a,ef} = \ell_a - 1{,}5\,d \tag{4b}$$

$$f_{v,k} = 6{,}5 \left(1 - \frac{\ell_{a,ef}}{100\,d} \right) \tag{4c}$$

$$d = d_{nom}, \quad d_h \approx 1{,}25\,d$$

3.5 Investigations and design proposal by BLAß ET AL.

The design proposal given by [BLAß ET AL., 1996], according to the authors, is confined to rods glued in timber perpendicular to grain. Disregarding this confinement, it shall be anaysed here, how the proposal applies to rods bonded parallel to grain, too; in this context it has be stated that the majority of proposals assumes indifference of the angle between rod and fiber direction. The proposal is very closely related to the equations given in [RIBERHOLT, 1988], whereby the following four modifications apply to eqs. (2a,b):

- the limit value for the $\sqrt{\ell_a}$ dependency is redefined as $l_a = 250$ mm,
- the fracture toughness parameters $f_{ws,mean}$, $f_{ws,k}$ are not specified individually for different adhesives; the values specified in eq. (2a,b) for Epoxy are assumed to apply also for 2component Polyurethanes,
- the density ρ_{sp} in eq. (2a) for computation of the mean resistance is redefined as ρ_k,
- diameter d conforms to the nominal resp. outer diameter $d = d_{nom} = d_a$.

3.6 Design proposal in European Prestandard (ENV): Eurocode 5 - Part 2 Bridges

The informative annex A in prENV 1995-2 specifies for the characteristic axial resistance in case of shear failure in the wood, i. e. no bond resp. rod failure, irrespective of the angle between rod and fiber direction and of adhesive type (ρ_k in kg/m³)

$$F_{ax,k} = \pi \, d_{equ} \, \ell_a \, f_{v,k} \qquad (5a)$$

where

$$f_{v,k} = 1{,}2 \cdot 10^{-3} \, d_{equ}^{\;-0{,}2} \, \rho_k^{\;1{,}5} \quad \text{N/mm}^2 , \qquad (5b)$$

$$d_{equ} = \min \left\{ d_h , 1{,}25\, d \right\} \quad \text{mm} ,$$

$d = d_a = d_{nom}$ threaded rods,

$d = d_a = 1{,}1\, d_{nom}$ deformed reinforcing bars.

Contrary to all afore mentioned design proposals, eqs. (5a, b) specify an overproportional influence of density and, most important, no influence of anchorage length.

4. VALIDATING TEST SERIES

4.1 Test program

The validating test series was performed with threaded rods with metric thread acc. to DIN 13; the normal resp. outer rod diameter, $d_{nom}=d_a$, was throughout 20 mm. In total, 24 pull out tests were conducted, thereof 18 with an anchorage length resp. slenderness ratio of l_a = 600 mm, $\lambda_a = l_a / d_a = 30$.

All rods, except two, were glued parallel to grain in homogeneously built-up glulam of German strength class BS 14 similar to European grade BS 28. The thickness of the lamellas was throughout 30 mm; the rods were always placed along entire anchorage length in one lamella. The densities of the fractured lamellas, incorporating the rods, conformed to solid wood strength class C 30; the mean density (± stand. dev.) of all lamellas was $\rho_{12} = 452 \pm 33$ kg/m³ (C.O.V. = 7,3 %).

As adhesives three different Epoxies and one 2component Polyurethane were used. Most of the tests were performed with a hole diameter resp. nominal glue line thickness of $d_h = 21$ mm, $d_L = 0{,}5$ mm; further, d_h and d_L values of 22 and 24 resp. 1 and 2 mm were investigated. The strength class of the longer rods should have been 8.8; by mistake two 5.6 qualities were used, consequently resulting in steel rod failure.

Table 1 gives a compilation of all individual specimen configurations. Figures 1a,b show the test set-ups A and B, used for determination of the axial resistance. Most tests were performed with the less demanding test configuration A, where the reaction force to the rod tension load is acting in compression at the end-grainface where the rod sticks out of the wood. Further, the wooden part of the specimen is subject to quasi clamped support conditions. Test set-up B, affording a twofold larger specimen, resembles a more practice relevant loading condition; now both specimen ends are loaded resp. supported through cardanic hinges.

Figure 2 depicts the details of the load-slip measurement in case of test set-up B. All tests were performed in stroke control with a displacement rate of 0,6 mm/min.

4.2 Test results

Figure 3 shows typical curves of obtained load-slip curves, here given for test configuration B. Up to 50 - 60 % of ultimate resistance $F_{ax,u}$ all specimens revealed an almost linear load-slip behaviour. The slips at proportionality limit were in the range of 0,3 - 0,5 mm. Above proportionality limit all specimens

adhesive type and product	test notation		current specimen No.	anchorage length ℓ_a		hole diameter	glue line thickness	strength class of threaded rod	density of fractured lamella	test set-up
	series	No.		$\ell_{a,nom}$	$\ell_{a,eff}$	d_h	d_L		ρ_{12}	–
–	–	–	–	mm		mm	mm	–	kg/m^3	–
2component Epoxy (without filler) EP.Ia	Ia[1]	1	1	100	113	24	2	4.6	–	A
		2	2		100	24	2	4.6	–	
	Ib	3	3		107	24	2	4.6	456	
		4	4		111	24	2	4.6	474	
	II	1	5	300	310	24	2	8.8	436	
		2	6		306	24	2	8.8	499	
2component Epoxy as EP.Ia but with filler EP.Ib	III	1	9	600	596	24	2	8.8	470	
		2	10		590	22	1	8.8	387	
		3	12		600	21	0,5	8.8	459	
		4	13		601	21	0,5	8.8	478	
		5	14		603	21	0,5	8.8	469	
2component Epoxy EP.II	IV	1	7	600	590	24	2	5.6	397	
		2	8		595	22	1	5.6	454	
		3	12		594	22	1	8.8	459	
		4	15		606	21	0,5	8.8	465	
		5	16		608	21	0,5	8.8	452	
		6	17		600	21	0,5	8.8	429	
2component Polyurethane PU.I	V	1	18	600	602	21	0,5	8.8	415	
		2	19		605	21	0,5	8.8	410	
		3	20		608	21	0,5	8.8	421	
		4	21		599	21	0,5	8.8	430	
		5	22		601	21	0,5	10.9	480	B
		6	23		604	21	0,5	10.9	517	
		7	24		600	21	0,5	10.9	479	

Table 1: *Compilation of individual specimen configurations of axial pull - out tests with threaded rods (metric thread) with nominal diameter of 20 mm glued parallel to fiber in glulam*

[1] *test series Ia: rods glued-in perpendicular to grain and board width*

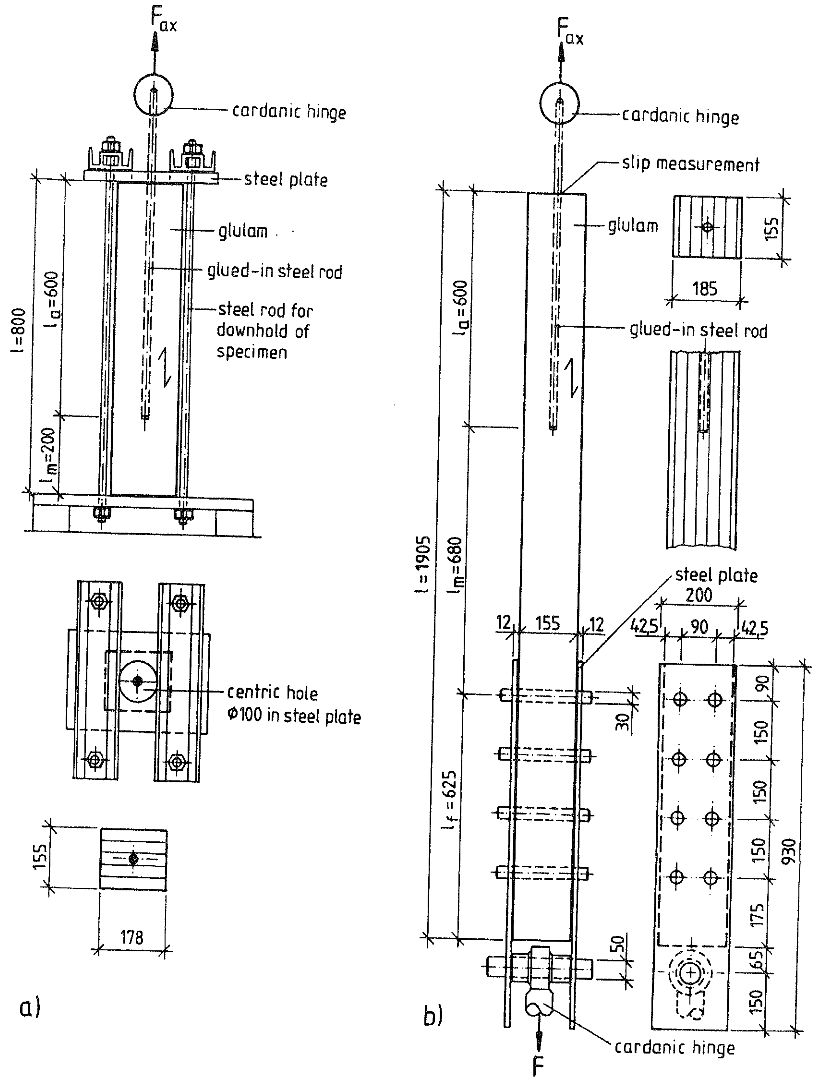

Fig. 1a, b: *Test set-ups A and B for axial pull-out tests of steel rods glued into glulam parallel to fiber*

a) test set-up A

b) test set-up B

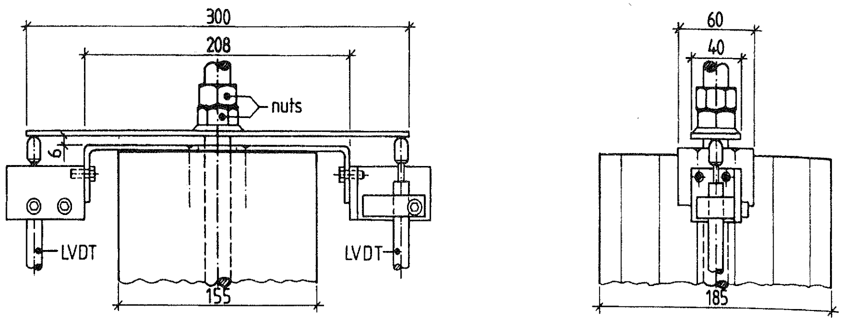

Fig. 2: *Details of load-slip measurement for test set-up B*

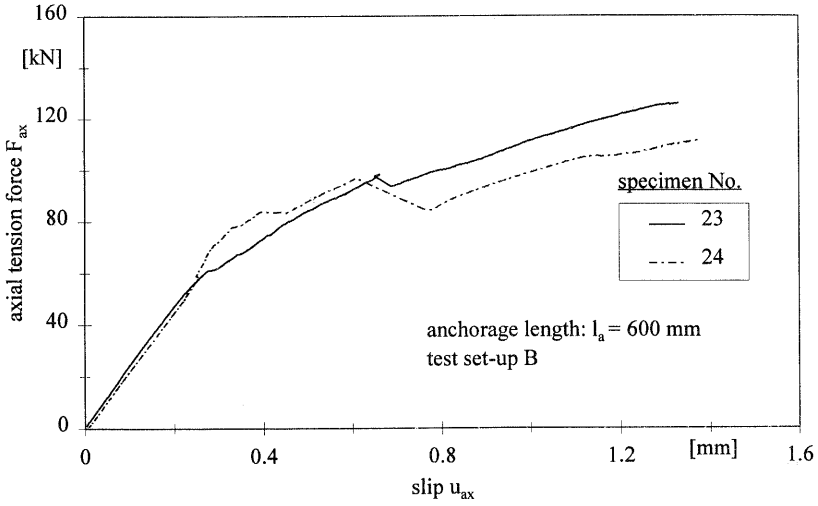

Fig. 3: *Load-slip curves in pull-out tests with test set-up B; the given curves represent the means of both symmetrically located slip measurement points*

with slenderness ratios $\lambda > 15$ showed a differently pronounced nonlinear load-slip behaviour, in general (80%) associated with one or two pre-peak load drops due to initial resp. progressive damage. The load level at first noticeable damage (in case of specimens with load drops) in average occurred at 0,85 $F_{ax,u}$; the first load drop was recorded at 0,6 $F_{ax,u}$ and some specimens showed the drop only a few percent (2 - 4) below $F_{ax,u}$. The occurance of pre-peak damages was not bound to specific adhesives, i.e. was similar for all four investigated ones.

The failures occured instantaneously; the slips at failure were in the range of 1 - 1,5 mm. In order to judge the failure mode - adhesive, bond or wood failure - the specimens were cut into two halves in a plane through the rod axis, exposing the cylindrical failure surface. In all cases an extensive wood failure had to be stated, i.e. never adhesion failure between rod and adhesive or cohesion failure of the adhesive. The wood fracture percentage was throughout in the range of 80 to 95 %. The most important test results are compiled in Tab. 2, revealing i.a. the following trends which have to be seen in view of the few specimen numbers:

- *influence of adhesive*
  for constant hole diameter and anchorage length (d_h = 21 mm, l_a = 600 mm) adhesives EP.Ib, EP.II and PU.I had an overall average bond strength of 3,2 N/mm² (related to d_h), whereby the different individual adhesive types delivered pronouncedly differing means of 3,7 , 2,8 and 3,2 N/mm². Thus although in all cases wood failure had been obtained, a strength difference of about 30 % between both epoxies had to be stated.

- *influence of glue line thickness*
  in case of Epoxy EP.II thicker glue lines of 1 or 2 mm compared to d_L = 0,5 mm delivered about 30 % higher bond strength. For Epoxy EP.Ib a similar, however less expressed trend was obtained.

A discussion of the magnitudes of the stated strength values is given in the following chapter in comparison with results acc. to the design proposals.

adhesive type and product	test notation		current specimen No.	ultimate axial load carrying capacity	load at 1st resp. 2nd pronounced pre-peak load drop	bond strength f_v related to		ensity normalised bond strength[2)]	max. tension stress in threaded rod	remarks[3)]
	series	No.		$F_{ax,\,u}$		d_a	d_h	f_v/ρ_{12}	$\sigma_{t,\,max}$	–
–	–	–	–	kN	kN	N/mm²		m	N/mm²	–
2component Epoxy (without filler) EP.Ia	Ia[1)]	1	1	45,80	–	6,45	5,38	–	187	W
		2	2	37,50	–	5,97	4,97	–	153	W
	Ib	3	3	39,62	–	5,89	4,91	1076	162	W
		4	4	55,30	–	7,93	6,61	1395	226	W
	II	1	5	125,70	114,48	6,45	5,38	1234	513	W
		2	6	141,98	86,29/127,70	7,38	6,15	1232	580	W
2component Epoxy as EP.Ia but with filler EP.Ib	III	1	9	140,56	125,97	3,75	3,13	666	574	W
		2	10	165,76	110,23	4,47	4,06	1049	677	W
		3	12	162,33	127,20	4,31	4,10	893	663	W
		4	13	127,58	125,20	3,38	3,22	674	521	W
		5	14	132,27	112,24/121,01	3,49	3,32	708	540	W
2component Epoxy EP.II	IV	1	7	>144,17	–	>3,89	3,24	816	589	S
		2	8	>130,99	113,27	>3,50	3,19	703	535	S
		3	12	136,76	133,94	3,66	3,33	725	558	W
		4	15	103,16	98,95/102,79	2,71	2,58	555	421	W
		5	16	107,64	–	2,82	2,68	593	439	W
		6	17	111,95	101,57	2,97	2,83	660	457	W
2component Polyurethane PU.I	V	1	18	105,42	98,44	2,78	2,65	639	430	W
		2	19	110,96	–	2,92	2,78	678	453	W
		3	20	132,04	96,66/110,83	3,46	3,29	781	539	W
		4	21	137,42	--	3,65	3,48	809	561	W[4)]
		5	22	125,70	121,17	3,33	3,17	660	513	W
		6	23	125,91	98,30	3,32	3,16	611	514	W
		7	24	111,37	96,96	2,95	2,81	587	455	W

Table 2: *Compilation of results of axial pull - out tests with threaded rods glued parallel to fiber in glulam*

[1)] see table 1 [2)] f_v related to d_h [3)] W,S = wood resp. steel rod failure

[4)] impact of 70°C on rod outside of anchored part for 30 h

5. COMPARISON OF TEST RESULTS WITH DESIGN PROPOSALS

The evaluation of the design equations was performed on the basis of a characteristic wood density of $\rho_k = 380$ kg/m^3 resp. a mean specific density of 410 kg/m^3. These densities, conforming to European solid wood strength class C 30 resp. German grade S 13, correspond well to the wood quality of the test specimens ($\rho_{12,\,\mathrm{mean}} = 452$ kg/m^3).

Figures 4a, b show the relations between mean resp. characteristic bond strength and anchorage length according to some of the stated design proposals altogether with here obtained empiric results. Similarly, Figs. 5a, b give the relations between density normalised bond strengths and anchorage length. From a pure qualitative judgement the empiric results seem to confirm proposals with an anchorage length dependant bond strength.

Table 3 gives a quantitative comparison of the empiric results with those of the proposed design equations for the primarily investigated anchorage length of $\ell_a = 600$ mm. Obviously the largest discrepancy of design equations vs. test results has to be stated for the European Prestandard prENV 1995-2, which delivers on the characteristic and mean strength level similarly for both investigated adhesive types roughly two times higher values.

For the Epoxy adhesive throughout a very good agreement between the test results and the proposal in [RIBERHOLT, 1988] has to be stated. The numbers obtained from [BLAß ET AL., 1996], being equal to afore mentioned reference in case of $f_{v,k}$, deliver slightly lower (5–10 %) results for mean bond strength resp. for the load capacities. In case of Polyurethane adhesive the proposals in [GEROLD, 1993; BLAß ET AL., 1996] meet the test results equally good, whereas the solutions acc. to [RIBERHOLT, 1988] in average overestimate the results by about 35 %.

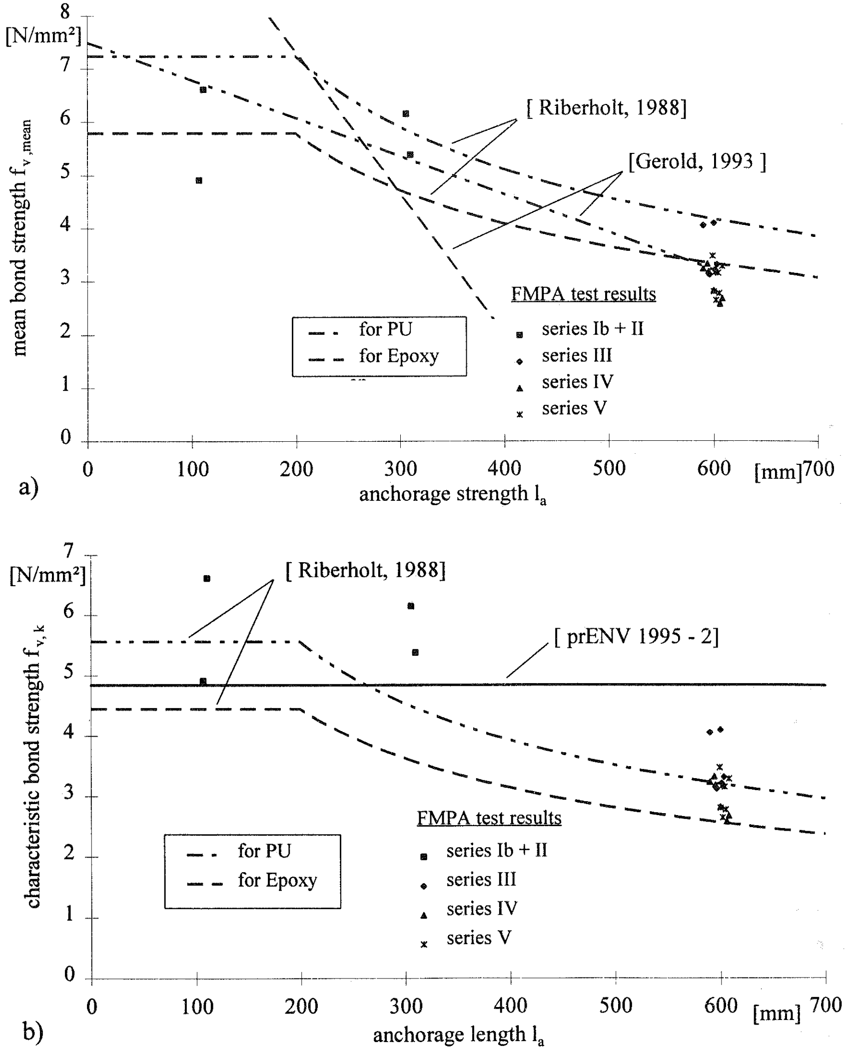

Fig. 4a, b: *Relationship of mean and characteristic bond strength with anchorage length for a characteristic density of* ρ_k *= 380 kg/m*^{3} *depending on adhesive type acc. to literature proposed design equations and here obtained test results*

a) mean bond strength *b) characteristic bond strength*

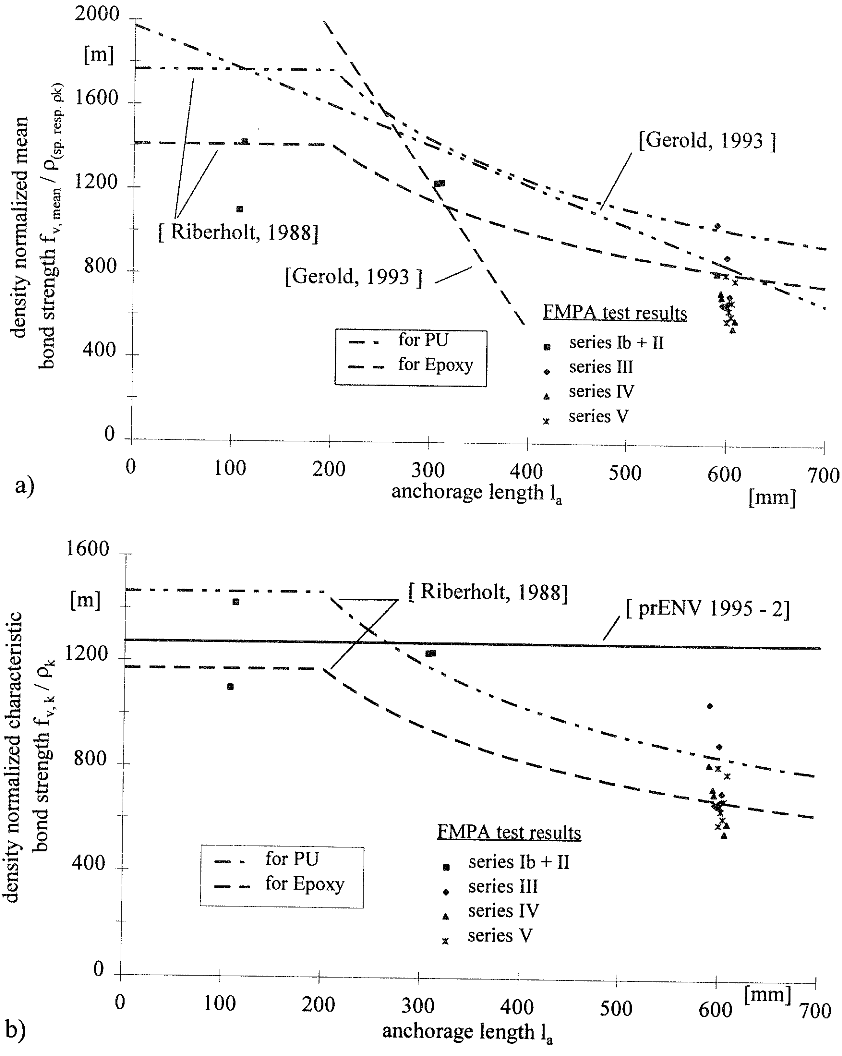

Fig. 5a, b: *Relationship of mean and characteristic density normalised bond strength with anchorage length depending on adhesive type acc. to literature proposed design equations and here obtained test results*

a) density normalised mean bond strength

b) density normalised characteristic bond strength

adhesive type	reference	bond strength f_v mean value $f_{v,\,mean}$	characteristic value $f_{v,\,k}$	axial load carrying capacity F_{ax} mean value $F_{ax,\,mean}$	characteristic value $F_{ax,\,k}$
		N/mm^2		kN	
Phenolic-Resorcinol (PR)	prENV 1995-2	6,05 1)	4,84	239,5 1)	191,6
	Riberholt (1988)	3,34	2,57	132,2	101,6
	Gerold (1993)	3,17	2,38	119,5	89,7
	Blaß et al. (1996)	3,10	2,57	116,7	96,8
Epoxy (EP)	prENV 1995-2	6,05 1)	4,84	239,5 1)	191,6
	Riberholt (1988)	3,34	2,57	132,2	101,6
	Blaß et al. (1996)	3,10	2,57	116,7	96,8
	here	3,24	2,59 1)	128,3	102,5 1)
2component Polyurethane (PU)	prENV 1995-2	6,05 2)	4,84	239,5 2)	191,6
	Riberholt (1988)	4,18	3,21	165,5	127,1
	Gerold (1993)	3,23	2,58 1)	121,8	97,4 1)
	Blaß et al. (1996)	3,10	2,57	116,7	96,8
	here	3,05	2,44 2)	120,7	96,6 2)

Table 3: *Comparision of mean and characteristic bond strength resp. axial capacity for glued-in threaded rods (Ø = 20 mm) with an anchorage length of 600 mm acc. to performed validating test series and literature proposed design equations*

1) values not stated explicitly in literature were complemented, based on given values, by the ratio: characteristic / mean = 0,8

2) due to small sample sizes, characteristic values were derived as stated in 1)

6. CONCLUSIONS

An orienting test series on the axial load carrying capacity of steel rods bonded parallel to grain into glulam by means of Epoxy and 2component Polyurethane adhesives was performed in order to validate literature known design proposals,especially in case of long anchorage length. The findings of the literature review and the performed tests with threaded rods of 20 mm diameter and an anchorage length of 600 mm bonded into lamellas of strength class C30 can be summarised as following:

- the literature review on design proposals revealed partly very inconsistant assumptions on the influence of adhesive type, effective rod diameter, wood density and especially anchorage length,

- the results of the validating test series forwarded a good quantitative agreement with the load carrying capacities and bond strengths acc. to some design proposals accounting for a strength decrease with longer anchorage length,

- an extreme discrepancy between the empiric results and the solution acc. to prENV 1995-2 was obtained; the European Prestandard delivers roughly two times higher values.

Generally speaking, the comparison of some literature known design proposals altogether with here obtained results, revealed a substantial demand for clarification in order to use glued-in rods as reliable to design connectors in timber engineering. A recently granted European Community research project dealing with glued-in rods in timber structures, coordinated by Swedish National Testing and Research Institute and joined by Universities of Lund and Karlsruhe, TRADA and FMPA - Otto-Graf-Institute - should i.a. resolve the described inconsistencies.

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