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DOI
10.1007/s00107-015-1001-2

Publication date
2016

Published in
European Journal of Wood and Wood Products

Eur. J. Wood Prod. (2016) 74:379–391
DOI 10.1007/s00107-015-1001-2

ORIGINAL

Pull-compression tests on glued-in metric thread rods parallel to grain in glulam and laminated veneer lumber of different timber species

Frank Hunger[1] · Mislav Stepinac[2] · Vlatka Rajčić[2] · Jan-Willem G. van de Kuilen[3]

Received: 8 January 2015 / Published online: 12 January 2016

Abstract Ongoing development of timber and timber products made from European hardwoods like ash and beech influences the selection of acceptable methods for connecting these elements and thus demands validation and application of current design methods for softwood and glulam. For the last 20 years, despite many national and international research projects and practical applications of glued-in rods in timber structures, there is still no universal standard with respect to their design. The use of adhesives available for bonding rods and timber is limited to softwood. This work shows the performance of different timber species Norway spruce (*Picea abies* Karst.), European ash (*Fraxinus excelsior* L.) and European beech (*Fagus silvatica* L.) and engineered timber products (laminated veneer lumber made of Norway spruce and European beech) based on comprehensive pull-compression tests of glued-in rods. For characterizing the elastic and elastic-plastic behavior, failure loads as well as stiffness and ductility were considered whereby the rod diameter and anchorage length were maintained constant. The aim of the research was to show that glued-in rods cannot only be used in softwoods and glulam members but also in hardwoods and in wood-based products such as LVL.

✉ Frank Hunger
frank.hunger@tum.de

1 Technische Universität München, Munich, Germany

2 Faculty of Civil Engineering, University of Zagreb, Zagreb, Croatia

3 Holzforschung München, Technische Universität München, Munich, Germany and Faculty of Civil Engineering and Geosciences, TU Delft, Delft, The Netherlands

1 Introduction

A comprehensive study on wide span truss girders in combination with different timber products reported on glued-in rods as a good possibility to connect various elements (Blaß and Enders-Comberg 2012). Hybrid glulam, where the outer zones of the beams are made of hardwood, are combined with laminated veneer lumber (LVL) and cross laminated timber (CLT) for wide-span trusses. The design of the timber structures can be optimized with regard to the material and cross sections used as well as the costs on the basis of the calculated stresses within the structural elements. Reduced cross sections when applying material of higher strength, as for example hardwood, require reinforcment of the joints, and for this reason glued-in rods are taken into account. The aim of this study was to show whether the used materials are, in principle, suitable to be connected with glued-in rods (GiR). This method has often been used in softwoods, but information about GiR in hardwoods or wood-based products is lacking. Pull-compression laboratory tests were done on a total number of 200 specimens. Specimens differed in terms of timber material, adhesive applied and exposure to alternating climate. Adhesives for GiR connection were standard adhesives often used for gluing steel rods into softwood. Epoxy and polyurethane based adhesives were applied and results show that they can also be applied to hardwoods and LVL. In this study, problems regarding different design approaches and lack of standardized design rules for glued-in rods were mentioned, discussed and compared with results from laboratory tests.

1.1 Glued in rods: overview

The topic of glued-in rods covers a lot of aspects that cannot be ignored, but to consider all of them would go beyond this study. Nevertheless they need to be mentioned at this place.

Besides the lack of standardized design rules for glued-in rods (GiR), there are no clearly defined test procedures. In the literature, several test setups for obtaining the pull-out strength of glued-in rods can be found. Bainbridge et al. (2000) performed pull-pull tests, where a rod is glued-in parallel to the grain on each side of the specimen. These two rods are loaded axially until failure on one side occurs. In addition, pull-compression tests as performed by Rajčić et al. (2006) are frequently found in literature (Stepinac et al. 2013). They were realized similar to the standard EN 1382 (1999)—"withdrawal capacity of timber fasteners", albeit glued-in rods are not mentioned in this standard. The scope of this standard covers only fasteners which are inserted into solid timber members or glulam including any type of nails, screws and staples. Tlustochowicz et al. (2011) noted that pull-compression test setup does not correspond to practical applications. This method seems to be appropriate for comparative tests assessing the capability for different materials because of simplicity of the experiment and the possibility of comparison with similar experimental work done by numerous scientists.

Typical failure modes observed in pull-pull tests are rod failure, shear failure either in the adhesive or in the timber around the adhesive and/or failure of the host timber member by splitting or tensile failure as shown in Fig. 1 and explained by Tlustochowicz et al. (2011). By varying the test setup and anchorage length different failure modes can be obtained or even excluded. Steiger et al. (2004, 2006) and Widmann et al. (2007), for example, managed the effect of shear stress peaks at the outer edge of the hole by removing the thread of the rod in the zone close to the surface of the wooden member and shifting the anchorage zone more to the interior thereby reducing stress concentrations and preventing local splitting due to shear forces and stresses perpendicular to the grain.

Different timber classes used for GIR applications can be found in literature. Timber of strength classes C24 or C35 (GIROD 2002; Blaß and Laskewitz 1999) has been used for some tests whereas glulam will be the preferred material when applying GIR in practical applications. Because most of the tests are performed to obtain knowledge of special applications (Kangas and Kevarinmaki 2001), glulam or LVL made of softwood (Harvey and Ansell 2000) are also used. Steiger et al. (2004, 2006) and Widmann et al. (2007) studied the influence of timber density on the pull-out strength. For glued-in rods parallel to the grain it was shown that the pull-out strength strongly depends on the timber density around the anchorage zone. Tests on hardwood have rarely been done (Otero Chans et al. 2008), although glued-in rods have often been used for retrofitting of historical buildings where hardwood was used. Polyurethanes and epoxies are mainly used as adhesives. Broughton and Hutchinson (2001b) tested the experimental pull-out behavior of different types of adhesives. The shear stress at the adhesive-timber interface is also considered in relation to the rod-embedment length. Broughton and Hutchinson (2001a) studied the influence of moisture content at the time of bonding on the pull-out strength of hardwood, but the long-term behavior has rarely been considered because of missing standardized approval procedures as well as time-consuming and expensive tests. Bainbridge et al. (2000), for example, studied the fatigue performance of bonded-in rods for different types of adhesives for glulam made from timber of strength class C35. The glued-in rods were exposed to cyclic loads at low frequency. Tests on the fatigue performance will play a key role, but standardized tests provide comparable test results that can be considered in the evaluation of the long-term behavior in the design rules. Regarding wood-wood bonding, Richter and Steiger (2005) pointed to the significant viscoelastic response of polyurethanes and epoxy adhesive at high temperature ranges which can be found in some practical applications like timber constructions used for brick factories or industrial bakeries (Blaß and Frese 2010).

A lot of studies on the geometric parameters mostly aim at validating one of the many design approaches. These studies have been compared and discussed in detail by Stepinac et al. (2013). However the benefit of this basic research lies in the comprehensive knowledge of the complex interaction between the geometric parameters and the pull-out strength. Steiger et al. (2004, 2006) and Widmann et al. (2007) addressed the geometry of the tested samples including anchorage length, rod diameter, slenderness as a ratio of the anchorage length and the drill-hole diameter. While there is a negative relationship between

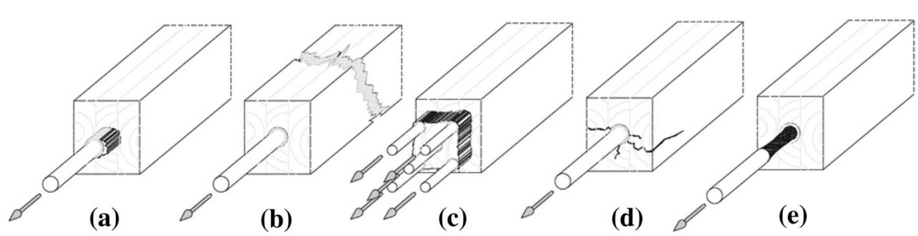

Fig. 1 Failure modes of glued-in rods: **a** shear failure along the rod, **b** tensile failure, **c** group tear out, **d** splitting failure, **e** yielding of the rod (Tlustochowicz et al. 2011)

the anchorage length and the shear strength in the anchorage zone, the shear strength increases at larger drill-hole and rod diameters. From this, a negative relationship between the shear strength and the slenderness ratio results, and the total pull-out force increases at higher slenderness values (Rossignon and Espion 2008).

Feligioni et al. (2003) found a good correlation between the pull-out strength of glued-in rods and the volume of the adhesive which depends on the anchorage length and the glue line thickness. The different behavior of the adhesives applied results from their rheology. It is concluded that the glue line thickness is an important parameter because it allows optimization of the stress transfer from timber to rod. Blass and Laskewitz (1999) studied the influence of spacing on multiple rods and the edge distances at axially glued-in rods. A decrease of the total load-carrying capacity is assumed when the spacing is less than 5 times the rod diameter and the edge distance less than 2.5 times the rod diameter. The results by Broughton and Hutchinson (2001a) validate the influence of small distances between multiple rods.

The aim of this paper is to present test results of comparative pull-compression tests on rods glued into different materials and timber species using different adhesives. Based on a comparison between the characteristic values of the test data and existing design approaches for rods glued into softwood products it shall be investigated if the range of application of the tested adhesives can be extended from Norway spruce glulam and LVL to European ash and European beech glulam and beech LVL.

2 Materials and methods

2.1 Test specimens

For preparation of the test specimens, the regulations given in two official German technical approvals (Z-9.1-705 and Z-9.1-707) for gluing in rods were applied and adapted to hardwood and wood-based products. The first adhesive tested (Z-9.1-705) is a two-component epoxy resin and the second (Z-9.1-707) is a two-component polyurethane casting resin. An overview of the specimens is given in Table 1. The wooden members, where the rods with diameter M12 are glued-in, were made of glulam or LVL with a cross section of 120 × 120 mm^2 except for European beech LVL where a cross section of 120 × 95 mm^2 was used. Glulam of Norway spruce (*Picea abies*), European ash (*Fraxinus excelsior*) and European beech (*Fagus sylvatica*) and LVL made of Norway spruce or European beech were examined. The glulam was made of three lamellas with a thickness of 40 mm without strength reducing characteristics. The Norway spruce LVL was produced by the Scandinavian producer MetsäWood and is known as Kerto S® and Kerto Q® (Z-9.1-100). Kerto S® consists of parallel arranged veneer layers of about 3 mm thickness, whereas in Kerto Q® every forth layer is arranged crosswise. The LVL made of European beech (Z-9.1-838) was provided by the German producer Pollmeier Massivholz GmbH & Co.KG for approval tests for the usage as a construction material, which were carried out at Holzforschung München (Knorz and van de Kuilen 2012).

Steel rods of grade 8.8 with metric threads were glued-in parallel to the grain in all specimens except for specimens made from European beech LVL, where steel rods of grade 10.9 were used. The rods were cleaned by compressed air and white spirit to avoid the presence of dust and oil. The glulam and the LVL were conditioned to equilibrium moisture content at 20 °C and 65 % RH until constant mass was attained prior to further processing.

To make sure that the axes of the rods were precisely glued-in perpendicular to the timber surface, special equipment was used. An additional drill hole perpendicular to the axis of the hole with rod was made for injection of the adhesive. It was positioned in such a way that it touches the bottom of the rod hole. The holes were cleaned from sawdust with compressed air. The rod was centered in the hole with an appliance (Fig. 2) to avoid contact with the sidewall inside. Complete filling of the free space of the holes and an equal bond line thickness was ensured by

Table 1 Number of test specimens examined in the laboratory tests

Material	Adhesive			
	Epoxy		PUR	
	Standard climate	Alternating climate	Standard climate	Alternating climate
Norway spruce (*Picea abies*)	10	6	10	6
European beech (*Fagus sylvatica*)	10	6	10	6
European ash (*Fraxinus excelsior*)	9	6	10	6
LVL Norway spruce (Kerto S®)	10	6	10	6
LVL Norway spruce (Kerto Q®)	11	6	10	6
LVL European beech	20	–	20	–

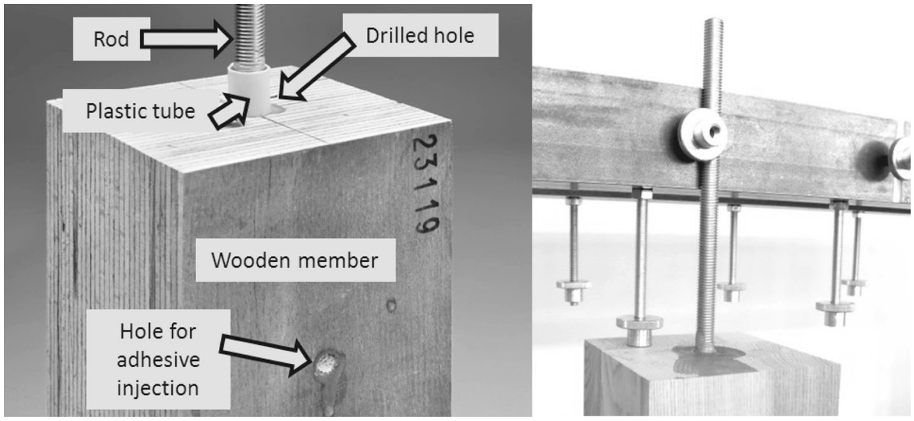

Fig. 2 Test specimen (120 mm × 120 mm × 360 mm), glued-in rod (M12) in LVL with epoxy (*left*), appliance used for gluing in the rod precisely positioned (*right*)

positioning the member upright and injecting the adhesive into the hole until it emerged on the top surface. Figure 2 illustrates the test specimens. For both adhesives, the resin and hardener were supplied in two separate cartridges. By using the injectors and the application gun provided by the producers a totally homogenous mixture of resin and hardener can be achieved. After injection of the resin, the injection channel was sealed by a dowel to prevent leakage.

Being faced with the situation of an undefined anchorage length caused by sagging of the adhesive during the hardening process and arising shear stress peaks at the outer edge of the drilled holes (Pörtner 2005; Del Senno et al. 2004; Serrano 2001), a plastic tube with a length of 30 mm was applied. The outer diameter (16 mm) of this tube was equal to the diameter of the hole. It encircled the rod and was put partly into the hole of the wooden member with a length of 10 mm as shown in Fig. 2. Thus, the rod was completely enclosed by the adhesive and an equal thickness of the adhesive of about 2 mm was ensured. The remaining length of 20 mm protruded from the surface and acted as a reservoir for the liquid adhesive. Taking this into account, an effective anchorage length of 90 mm could be calculated exactly, and the shear zone was shifted more to the interior of the drilled hole. During the hardening process of the adhesive, the test specimen remained in the appliance for at least 12 h, followed by storage of the specimen at a temperature of 20 °C and 65 % relative humidity for several days for complete hardening.

All specimens have equal geometric specifications for gluing in the rods which is necessary to compare the test results. An effective anchorage length of 90 mm which is shifted 10 mm beneath the surface, a metric thread rod diameter M12 and a bondline thickness of 2 mm are requirements for all specimens.

2.2 Climate conditioning

Prior to testing, the specimens were randomly grouped and exposed to different climate conditions within the given product specifications of the adhesives. A standardized procedure is not given. Therefore this specific procedure was adopted to cause stress levels of practical relevance. One group remained in standard climate at a temperature of 20 °C and 65 % relative humidity (RH), and the other group was exposed to an alternating climate. The number of specimens and their treatments are given in Table 1.

The changes in temperature and humidity resulted in a change in moisture content as well as in a moisture gradient. Mechanical stresses caused by swelling and shrinkage could simulate natural variations in joints. In preliminary tests, the effective duration was examined by long term temperature measurements and electrical moisture measurement at different positions inside some specimens. While steel rods are good heat conductors and the temperature changes rapidly in the specimens around the rod, humidity changes need much more time in the adhesive layer and timber surrounding the rod. The alternating climate, which is explained in detail in Fig. 3, started at a standard climate of 20 °C and 65 % relative air humidity. At the beginning, the relative humidity was kept constant at 65 % and the temperature changed frequently from 10° to 50° three times. Duration of each of these intervals was 12 h and temperature changes occurred rapidly. The temperature was measured inside the timber of three specimens. In Fig. 3, the measurements at a depth of 40 mm below the surface are shown for a European beech specimen. Afterwards, the specimens were exposed to a relative humidity of 85 % for 600 h followed by 35 % relative humidity for 505 h at a temperature of 20 °C. The changes in moisture content were measured at a depth of 40 mm below the surface close to the point where the temperature

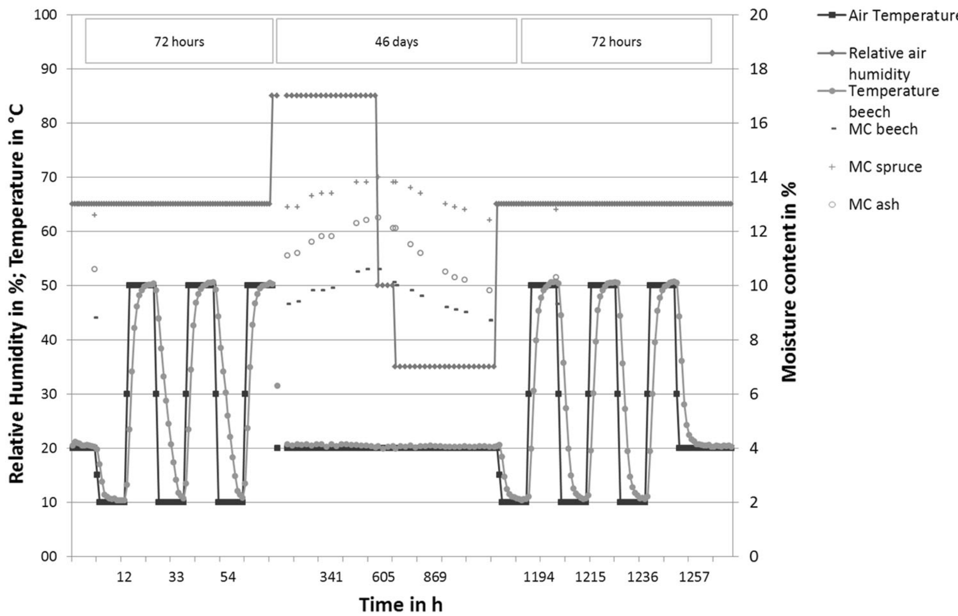

Fig. 3 Storage at alternating climate (time scale in the middle section is compressed)

was measured. The procedure was exactly repeated at the end of the alternating climate storage. Specimens were then conditioned to standard climate prior to the tests.

2.3 Test setup

Pull-compression tests were performed according to test protocol of EN 1382:1999. Failure modes like tensile failure (see Fig. 1b) are excluded from this test setup. Splitting of the specimen (see Fig. 1d) may be detained by friction between the timber and steel plate. Shear failure can occur: (1) along the rod in the adhesive layer, (2) in the timber surrounding the rod, (3) often a combination of 1 and 2 and (4) yielding of the rod. Figure 4 illustrates the test setup. To avoid rotation or angular movement, the loading equipment is self-aligning. The solid steel plate has a grommet hole of 76 mm, thus the distance from the axis of the rod to the bearing is more than three times the diameter of the rod. Tests were performed deformation controlled and so the load was applied at a constant rate between 0.5 and 1.5 mm/min until failure. The loading equipment was capable of measuring the load with an accuracy of 1 % of the applied load and for loads less than 10 % of the maximum load with an accuracy of 0.1 % of the maximum load. For the measurement of the displacement, two inductive displacement sensors were positioned such that the effect of distortion was minimized. The measuring equipment was capable of measuring joint slip under load with an accuracy of 1 %. The total slip measured by the sensors was a result of the displacement in the joint and an additional elongation of a small part of the rod that protrudes from the timber surface. This additional part

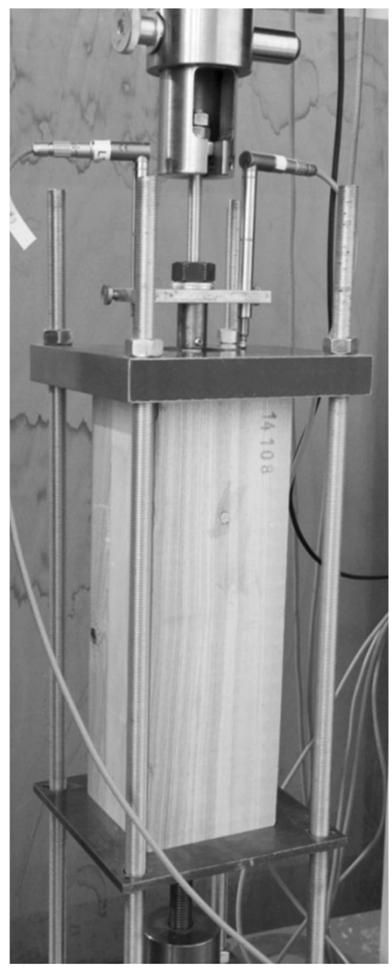

Fig. 4 Test setup for pull-compression tests using two inductive displacement sensors (max. 20 mm) and load cell (max. 5 t)

was equal to the thickness of the steel plate because the fixing points of the displacement sensors were on the top side of the steel plate. The thickness of the steel plate was 30 mm, and by reference measurements the elongation of this part can be calculated as a mathematical function of the load. It is subtracted from the total shift to calculate the displacement of the joint. The load was applied such that the maximum load was reached within 300 ± 120 s except in the case when yielding of the steel occurred. Due to the long term storage of the test specimens at standard climate, the average density of the timber was estimated by measuring the dimensions and weight.

In the elastic range, the stiffness is calculated as a ratio of the increase in the load and the displacement from 10 to 40 % of the maximum load except for load slip curves with coefficient of determination (R^2) less than 0.99 in the range where the range has been adjusted. Stiffness of the whole joint was calculated according to:

$$k_i = \frac{\Delta F}{\varepsilon_i} \tag{1}$$

where $k_i =$ stiffness of the joint, $\Delta F = F_{40\%} - F_{10\%} =$ increase of the axial load and $\varepsilon_i =$ slip of the joint.

In the plastic range, the ductility of the full joint for each specimen is determined according to EN 12512:2001, even though no cyclic load was applied. This European Standard specifies a test method for determining the ductility, impairment of strength and energy dissipation properties of joints made with mechanical fasteners. For this, the yield load (F_y) and the yield slip (V_y) were determined by intersection of two well-defined linear parts on the load-slip curve in the elastic and plastic range. If they were not well-defined in the plastic range, the second line would be a tangent with an inclination of 1/6 of the line in the elastic range. The ultimate load (F_u) corresponds to the failure, 80 % of the maximum. The ultimate slip (V_u) corresponds to the ultimate load. The ductility of the full joint was calculated as:

$$D = V_u / V_y \tag{2}$$

where $D =$ ductility of the joint; $V_u =$ ultimate slip of the joint and $V_y =$ yield slip of the joint. EN 12512:2001 states that these definitions may also be used for monotonic load-slip curves.

3 Results

3.1 Basic test results

Typical failure modes that most frequently occurred were shear failure along the rod in the surrounding timber more or less in combination with shear failure along the rod in the adhesive layer and shear failure along the rod in the interface between the adhesive and the surrounding timber. In only a few tests, failure of the rod occurred.

Test results are shown in Fig. 5. Apparent shifts from the origin of the ordinates are caused by bearing clearance at the test setup. It has no negative impact on the test results.

The load-slip curves for European ash and European beech show a very small scatter. For softwood and LVL, failure occurs at much lower loads. In most cases the failure can be characterized as shear failure along the rod whereby a different ratio of timber and adhesive is involved. For higher loads in European ash and European beech occasional yielding of the rod happens. Figure 6 shows the test results by means of error bars at a 95 % confidence interval grouped by the different climate exposures prior to testing. Figure 7 compares the influence of different climate exposures prior to testing on the yield load and the ultimate load by means of error bars at a 95 % confidence interval. Ductility values close to one are in fact not advantageous. Nevertheless the values are given for all tests or test groups respectively.

Based on the results, cyclic humidity alone does not lead to degradation of the load carrying capacity, nor does it lead to any delayed hardening of the adhesive.

3.2 Yield load and stiffness

Considering the yield load and the stiffness of the joint in Fig. 8, the specimens made of hardwoods show similar characteristics, which differ clearly from those of the tested Norway spruce. An influence of the adhesives on these characteristics could not be found. For the European beech LVL tested, higher values than for Norway spruce and lower values than for hardwood are obtained. It could be noticed that especially the yield load of hardwood LVL with epoxy shows a larger scatter and reaches minimum values equal to Kerto®. The values for Norway spruce scatter slightly more than for Kerto®.

3.3 Elastic-plastic behavior

Ductility in a GiR connection is in most cases assigned to the steel rods. In this study, relatively thin rods were used which will allow greater ductility. Nevertheless, ductility of the whole joint is different when using different timber materials. Figure 9 shows the ultimate load compared with the ductility of GiR connections. Whereas the tested engineered wood products and Norway spruce do not show a ductile behavior, the specimens made of hardwoods allow a larger deformation until the ultimate load is reached. Within hardwood a distinction should be made: European ash with epoxy clearly shows lower ductility than

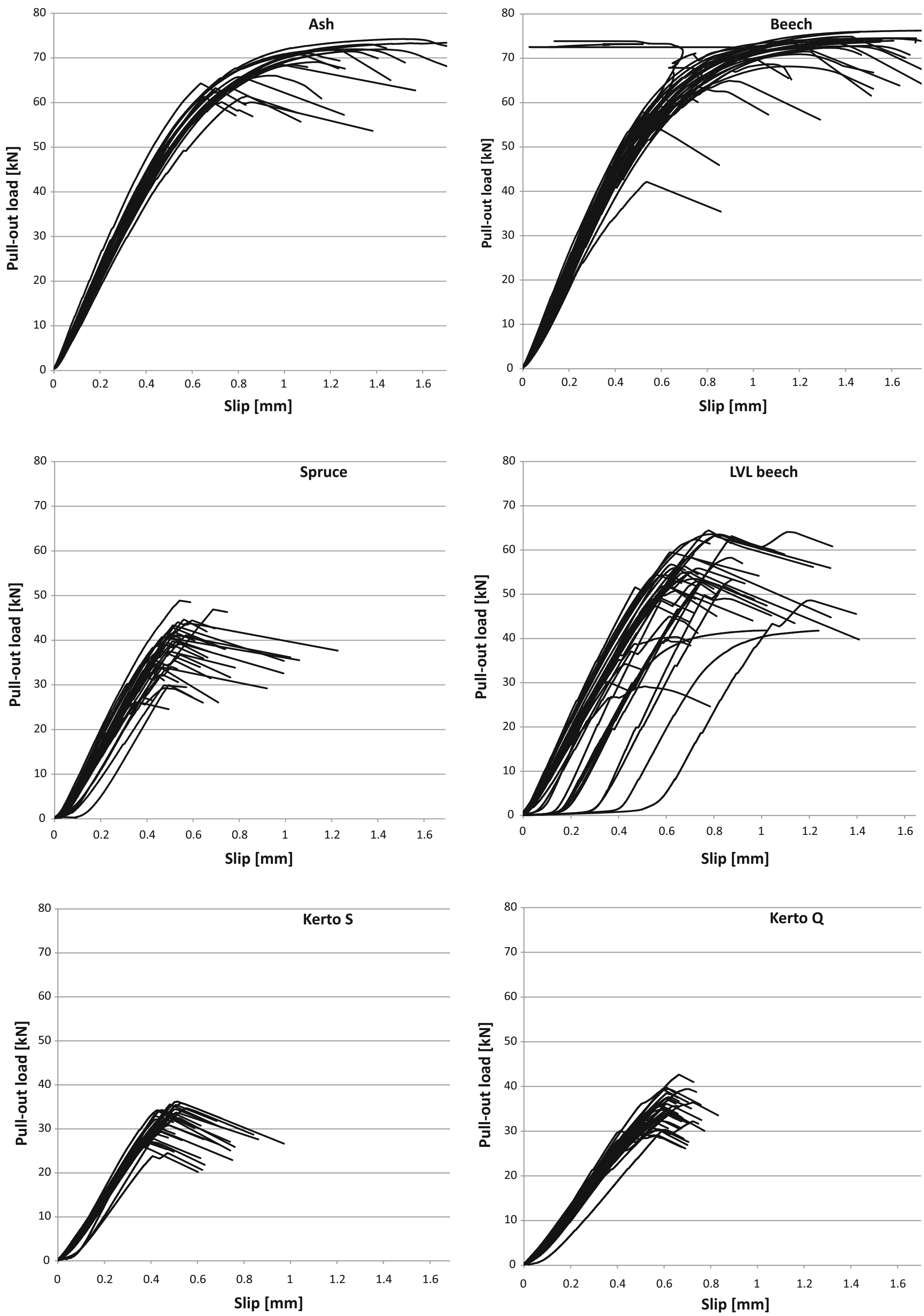

Fig. 5 Load-slip-curves of all specimens tested

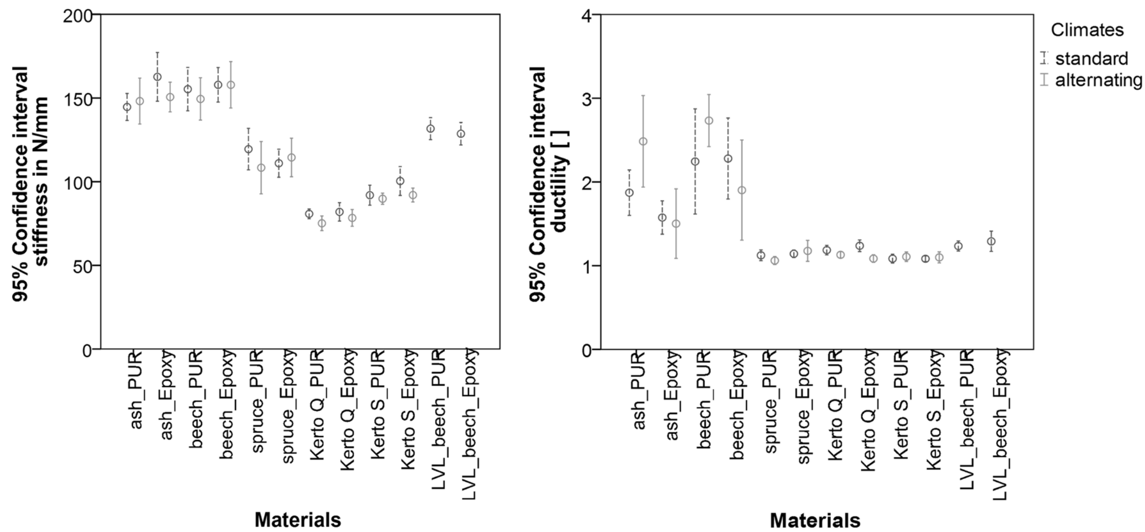

Fig. 6 *Error bars* with 95 % confidence interval of the stiffness k_{joint} (*left*) in the linear-elastic range and of the ductility D (*right*) for constant and varying climates

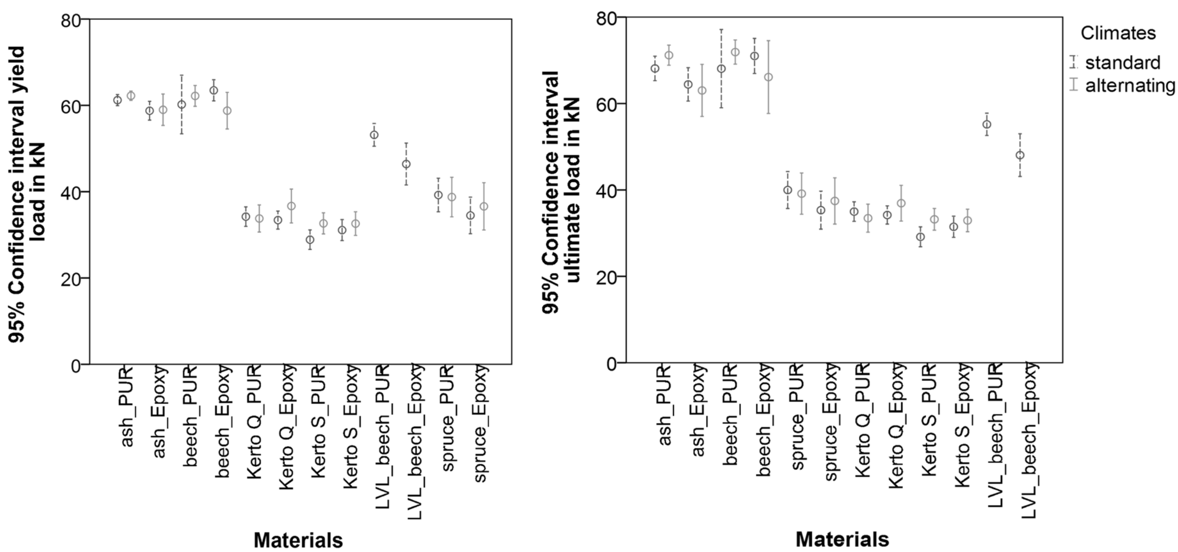

Fig. 7 *Error bars* with 95 % confidence interval of the yield load F_y (*left*) and of the ultimate load F_u (*right*) for different climates

European beech with polyurethane. In comparison, the mean value of hardwood ductility is about one third of that level of the used steel.

Table 2 summarizes the test results for the yield load F_y, ultimate load F_u, maximum load F_{max}, elastic stiffness k_{joint} and the ductility D, giving the mean values $\bar{y}$ and the standard deviations s_y. The characteristic values m_k for load or m_{mean} for stiffness values are shown with regard to the k_s-factors according to EN 14358:2013 in order to consider small sample sizes.

Due to the homogenization effect with glulam and LVL a very low scattering of the density is determined.

4 Discussion

Within the tested climate range of the two adhesives for gluing in rods in softwood, no substantial differences in the mechanical properties were found when comparing the two climatic pretreatments. This is true for the present test setup and deformation controlled loading. Load controlled loading may lead to lower ductility values.

The elongation of the embedded rod is not linear because it is hindered by the adhesive dependent on the shear stress distribution over the length. There is also deformation in the adhesive layer, the surrounding timber

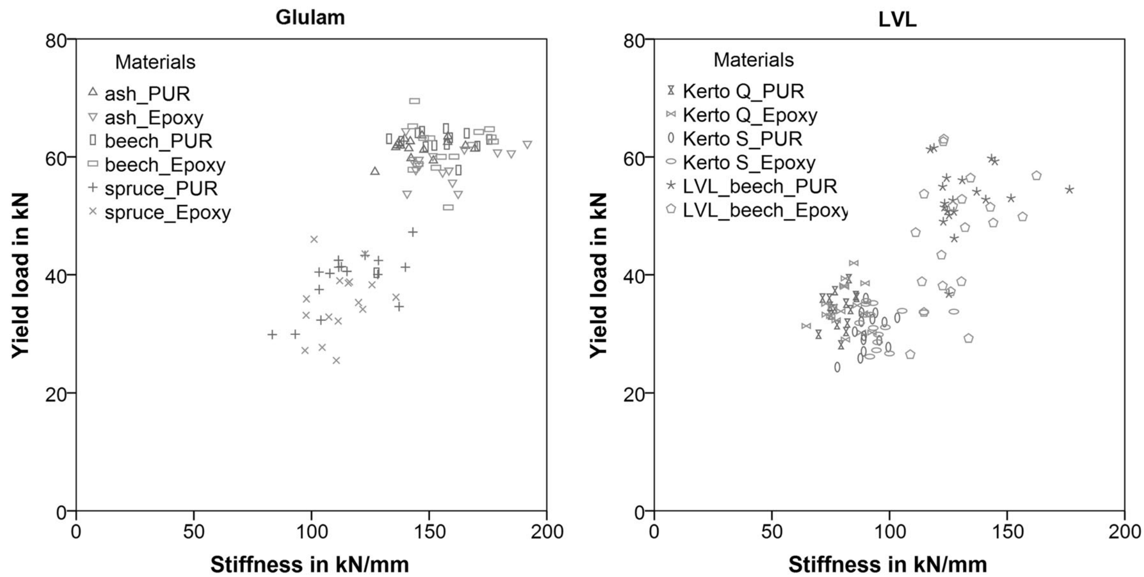

Fig. 8 Yield load F_y as a function of the stiffness of the joint k_{joint} in the linear elastic range for different test materials

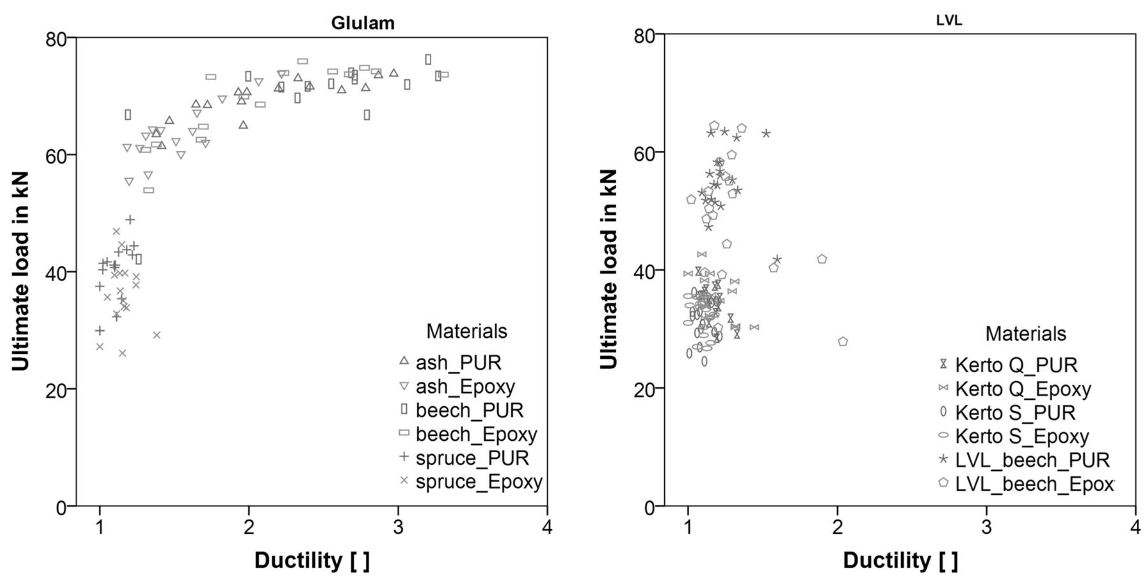

Fig. 9 Ultimate load F_u as a function of ductility D for the different test materials

and the interface between the adhesive and the timber as well as in the interfaces.

The higher modulus of rigidity of hardwoods may lead to higher shear stress transfer from the adhesive layer into the timber. Stress peaks at the outer zones (Pörtner 2005) can be reduced. This leads to higher ductility values determined for European ash and European beech specimens.

Except for the European beech LVL, no clear differences between the two adhesives tested can be found. In general, the engineered wood products show lower strength and stiffness values than the respective glulam, whereas the differences for Norway spruce are not very distinct. The reason for the lower strength values of European beech LVL in comparison to solid beech might be explained by the production process. By producing rotary cut veneer, the inner side of the veneer is overstretched causing small longitudinal cracks. During the production process of LVL these cracks were not filled with adhesive in European beech LVL, whereas in Norway spruce LVL they were filled as shown in Fig. 10. Cracks reduce the local shear strength in the timber around the glued-in rod more than other influences. The adhesive layers between the thin veneers result in a higher modulus of elasticity compared to

Table 2 Test results

	Glulam						Engineered wood products					
	European beech		European ash		Norway spruce		Kerto Q®		Kerto S®		LVL beech	
	PUR	Epoxy	PUR	Epoxy	PUR	Epoxy	PUR	Epoxy	PUR	Epoxy	PUR	Epoxy
n	14	15	16	15	16	16	16	17	15	16	20	20
k_s load	2.0	1.99	1.98	1.99	1.98	1.98	1.98	1.97	1.99	1.98	1.93	1.93
k_s stiffness	0.19	0.18	0.17	0.18	0.17	0.17	0.17	0.17	0.18	0.17	0.15	0.15
F_y (kN)												
Average	61.1	61.6	61.6	58.9	39.1	35.3	34.1	34.6	30.4	31.7	53.2	46.4
5_{perc}	40.3	51.4	57.4	53.7	29.9	25.5	28.2	29.1	24.4	26.2	37.2	26.7
COV	0.10	0.07	0.05	0.05	0.13	0.16	0.09	0.10	0.11	0.10	0.11	0.22
m_k	47.8	53.7	58.5	52.9	29.9	25.3	28.3	28.1	24.4	25.7	42.5	28.4
F_u (kN)												
Average	69.7	69.1	69.3	63.9	39.7	36.1	34.4	35.2	30.8	32.0	55.2	48.1
5_{perc}	42.1	53.9	61.4	55.5	29.9	26.1	28.4	30.3	24.5	26.7	42.1	28.0
COV	0.12	0.10	0.05	0.08	0.13	0.16	0.09	0.10	0.11	0.10	0.10	0.22
m_k	51.7	56.1	62.4	54.1	29.6	25.8	28.4	28.8	24.5	26.1	45.2	29.7
F_{max} (kN)												
Average	70.2	69.3	69.5	63.9	40.0	36.1	34.7	35.4	30.8	32.1	55.2	48.2
5_{perc}	42.1	53.9	61.4	55.5	29.9	26.1	29.1	30.3	24.5	26.7	42.1	29.2
COV	0.12	0.10	0.05	0.08	0.13	0.16	0.09	0.10	0.11	0.10	0.10	0.22
m_k	51.6	56.2	62.2	54.1	30.0	26.0	29.0	28.9	24.5	26.1	45.1	30.0
k_{joint} (kN /mm)												
$\bar{y}$	153	158	146	158	115	112	79	81	91	97	132	129
m_{mean}	150	156	144	155	112	110	78	79	90	95	130	126
COV	0.09	0.08	0.08	0.10	0.15	0.10	0.06	0.09	0.07	0.11	0.11	0.11
D (−)												
$\bar{y}$	2.45	2.13	2.10	1.55	1.10	1.15	1.16	1.18	1.09	1.09	1.23	1.29
m_{mean}	2.33	2.02	2.01	1.49	1.09	1.13	1.15	1.16	1.08	1.08	1.21	1.25
COV	0.26	0.29	0.25	0.20	0.07	0.08	0.06	0.09	0.06	0.05	0.11	0.20
ρ (kg/m^3)												
$\bar{y}$	746	745	647	642	449	459	516	515	503	502	717	721
COV	0.02	0.02	0.05	0.04	0.04	0.09	0.01	0.01	0.01	0.01	0.01	0.02

European beech glulam. This can be confirmed by comparison of the technical approval of European beech LVL (Z-9.1-838) and glulam (Z-9.1-679). In this way, much lower values for the ductility are caused, which was not observed for Norway spruce LVL.

4.1 Comparison with design equations

When comparing characteristic values based on experimental results with present or past standards and proposals for pull-out strength of glued-in rods, huge variations in results are found. Over the last three decades a great number of equations have been proposed and standardized, but there is still no universally accepted design rule. Steiger et al. (2004, 2006), Widmann et al. (2007) and Stepinac et al. (2013) explained this in detail. Stepinac et al. (2013) concluded that prEN 1995-2:2003, DIN 1052:2008 and GIROD formulation are the design procedures most commonly used in practice. Here, four calculation rules are compared with experimental results of the present study. Since sample sizes in this study are too small to suggest a new design approach, focus is put on available design equations whereby it is to be noted that in most cases they had been developed for GIR in softwood.

The characteristic values of the DIN 1052 equation have been calculated on the basis of the characteristic value of the bond strength $f_{k,1k} = 4.0\ N/mm^2$ given in DIN 1052. It has also to be taken into account that comparison based on small sample sizes and comparing mean values may lead to other proportions.

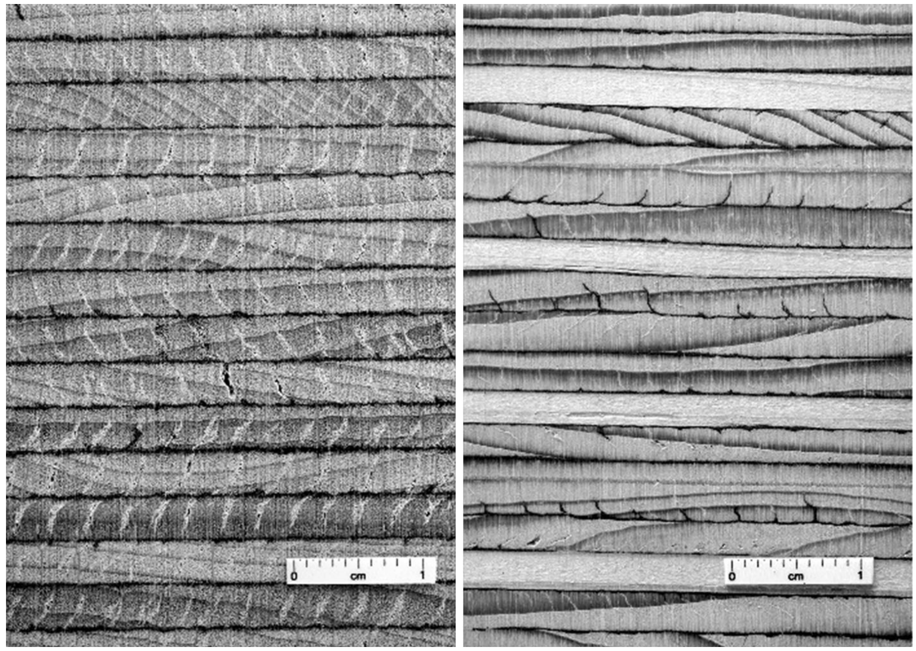

Fig. 10 Example of open cracks (*bright*) in European beech LVL (*left*) and sealed with resin (*dark*) in Norway spruce LVL (*right*)

Design equations for characteristic values are shown below:
Riberholt (1988) equation:

$$R_{ax,k} = f_{w1} \cdot \rho_c \cdot d \cdot l_g \quad (3)$$

prEN 1995-2, 2003:

$$R_{ax,k} = \pi \cdot d_{equ} \cdot l_a \cdot f_{ax,k} \cdot (\tan\omega)/\omega \quad (4)$$

GIROD 2002:

$$P_f = \tau_f \cdot \pi \cdot d \cdot l \cdot (\tan\omega/\omega) \quad (5)$$

DIN 1052:2008:

$$R_{ax,k} = \pi \cdot d \cdot l_{ad} \cdot f_{k1,k} \quad (6)$$

where: $R_{ax,k}/P_f$ characteristic value of axial resistance (N), (kN), $l_g/l_a/l/l_{ad}$ glued-in length/effective anchorage length (mm), d nominal diameter of the rod (mm), d_{equ} equivalent diameter (mm), ω stiffness ratio of the joint, τ_f local shear strength of the bond line (N/mm^2), $f_{w1}/f_{ax,k}/f_{k1,k}$ strength parameter/characteristic value of the shear strength of the wood at the angle between the rod and grain direction/characteristic value of the bond line strength (N/mm^2), ρ_c characteristic density (kg/m^3).

A comparison of the test results with the different design equations is shown in Fig. 11. When comparing experimental results with common design rules it can easily be concluded that there are huge differences in the results. The former prEN 1995-2:2003 and DIN 1052:2008 equations are on the safe side. This is true both for glued-in rods in solid timber and in LVL. It has to be noted that in prEN 1995-2:2003, the minimal anchorage length is ten times the rod diameter, but in this experiment the anchorage length has been reduced to 7.5 times the diameter. To avoid yielding of the rod this was accepted, but it should be taken into account for comparison in Fig. 11. This research can verify which design approach fits best to LVL-materials. If the pull-out strength is estimated using equations of the proposed standards and then compared with obtained experimental data, various conclusions can be made. Whilst all values for pull-out strength are higher than the values obtained by DIN 1052:2008 in all cases, values for LVL made from beech and

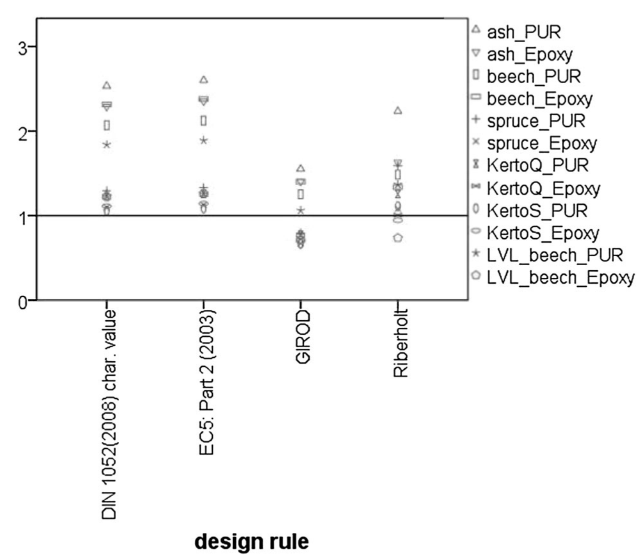

Fig. 11 Ratio of characteristic values from the experimental results and characteristic values of the design rules (proposals)

Norway spruce differ a lot. The pull-out strength of glued-in rods in LVL made of beech is always underestimated, while results obtained for engineered wood products, like LVLs, are much smaller than the ones calculated with all design proposals. Riberholt's formulation gives a pretty correct approximation for the LVL but underestimates pull-out strength for glued-in rods in solid timber by at least 33 % (European beech) and 63 % (European ash). The reason is that the adhesive strength parameter defined in Riberholt's formulation both for epoxy and PUR adhesives appears to be on a very safe side when modern and better adhesives are used. When estimating the pull-out strength using the equation proposed in GIROD project (GIROD 2002), again doubts about the applicability of the approach arise. Whilst for some materials the equation is on the safe side, the characteristic values here determined are overestimated by about 40 % for Norway spruce and Kerto.

5 Conclusion

From this research and the variability in design rules it can be concluded that, although there are a number of design rules, there is an urgent need for a comprehensive design rule such as prEN 1995 or a set of technical approvals for each of the different applications of glued-in rods. The tested adhesives can be used to glue steel rods with metric thread into hardwood (European beech and European ash) glulam and LVL made of beech. In short-term testing of specimens with specific geometrical properties an increase in load carrying capacity compared to GIR in Norway spruce glulam and softwood LVL could be shown. The long term behavior however, has not been subject of research and needs further experimental investigation.

Acknowledgments The work described in this report was conducted at Holzforschung München and financed partially by industry and COST framework. The authors wish to thank the Henkel and Lübbert Warenhandel GmbH for providing adhesives and Gebr. Schütt KG, MetsäWood and Pollmeier Massivholz GmbH & Co. KG for providing the test specimens. We would also like to acknowledge representatives of COST office for their Short Term Scientific Mission grant for Mislav Stepinac who spent 2 months in Munich doing researches on this topic.

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