Glued Laminated *Robinia* Hardwood Timber for Structural Use

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Robinia wood has a high technical and economic potential due to its future availability, its mechanical properties, and its durability. This also applies to its use in structural timber construction. Such applications require the manufacture of bonded construction products from this type of wood in order to compensate for dimensional shortcomings. In an application-oriented research project, tests were carried out for manufacturing technologies and resulting properties of glued laminated timber made from the hardwood species *Robinia* for structural purposes. Based on adapted visual grading rules, the strength and stiffness profiles of *Robinia* laminations were evaluated. The influence of different adhesive types and of production parameters on the strength and durability properties of glued finger joints and glulam bond-lines were characterised. By means of a simulation model based on X-FEM methods in combination with Monte Carlo simulations, the property potential of glued *Robinia* laminated timber was calculated. The model was calibrated by means of input parameters from the empirical lamination and finger joint test data and verified by a small series of full-scale glulam tests. The investigations showed the great potential of *Robinia* glulam, especially in highly loaded and heavily weathered applications.

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INTRODUCTION AND STATE OF THE ART

Robinia pseudoacacia

The cultivation of *Robinia pseudoacacia* (common name: black locust) as an economically relevant wood species is increasing throughout Europe. Today, European *Robinia* wood mainly comes from the south-eastern European region. However, *Robinia* is increasingly being cultivated in other parts of Europe, too. In Germany, cultivation is occurring especially on degraded sites such as former open-cast mines or slag heaps because of the species' low demands on soil quality and its positive properties as a soil conditioner. In addition, the high tolerance to drought makes this species interesting in view of low precipitation levels over the past years, which can be regarded as probably typical for the effects of the ongoing global climate change.

Robinia has a height of about 20 m when fully grown in Germany. However, the branch-free trunk length is usually only a maximum of 10 m. In addition, the stem diameters are limited, which considerably restricts the species' potential use as a non-glued structural building products today. Moreover, *Robinia* is extremely prone to crookedness, out-of-roundness of the trunk cross-section, and already deep-set twig growth (Grosser 1998).

Robinia wood is characterised by a high density and – at least on the level of clear wood – the mechanical properties surpass all other species growing in Central Europe. The excellent strength, hardness, and stiffness values makes *Robinia* wood an interesting candidate for demanding structural application. However, the mechanical properties decrease in many cases due to the aforementioned growth characteristics. For example, the tensile strength is already reduced by 20 to 22% at a fiber deviation of 3° (Göhre 1952).

The unique advantage of *Robinia* heartwood and the main reason for increasing interest in the application of this species for structural purposes are its excellent biological resistance properties. According to EN 350, it is assigned to the resistance class 1 to 2 against fungal attack ("very durable" to "durable"). This means that it surpasses the properties of all native European wood species and is in direct competition even with very durable tropical hardwoods. According to EN 460, *Robinia* wood can thus usually be used in hazard class 3.2 according to EN 350, *i. e*., permanent weathering without additional protection or even in hazard class 4 (in contact with soil or fresh water) without additional – for example, chemical – protection. Thus, *Robinia* wood with soil contact has a service life of over 25 years, and even 60 to 80 years for direct weathering without soil contact (Müller 2006). However, according to Koch and Dünisch (2008), there are some observations that this excellent resistance is restricted to mature wood, and the durability of the juvenile wood may be considerably lower.

Due to its typical growth characteristics, large straight, defect-free lengths can only very rarely be sawn from the trunks. One way to compensate for this is to use *Robinia* wood in the form of glulam. This offers the advantage that components of almost any dimensions can be produced from timber of short length and small dimensions. At the same time, local wood defects, such as knots or strong fiber deviations, can be compensated. However, the process of glulam production is a technologically demanding process.

Bonding of *Robinia*

The bonding of *Robinia* wood has already been investigated in a number of studies and research projects. The focus of such projects considering the main topic of this paper, the structural bonding of *Robinia* wood for load bearing building components, has been on surface bonding. However, in a limited number of investigations, finger-jointing has also been considered.

Surface bonding

In the literature, data on the surface bonding of *Robinia* wood can be found in various contexts. In the publications considered, adhesives based on one-component polyurethanes (PUR), phenol-resorcinol-formaldehyde (PRF), melamine-urea-formaldehyde (MUF), and epoxy resins (epoxy) were primarily investigated (Schickhofer and Hasewend 1999; Schickhofer and Obermayr 1999; Pitzner *et al*. 2001; Frühwald *et al*. 2003; Borysiuk *et al*. 2011; Voulgaridis *et al*. 2012; Konnerth *et al*. 2016; Kamperidou and Barboutis 2017). The bonding of *Robinia* is also a topic of current research (Berthold 2022).

When regarding the results of these publications, a high variety of the scientific statements are noticeable. This occurs both between different publications, and also within single publications. Thus, the bonding quality showed a strong dependency on the specific adhesive product or manufacturer, even within an adhesive family (Pitzner *et al*. 2001). The respective environmental conditions, and the wood moisture content, obviously also had a significant effect on the bonding quality, whereby the strength of the influence varied strongly in the different studies. Another parameter with reported effects is the applied clamping pressure during the bonding process (Kamperidou and Barboutis 2017). In addition, surface pre-treatments for optimising bonding were tested in a series of investigations (Varga and van der Zee 2008; Borysiuk *et al*. 2011; Lehringer 2014).

In general, however, a very heterogeneous picture is observed, so that no clear and consistent trends can be identified. In total, the PRF and MUF resins in particular showed positive results, primarily with regard to the shear strength achieved and also with regard to high wood fraction of the fracture surfaces. In addition, some PUR adhesives stood out as well.

However, the durability of the bond-line integrity – usually assessed by delamination tests – was studied only in very few investigations (Konnerth 2016). Being a generally accepted pre-requisite for the use in load-bearing timber structures, the lack of research on this topic is one of the current barriers for an introduction of bonded *Robinia* elements for structural use.

Glued finger joints

Due to the very uneven growth behaviour of *Robinia* and the resulting mostly very short sections of defect-free *Robinia* wood, a process for finger-jointing is urgently needed in order to be able to produce lamellas with a practical length. For non-loadbearing use, finger-jointed products are available on the market (*e.g*., Eurobinia). Examples of applications here are decking boards or cladding. The production of finger-jointed *Robinia* has proved to be problematic with regard to its suitability for use in load-bearing structures (Bernasconi 2004). However, some mechanical tests with structural finger joints are reported in some studies. A detailed paper on this subject is presented in Müller (2006), where different adhesives and finger joint geometries are investigated, and the results are compared. Frühwald *et al*. (2003) describe investigations on PUR-bonded finger joints and presents these as a significant strength weakness of *Robinia* laminated timber. However, it is problematic to derive clear lines or trends for certain processes or results in the available documentations. This again shows the difficulties in bonding *Robinia* wood and the very individual approach that is necessary when considering appropriate bonding methods.

EXPERIMENTAL

Material and Sampling

The investigations were carried out within an applied research project. The aim was to investigate the bonding properties of *Robinia* wood with regard to applications in the construction sector.

The *Robinia* timber used for the test program was of western Serbian origin, especially from the area of Bajina Basta. The trees used for the timber were about 30 to 50 years old. The saw mill, where the boards were sawn, usually produces timber for cladding, facades and other non- (or semi-) structural purposes. The timber was kiln-dried to a target moisture content of about 12%. Based on experience with glued non-structural products, only boards with small thicknesses of about 26 to 30 mm (after kiln-drying, but before planing) with target thicknesses for laminations in glued-laminated timber (after planing) of 20 mm were used. Most boards had a width of 120 mm, and some smaller boards with 50 mm width were produced. The boards were pre-graded and cut in two different ways for different purposes:

1. For the laboratory bonding tests of finger joints, short boards with 1 m length, free of knots and strong fiber deviations near the end-grain faces, *i. e.* graded according to the requirements of EN 14080, Annex B.3.1, were produced.
2. For the grading and tensile testing of boards without finger joints, boards with a length of 2 m and nearly saw falling quality (unsorted quality) were cut. Only a minor pre-grading was applied: Boards with extreme knot sizes, fiber deviations or mechanical damages were excluded by the staff of the saw mill, following the internal rules for “usual production quality” normally used also for non-structural products.
3. For production of glued-laminated timber and also for the industrial finger joint specimens, boards of the same origin, dimensions, and quality as for the lamination testing were produced; however, these had a smaller length of about 1 m, being the typical length of boards available for the “usual production quality”, *i.e.* with some minimum grading requirements.

In total, an amount of about 10 m^3 of *Robinia* timber was produced and sent to the cooperating laboratories in Dresden and Stuttgart. The test program comprised the following steps:

- Strength grading of the laminations
- Tensile tests of boards without finger joints according to EN 408
- Tensile and bending tests of glued finger joints produced under laboratory and industrial conditions according to EN 14080, Annex E
- Adhesive tests according to EN 302-2
- Bending tests of glued laminated timber produced under industrial conditions according to EN 408

For the tensile tests a servo-hydraulic tensile/compression testing machine (MFL/Zwick 600kN, made in Germany) was used. The bending tests with laminations were performed by means of a electro-mechanical testing machine (Zwick 100 kN, Germany), whereas the bending tests with glulam beam were performed by a hydraulic testing machine with 8 pistons of a capacity of 200 kN each (Schenk, Germany). The delamination tests were conducted by means of the testing system “easyQ DLA-T” consisting of a pressure/vacuum vessel and a kiln dying unit (by KEMPF GmbH Solution+Project, Germany)

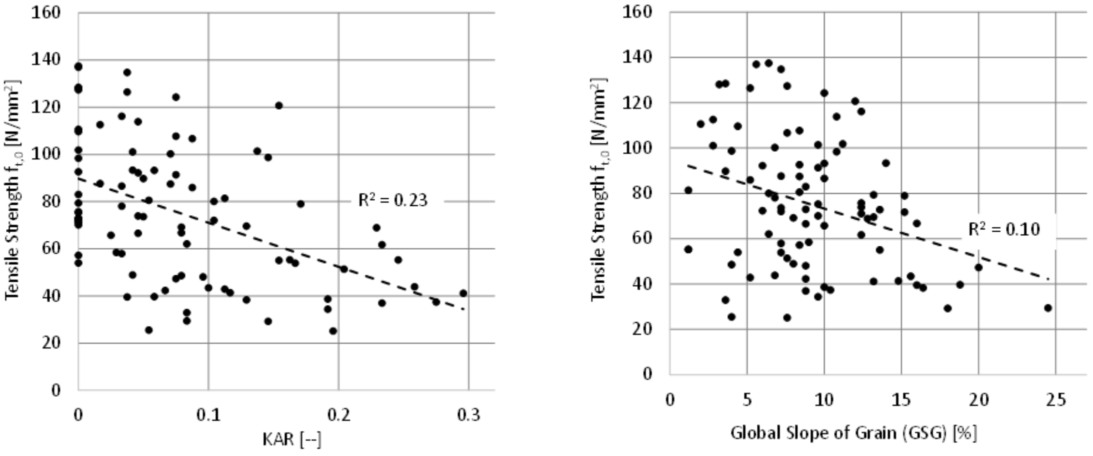
Grading and Strength Assessment of Laminations without Finger Joints

Visual grading was performed for the available 89 Robinia boards with a length of 2 m and cross-sectional dimensions of thickness t = 20 mm and width w = 120 mm. The grading was based on the definitions and criteria of the German standard for grading of hardwood DIN 4074-5. However, the grading and subsequent strength assignment aimed at a more tailored classification deviating from the threshold values of the standard grades LS7, LS10, and LS13.

Detailed inspections of *Robinia* boards showed that the most decisive properties were on one hand the knot area ratio (KAR), *i. e*. the knot or knot cluster size related to the board width, and on the other hand the global slope of grain. Thus, the individual values for these two grading parameters for all specimens were evaluated in this study. All other parameters defined in DIN 4074-5 conformed to the threshold values of the visual grade LS10. Although the presented study relates to the German visual grading standard DIN 4074-5, the most relevant parameters (KAR and global slope of grain) are part of most visual grading standards around the world.

Table 1. Tensile Tests of *Robinia* Boards Without Finger Joints

	Parameter	Raw Density ρ (kg/m^3)	Tensile MOE $E_{t,0,l}$ (N/mm^2)	Dynamic MOE $E_{dyn,l}$ (N/mm^2)	Tensile Strength $f_{t,0,l}$ (N/mm^2)
	Mean value	777	14200	16800	75.2
	Max. value	977	20700	24700	137.4
	Min. value	677	9800	12000	25.1
	Stand. Dev.	48	2000	2200	29.5
	COV	0.06	0.14	0.13	0.39
	char. value EN 14358	695			32.3



a) **b)**

Fig. 1. Correlations between visual grading parameters and tensile strength. a) Tensile strength *vs.* knot area ratio (KAR). b) Tensile strength *vs.* global slope of grain (GSG)

For all specimens, the mass, dimensions, and the natural frequency of longitudinal vibration were recorded, and the raw density and the dynamic MOE were determined. The moisture content was determined by oven-drying method according to EN 13183-1. The tensile tests parallel to fiber direction were performed according to EN 408, section 13, in a servohydraulic test machine with special hydraulic clamps, which enabled a smooth load transfer in order to avoid unintentional fractures at the clamps. The free span of *w* = 1080 mm conformed to EN 408 and EN 384.

During the ramp load tests, the strain was measured by means of an extensometer and the tensile MOE was determined according to EN 408, section 12. The MOE and the raw density were adjusted to the standard moisture content of 12% according to the provisions of EN 384, section 5.4.2. The tensile strength was determined from the ultimate loads and the individual cross-sectional dimensions. Table 1 summarises the statistical parameters derived from the test results for tensile strength, adjusted MOE, adjusted raw density and moisture content.

Figure 1 shows the correlations between tensile strength and the visual grading parameters knot area ratio (Fig. 1a) and global slope of grain (Fig. 1b). The correlation coefficient 0.23 for KAR *vs*. tensile strength was larger compared to the value 0.10 for global slope of grain (GSG) *vs.* tensile strength. A statistically verified correlation could not be found in either case.

In order to investigate the relation between the accessible mechanical properties and the possible yield, three visual grade models with one grade (model 1) and two grades (models 2 and 3) were applied and compared. In Table 2, the threshold values for the visual parameters are given for the different definitions. The resulting characteristic values – determined from the test results according to EN 14358 – for tensile strength, MOE and raw density as well as the resulting yield ratios are also given.

Figure 2 shows exemplarily for the grade models 1 and 2 the effect of visual grading on the cumulative frequency of tensile strength.

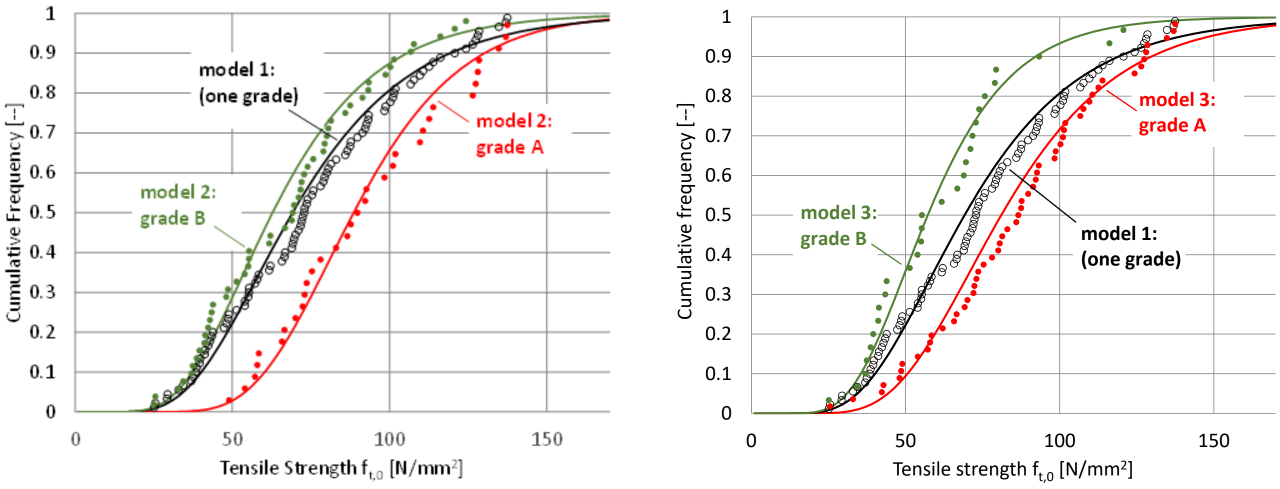


Fig. 2. Effect of visual grading on the strength distributions: Comparison of model 1 (only one grade, no rejects) and model 2 (left) and model 3 (right) with two grades each. The individual strength values and the respective lognormal distributions are given.

Table 2. Definitions and Results for Three Different Visual Grading Models

Model No.	Grade A						Grade B					
	Grading thresholds		Characteristic values			Yield	Grading thresholds		Characteristic values			Yield
	KAR	GSG	$f_{t,0,k}$	E_{mean}	$\rho_{k,}$		KAR	GSG	$f_{t,0,k}$	E_{mean}	ρ_{k}	
	(--)	(%)	(N/mm^2)		(kg/m^3)	(%)	(--)	(%)	(N/mm^2)		(kg/m^3)	(%)
1	< 0.3	< 25	32.3	14200	695	100	--	--	--	--	--	--
2	≤ 0.05	≤ 12	50.8	14800	712	37	≤0.33	≤ 16	30.0	13900	689	57
3	≤ 0.15	≤ 12	41.7	14600	699	62	≤0.33	≤ 16	28.5	13500	688	32

If significantly higher strength values are desired, then model 2 would be the appropriate choice: In the higher grade A – with a yield of about one third of the total population – a characteristic tensile strength value of more than 50 N/mm^2 was achievable, whereby the MOE was only slightly increased. It is interesting to note, that the lower class B for this model 2 shows only marginal reduction of strength and stiffness values compared to model 1 with only one strength class.

Model 3 is an example of a moderate increase of tensile strength in the higher grade A, but accompanied by a much higher yield of 60%. The lower grade B shows a somehow more pronounced reduction of strength and stiffness compared to the ungraded material. All three models show a very high total yield of 100% for model 1 and 94% for models 2 and 3.

Glued Finger joints

The finger joints were produced both on a laboratory scale and in an industrial plant. The milling in both cases was done by means of an industrial device, and the adhesives were always applied to the fingers manually. In the case of the laboratory production, the cramping pressure was applied by a testing machine in order to carefully vary pressure and cramping time. In the case of industrial production, an assembly press was used. The finger joint profile conformed to the most commonly used profile in central Europe with a length of 15 mm and a pitch of 3.8 mm. For characterisation of the performance of the finger joints, flatwise bending tests and tensile tests according to EN 14080 and delamination tests according to EN 301 Annex A were performed.

Laboratory production

During the preparation of the finger joint specimens, the importance of the quality of the milling equipment became apparent. Tests were carried out using milling tools with different service lives. For example, results when using a freshly sharpened tool could be compared with those for a tool that was already close to the end of its service life. The samples were then bonded and tested with the same adhesives and under the same conditions. One effect of the freshly sharpened tool could be observed with respect to the gap tip of the glued finger joint: With the worn cutter, the gap tip dimensions were in the range of approximately 2 to 4.5 mm, beyond the standardised range of max. 1.2 mm (for 15 mm finger joint length). On the other hand, when using the freshly sharpened cutter, care had to be taken that the tip gap did not become too small (standard value: <0.15 mm), which would result in reduced cramping pressure at the finger flanks and splitting of the wood at the base of the joint.

For the laboratory finger joint specimens, three adhesive systems (PU, MUF, and PRF systems) were used that had already been tested positively according to EN 301 or EN 15425 for load-bearing timber bonding. The specimens had cross sections between 52 mm and 60 mm and thicknesses between 20 mm and 24 mm. For comparison, solid *Robinia* wood specimens with the same dimensions and from the same batch were also tested.

The characteristic bending strengths of the finger joints bonded with PU and PRF adhesives exceeded with $f_{j,m,k}$ (w= 62, PRF) = 71.8 N/mm^2 and $f_{j,m,k}$ (w = 62, PU) = 72.5 N/mm^2. For comparison, the characteristic strength values of the solid *Robinia* wood from reference tests $f_{m,k}$ (solid wood) was 68.5 N/mm^2, as usually requested for finger joints in softwoods. For the MUF adhesives, however, the characteristic value $f_{j,m,k}$ (w= 62, MUF) = 50.0 N/mm^2 was smaller than the reference values (for strength distributions, see Fig. 3).

The delamination tests revealed even greater differences. The PRF samples delivered the best values that were clearly below the limits of the requirements of EN 301. PU and especially MUF adhesives showed higher delamination values beyond the limits of the EN 301, with MUF performing the worst.

In summary, PRF adhesives performed best, fulfilling the standard requirements. The PU adhesives exhibited good strength values, but they did not fulfil the delamination requirements. The tested MUF adhesives showed the least promising behaviour both with respect to strength and delamination resistance. In subsequent research, it should be clarified whether a significant improvement of the finger joint performance could be achieved by special measures such as surface pre-treatment or specially structured milling cutters.

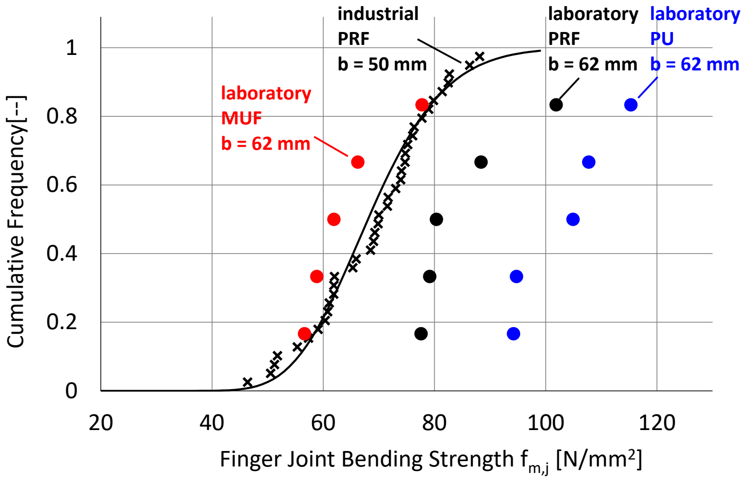


Fig. 3. Cumulative distributions of finger joint bending strength: results of three test series with specimen produced at laboratory conditions bonded with different adhesive types (MUF, PRF and 1K PU) and one test series with industrial specimens (PRF adhesive)

Industrial production

Based on the results from the laboratory tests, industrial scale trials were carried out to produce finger joints. Finger joint specimens with two pronouncedly different widths (w=50 mm and w=120 mm) were produced. The jointed *Robinia* laminations were obtained from the same batch as the non-jointed tensile test specimens. The timber conformed to grade model 1, *i.e.*, no timbers were rejected according to visual grading rules. However, the board end grain faces were selected or cut in such a way that the vicinity of the finger joint was free of knots. A PRF adhesive system was used, and the adhesive was applied manually on the finger flanks of both adherends. Compared to the laboratory tests, the clamping pressure was significantly lower than in the laboratory tests, *i.e.* 10 MPa instead of 18 MPa. The lower clamping pressure had been chosen after some pilot tests in order to avoid occasionally observed crushing of the finger grounds. However, it became apparent that the lower clamping pressure contributed to far too large tip gaps in many cases and subsequently in partly very poor finger joint strength values.

The distribution of the test results of the bending tests with the specimens with smaller width (w = 50 mm) are given in Fig. 3 together with the laboratory tests. It turned out that the strength values were significantly smaller than the respective laboratory specimens glued with the same PRF adhesive system, however, with a still satisfying characteristic bending strength value of 48 N/mm^2. The bending strength distribution of the specimens with the larger width of 120 mm showed pronouncedly smaller values; however, due to less variation, they showed roughly the same value on the characteristic level.

The tensile tests were performed according to EN 14080, Annex E. The resulting finger joint tensile strength revealed a significant width effect: Whereas the characteristic strength for the smaller width was $f_{j,t,0,k}$ (w=50) = 26.4 N/mm^2 the respective value for the larger width was considerably lower $f_{j,t,0,k}$ (w=120) = 16.5 N/mm^2. The latter was caused by a rather large COV=35%. For an illustration of the strength distribution see Fig. 6. The resulting strength value on the characteristic level was rather low, even compared to softwood finger joints of lower softwood strength classes. Although the high strength values of the finger joints produced under laboratory conditions demonstrated the potential opportunities of finger joints in *Robinia* laminations, the results of the tests with industrially produced finger joints shows the risks of unfavourably adapted production parameters such as inadequately low cramping pressure.

Adhesive Tests

In Europe, the use of face-bonded glued timber products for structural use (including glued laminated timber (GLT), glued structural timber (GST) or cross-laminated timber (CLT)) is bound to a successful classification of the applied adhesives. In a two-step system, the adhesive is first assigned to an adhesive type for the bonding of spruce and pine following an exhaustive test programme defined in the standards EN 301 (PRF and MUF/MF adhesives), EN 15425 (1K PU adhesives) or EN 16254 (for EPI adhesives). In a second step, the applicability of the adhesive for other wood species (either hard- or softwoods) is evaluated by delamination tests according to EN 302-2 and a classification according to the requirements of EN 301. EN 302-2 prescribes not only the test procedure with wetting and drying cycles, but also the specific dimensions and layup of the small, laboratory-scale specimens.

Three different adhesives – one PRF adhesive and two different 1K PU adhesives – were tested according to EN 302-2 with *Robinia* laminations. All used adhesives were assigned to “type 1” for spruce and pine. According to the provisions in the test standard, the maximum thickness of the *Robinia* laminations – here 20 mm – was used. The timber was sampled from the same material used for bending tests; however, samples were specifically selected that were as defect-free as possible according to the criteria of EN 302-2. For one PU adhesive (“PU1”), two test series – one with planed laminations and one with sanded laminations – were performed. For the second PU adhesive (“PU2”), the – always planed – surface was treated in different ways: In addition to a reference series without treatment, five series with application of water based sprayed-on primer solutions were employed. The concentration of the primer solution ranged from 0% (only water without primer) to 2.5%, 5% and 10% and the relative amount of sprayed-on solution varied between 10 and 20 g/m^2.

Figure 4 gives an overview of the delamination results of the different configurations. In addition to the delamination percentages represented by columns, the requirement of EN 301 for the classification “type 1” in case of special, high density hardwoods, *i.e.* a maximum value of 8% delamination, is given as a red dotted line.

For the cases of untreated lamination surfaces, the PRF adhesive showed the best performance; however, it clearly still did not fulfil the requirements of EN 301 for adhesive type 1 – a maximum delamination of 8% is required here for specific hardwood species. PU 1 showed generally quite high delamination values up to more than 40% with slightly smaller values for sanded surfaces (over 30%). The delamination results for the adhesive “PU 2” without treatment were extremely high (over 70%). However, surface treatment with a water-based primer solution improved the results for PU 2 significantly, *i.e.* the delamination percentages could be reduced by factors between *ca.* 2.5 and 6. Irrespective of application amount and concentration, all delamination values were well below 20%. The best results – in this case even fulfilling the “type 1”-requirements (delamination percentage smaller than 8%) – were observed for the configuration with a relative application amount of 10 g/m^2 and a concentration of 10%.

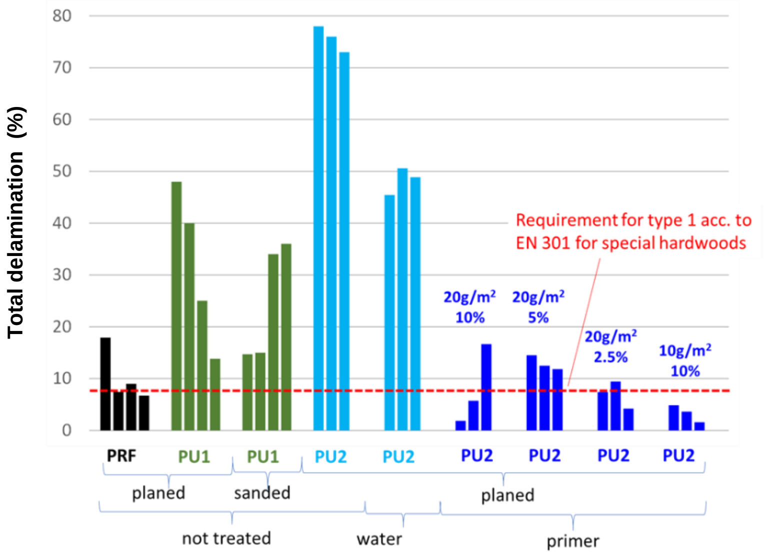


Fig. 4. Results of delamination tests for different adhesives and different surface treatments

Glued Laminated Timber

As a basis for experimental verification of strength modelling results, bending tests of full-scale glued-laminated *Robinia* timber beams were performed, as shown in Figs. 5 and 6. The beams consisted of 20 laminations resulting in a cross-sectional height H of 360 mm, a width *W* of 110 mm and a length *L* of 6700 mm. Due to limited *Robinia* material, the number of test specimens was limited to 4 specimens in total. The laminations were sampled from the same batch as the boards and finger-joint specimens and were finger jointed in the same industrial production process as described above. The four point bending tests were carried out according to the provisions of EN 408 by means of a hydraulic testing machine, whereby the span was 6480 mm (= 18 *H*), a distance between the two pistons of 2160 mm (=6 *H*) and a distance between each piston to the nearest support, i.e. the lever arm a = 2160 mm (= 6 *H*). The global and local deflections were measured and recorded during the tests. From the ultimate load, the bending strength and from the load-deflection curves the local and global MOE were determined. Table 3 gives the individual results and the statistical parameters of all four tests. All beams broke at the bending-tensile edge within the zone of maximal bending moment. The initial fracture was always located at a finger joint of the outer lamination. The COV of the bending strength values COV_{beam} = 10% was much smaller compared to the variations of the tensile strength of the laminations COV_{lam} = 39% and the variation of the finger joint tensile strength COV_{fj} = 35%.

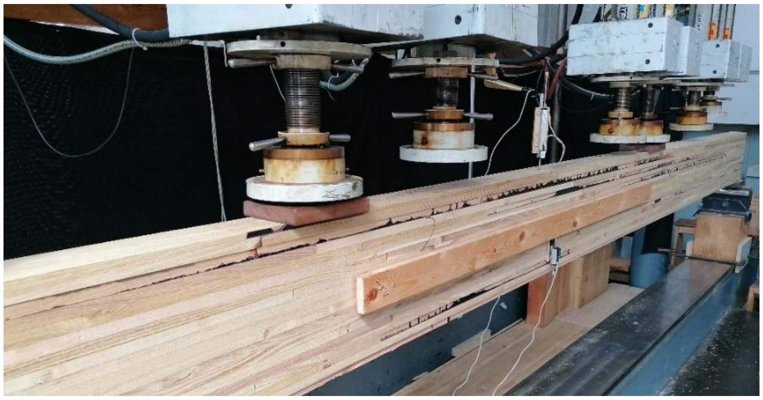


Fig. 5. Test set-up of the full-scale bending tests with *Robinia* glulam (Schenk 8piston/200kN, Darmstadt, Germany)

Fig. 6. Typical fracture pattern of a *Robinia* glulam beam after failure

Table 3. Results of the Bending Tests of Full-scale *Robinia* Glulam Beams

Beam No.	Ultimate Load F_{max} (kN)	Bending Strength $f_{m,g}$ (N/mm²)	Global MOE $E_{g, global}$ (N/mm²)	Local MOE $E_{g, local}$ (N/mm²)
1	60.1	54.7	14780	17130
2	69.6	63.3	15010	17430
3	65.6	59.7	14480	16790
4	55.3	50.3	13780	15990
Mean value		57.0	14510	16830
COV		0.10	0.037	0.037
Charact. value acc. to EN 14358		43.3		

FEM-Model and Monte Carlo Simulations

The computational modelling of the glulam beams – especially with regard to the calculation of bending strength and bending E-modulus – was implemented using a finite element model with an “X-FEM” approach to represent the full non-linear and damage behaviour. This advanced FE method can on the one hand handle yielding phenomena on the compression side and on the other hand accurately represent the softening damage behaviour on the tension side accompanied with localization of damage and load redistribution to adjacent laminations. The FE calculations were carried out using the ABAQUS program package, which is particularly suitable for nonlinear calculations. The model was fully parameterized so that Monte Carlo simulations could be carried out by means of targeted stochastic variation of the input variables, from which the distribution of the glulam strength and stiffness distributions, and finally the characteristic 5% quantile values were to be derived. The computational model also had the potential to predict the expected size-scale effect (*i.e.*, the dependence of bending strength on beam height) and the effects of a possible combination of different strength classes in the glulam cross-section. The model had originally been developed for the simulation of bending properties of glulam made from oak laminations (Tapia and Aicher 2018; Tapia 2022) and was adjusted to the properties of *Robinia* timber.

Input Data and Simulations

For the stochastic FE-modelling, the distributions of strength and stiffness properties of the laminations as well as of the finger joint strengths are needed as input data. Furthermore, a strength model based on the local correlation between strength and stiffness and a damage/failure model are needed. The different steps for the lamination strength model have been described in detail (Tapia and Aicher 2019; Tapia and Aicher 2021; Tapia and Aicher 2022) for the example of oak boards. Due to a relatively similar defect structure of the species oak and *Robinia*, some of the more elaborate investigations on the correlation functions, the typical length of weak sections, the fracture energy, and the ratio between tensile and compressive strength were transferred from data collected on oak boards. For calibration to the wood species *Robinia*, the following data sets of the matched laminations sets were used:

- Empirical tensile strength distribution and distribution of tensile E-Modulus of the laminations without finger joints (strength grading model 1),
- Empirical tensile strength distribution of industrially produced finger joints,
- Empirical data of distribution of distances between two finger joints within the laminations.

In order to estimate the bending strength and bending MOE distributions, a set of 1000 numerically simulated beams was performed.

Comparison of Empirical and Modelling Results

In Figs. 7 and 8, the simulation results of the Monte Carlo simulations of the FE-model are compared to the empirical data of four bending tests with glulam beams. In order to visualize the pronounced homogenisation effects, selected data of the laminations are also additionally plotted in the figures.

Figure 7 shows the bending MOE of glued laminated timber for the four empirically tested beams (filled blue symbols) and for the numerically simulated glulam FE-models (open blue symbols). Additionally, the empirically determined tensile MOEs of the laminations are plotted in the figure as filled green symbols. It can be clearly seen that the simulations gave a very good estimation of the mean glulam MOE and also of the expected variation. It is striking to see the extreme reduction of spread when the tensile MOE of laminations is compared to the calculated as well as the empirically measured glulam MOE Whereas the mean values of lamination MOE ($E_{\text{mean, lam}}$ = 14200 N/mm^2), simulated MOE of glulam ($E_{\text{mean, GL, simu}}$ = 14340 N/mm^2), and empirical bending MOE of glulam ($E_{\text{mean, GL, emp}}$ = 14500) were close together, the COVs of the lamination MOE (13.7%) was by a factor of *ca.* 4 to 5 larger than the COV of the simulated glulam MOE (2.7%) and the COV of the empirically derived COV (3.7%).

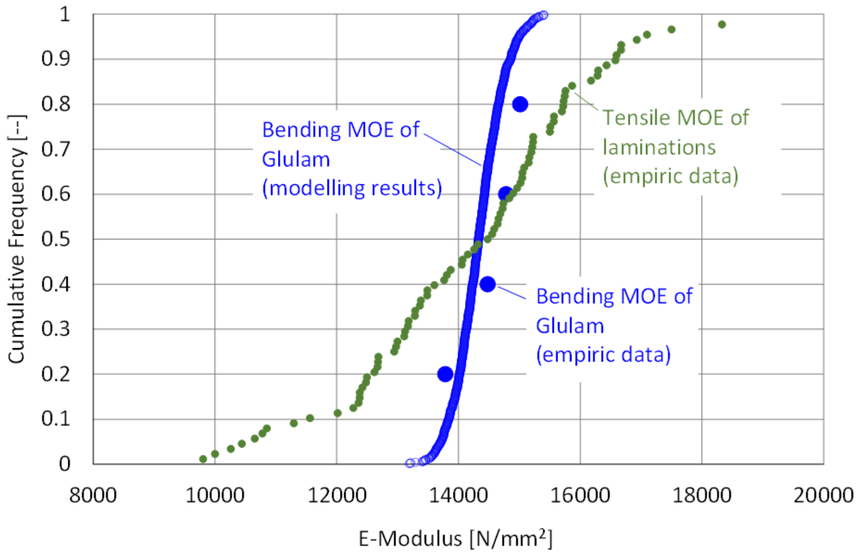


Fig. 7. Comparison of E-Modulus results: Empirical data of laminations and glulam and simulation results for glulam

Figure 8 shows the bending strength data of glued laminated timber of the four empirically tested beam (filled blue symbols) compared to the results of the numerically simulated glulam FE-model calculations (open blue symbols). Additionally, the empirically determined tensile strength distributions of the *Robinia* boards and of the industrially produced finger joints are plotted as filled green symbols (boards) and filled orange symbols (finger joints). Obviously, the glulam simulation results showed a good agreement with the test data in a qualitative sense: Compared to the board strength values the variation was reduced to an extreme extent and the strength was shifted to lower values due to the influence of the relatively weak finger joints. Compared to the finger joint strength distribution, the glulam bending strength – for the simulation as well as for the test results – showed pronouncedly higher values resulting from a strong homogenisation effect. However, looking at the quantitative comparison between simulations and empirical glulam results in more detail, it is noticeable that the numerical results exhibited lower strength prediction on the mean and the lower 5%-quantile level. Only the upper branch of the distributions fit well with the maximum value of the empirical data. The reason for the underestimation of the glulam strength could for instance be due to the partial model calibration with oak instead of (not available) *Robinia* data. But it must also be considered that the empirical data set of only 4 beams – even if these 4 beams consisted of in total more than 500 different pieces of *Robinia* boards – was very limited. Thus, for the conclusions, the conservative results of the simulations – which were even lower than the full-scale glulam tests – shall be used.

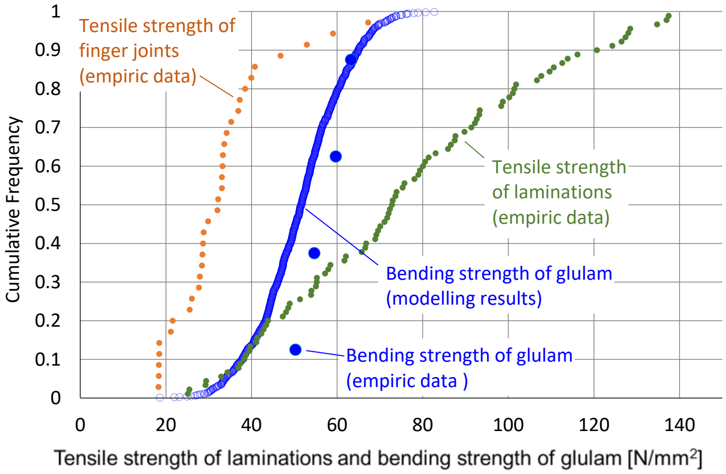


Fig. 8. Comparison of strength results: Empirical data of tensile strength of laminations and finger joints and of bending strength of glulam and simulation results for bending strength of glulam

Discussion of the Glue-Laminated Timber of Robinia

The surface bonding of *Robinia* posed a great challenge in the project. Although good shear strengths were achieved with several adhesives, achieving a durable bond-line integrity that meets the specifications of the relevant standards – being mandatory for structural use – was a major hurdle. Even with a PRF adhesive, which is successfully used for the production of non-load-bearing *Robinia* products, a sufficient quality of the bond-lines was not achieved. By far the best results were achieved with adhesive tests on the scale of laboratory specimens by application of a PU adhesive combined with prior water-solution-based primer treatment. Despite the lack of optimisation of the bonding process, delamination values were achieved matching the target values of the relevant standards for a specific parameter set. Due to the boundary conditions of the industrial partner, however, it was not possible to apply the PU/primer technology on the industrial scale, because the application technology for use of one-component PU adhesives differs considerably from the technology for two-component polycondensation adhesives such as MUF or PRF. Here it can be assumed that further investigations and an improvement of the gluing process can lead to safe bond lines also under industrial production conditions.

In the production of finger joints, good values were achieved right away in terms of both the strengths and the durability with PRF on a pilot plant scale. However, implementation on an industrial scale still proved to be difficult, as the results obtained were very strongly dependent on the special production conditions. Further optimisation, especially with regard to cramping pressure and times as well as optimal adhesive application, is necessary here. These developments promise a high potential to achieve such high bonding properties. However, it should be kept in mind that today the industrial production of PRF bonding is being implemented less and less frequently. For this reason, further research effort should go into investigating alternatives to PRF adhesives in the production of finger joints and glulam production from *Robinia*. More comparative studies on adhesives, particularly those suited for structural applications under harsh environmental conditions, are necessary here. First steps towards the judgement of the durability under extremely varying moisture and temperature changes were done by the use of the delamination test method usually seen as the state-of-the-art procedure to predict long term behaviour of bond-lines. Further research should also focus on use of the latest development of novel hardwood adhesives (*e.g.* Holeček *et al.* 2023; Kariž *et al.* 2024).

During the implementation of the finger joint production from the laboratory tests into industry-related tests, two main parameters to be optimised were identified: The clamping pressure has to be chosen optimally to avoid splitting and on the other hand ensure sufficiently small finger tip dimensions. Furthermore, the wear of cutters has to be monitored carefully, as reduced milling quality significantly influenced finger joint bond strength.

Due to its typical growth characteristics, *Robinia* wood shows an extreme variance in the mechanical properties, with variation coefficients up to about 40%. Although the properties on the mean value level showed quite high values, the characteristic values were limited. The results of the presented study confirm that an application of sawn *Robinia* wood as a building product would lead to very low design values without further bonding. The application of newly developed visual grading models based on the German grading standard DIN 4074-5, but with deviating threshold values, resulted in increased characteristic levels, however, with the reduced yield or reduced available lengths of the timber members.

The production of glulam from *Robinia* lamellae showed a very pronounced lamination and homogenisation effect being considerably stronger than for glulam made from usual softwood species such as spruce. In spite of non-optimised finger joints, limited bond-line quality and usage of saw falling timber without grading, the variations of strength and stiffness parameters of the produced glulam were extremely reduced and comparably high characteristic values were achieved. Thus, *Robinia* glulam has a promising potential as a high-quality product for the building industry. The lamination and homogenisation effects can be modelled well with the stochastic Finite Element simulation tools adapted to the properties of *Robinia* wood in the project. A reliable prediction of the glulam properties derived from the properties of the components laminations and finger joints can thus be implemented even with limited experimental testing. This also opens up the possibility of accurately predicting the properties of bonded *Robinia* laminated timber from other *Robinia* wood qualities than those used in the project. In addition, the model also offers the possibility of predicting the effects of further optimisation of the production process.

CONCLUSIONS

1. In the project, it was possible to produce glulam from *Robinia* wood with comparatively high strengths and a high modulus of elasticity.
2. The adapted visual strength grading of the *Robinia* wood used enabled high mechanical properties to be achieved with a high material yield at the same time.
3. Finger joints in *Robinia* wood lamellas were successfully produced using phenol-resorcinol-formaldehyde (PRF) adhesives. The normative specifications were also met in terms of durability. The quality of the finger joints depended heavily on the manufacturing conditions, such as the degree of wear of the milling tools used and the pressing pressure. When using PU and MUF adhesives, it was not possible to fully meet the requirements for delamination resistance in particular.

4. For the surface bonding of *Robinia* wood lamellas, the sufficient durability requirements could only be met when using a 1C PU adhesive system in combination with a primer pre-treatment. As *Robinia* is generally considered to be one of the most difficult wood species to bond, the combination of primer pre-treatment and 1C PU adhesives could also be considered promising for use with other hardwood species that are problematic to bond.
5. Using a combined X-FEM and Monte Carlo simulation, the properties of glued laminated timber made of *Robinia* could be predicted from the property distributions of the used *Robinia* wood and the finger joints. The developed methods can generally be used for modelling of the mechanical properties of upcoming other novel load-bearing hardwood timber products.
6. Further research is needed especially with respect to finger-joint bonding: Either surface pre-treatment methods should be found that can be applied to the finger-jointed flanks or newly developed (preferably bio-based) hardwood-adhesives should be tested for this particular application.
7. Due to the unpredictable availability of individual softwood and hardwood species in the future, generalizable testing and assessment methods should be developed and validated in the future to enable varying and possibly even mixed use in load-bearing timber construction products.

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