



Bondline shear strength and wood failure of European and tropical hardwood glulams

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Abstract

The study reports on block shear investigations with bondlines of face-glued laminations and matched solid wood specimens from hardwood glulam (GLT) beams produced industrially from eight technically and stand volume-wise important species. The European hardwoods comprised oak, beech, sweet chestnut and ash and the tropical species were teak, keruing, melangangai and light red meranti. The adhesives were phenol-resorcinol and melamine-urea. When combining all species in one sample, a rather strong linear relationship of bond and wood shear strength was observed. The ratio of bond vs. wood shear strength was for all species on the mean value level ≥ 0.9 , and likewise (with one exception) for the respective strengths' 5%-quantiles. Consistent with literature, the test results showed no significant correlations between bond shear strength and density, wood shear strength and wood failure percentage of individual species, respectively. The investigations render the methodological basics of some international standards on bond quality verification as being inappropriate. New, empirically validated hardwood GLT bond requirements are proposed for discussion and implementation at the CEN and ISO levels. The strength ratio specifications reflect respective *ANSI* provisions, yet the reference quantity wood shear strength is now determined in an unbiased manner from matched GLT specimens. The wood failure verification proposal is based on the 10%-quantile and mean level for initial type testing and factory production control. The requirements further account for the pronounced difference observed in scatter of wood failure between European and tropical species.

1 Introduction

For any glued composite material, strength and integrity between the laminations or plies constitute the basic prerequisite of the compound effect of the assembly. In the case of one or more weak bonds or even delaminations, the load capacity of the compound drops to a fraction of the intact cross-section. Some locally weak bondlines may be tolerable for spacious plate-type products, for example cross laminated timber (CLT), yet in the case of beam type construction elements such as glued laminated timber (GLT) the highest degree of bond performance is required throughout to ensure the short- and long-term safety and serviceability

level. From the very beginning of the use of glued wooden structural products for aircrafts and buildings, the test methods and requirements on bond performance were one of the major tasks in the development of the glued products (Truax 1930; Egner et al. 1963). The eminent importance of adequate bond strength verification is emphasized by the fact that deficiently manufactured and further long-term degraded bondlines have led in the past to many GLT damages and even to catastrophic failures, such as the collapse of the glued wooden roof of a large ice-rink in Bad Reichenhall, Germany, in 2012.

Block shear tests represent, next to delamination testing which is of even higher importance, one of almost exclusively used test and assessment methods for both bondline strength and integrity of GLT and glued solid timber (GST) worldwide. The present European (EU) standard on GLT and GST considers solely softwoods, whereas the US and Japanese GLT standards allow the use of hardwoods as well, and the Malaysian GLT standard considers exclusively hardwoods. One of the major reasons to exclude hardwoods from the present EU GLT standard contrary to the previous standard version EN 386 (2001) were the split opinions on

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the issue of reliable methods for verification of constancy of performance of the beams. Although the fact of several existing, well performing, load bearing structures made of GLT from different hardwood species was not contested, the standardization discussion in CEN focused on the lack of consistent experimental data and respective theoretical considerations to establish realistic, industrially feasible yet safe requirements for bond shear strength and delamination tests for hardwood GLTs.

One major reason for the difficulty in establishing reliable requirements for bonds of hardwood GLTs stems from the vast diversity of hardwoods as compared to softwoods. This is highlighted by the fact that worldwide softwoods comprise about 650 species grouped in seven botanical families, whereas for hardwoods, over 40.000 species within some 60 families exist (Fine and Ree 2006; Slik et al. 2015), from which however only a very minor part is commonly used for construction purposes. Further, the heterogeneity of the structurally used hardwood species is far higher than that of softwoods, which can be easily demonstrated by wood density. The worldwide industrially mostly used softwood family of *Pinaceae* comprises a density range of roughly 350–550 kg/m³ compared with the densities of technically relevant hardwoods used for GLT which range from about 300 to 1000 kg/m³. Further, the differences within hardwoods resulting from wood structure (ring-/semi-ring-/diffuse-porous) and material contents, for example tannic acid, are considerably larger as compared to softwoods.

In view of the pronounced species-dependent density and growth characteristics of hardwoods, one possible solution for the derivation of bond strength and wood failure requirements would be to tackle the problem species-wise as done in the US or to form groups of hardwood species and density ranges in a manner similar to Japan. Such an approach would be entirely different from the present EU procedure for softwood GLTs, where irrespective of species and density, the same requirements for bond strength, wood failure and delamination are specified.

The derivation of reliable GLT bondline shear tests and assessment criteria was a major task in a recent European research project on hardwoods (WoodWisdom “EU hardwoods”—<http://www.eu-hardwoods.eu>). This paper reports on condensed, relevant literature-based experimental bond shear investigations and results with GLTs made from several European and tropical hardwoods. Deepened discussions of underlying physical phenomena of observed performances are outside the scope of the paper and addressed separately. A new species-encompassing proposal for bond shear performance verification is presented.

2 Literature review

The literature study uncovered a substantial number of block shear investigations on bondlines of GLT made from hardwood species. Details of the evaluation of about 60 publications and reports are given in Hirsch and Aicher (2017). Essential results of the literature review are provided in Figs. 1 and 2. Figure 1 shows the relationship of the mean wood failure percentage (*WF*) and the mean bond shear strength ($f_{v,b}$) for each of the 62 reported test series with about 40 EU, US and tropical (TR) hardwood species (for references see caption of Fig. 1). Figure 2a specifies for most of the test series from Fig. 1 and some additional ones the relationship of bond strength vs. wood density. Figure 2b shows for a subsample of 26 test series from Fig. 1 (and one additional) the relationship of bond vs. wood shear strength on the level of the strength means.

All presented shear strength data stem from block shear tests, performed and evaluated respectively according to EN 14080 (2013) and EN 392 (1995), ASTM D905 (2009) and ASTM D2555 (2016), MS 758 (1981), JAS SE-9 (2000) and JAS 234 (2003) as well as respective previous standard versions. The shearing lengths parallel to fiber ranged from 20 to 55 mm. The shear areas had sizes of 460–3025 mm². The moisture content was nearly throughout in the range of

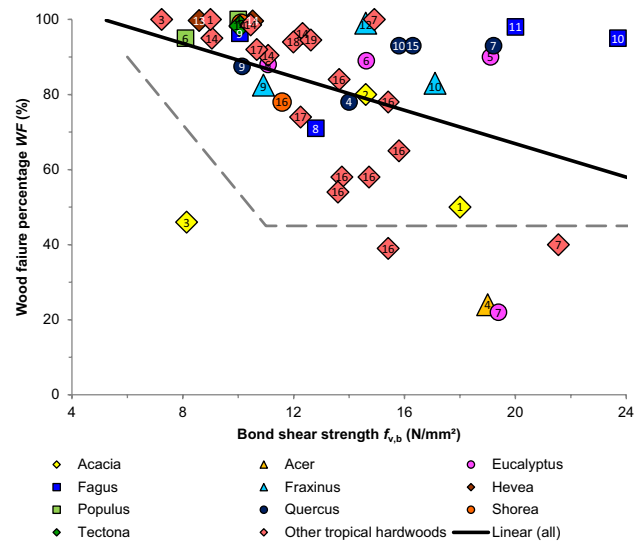
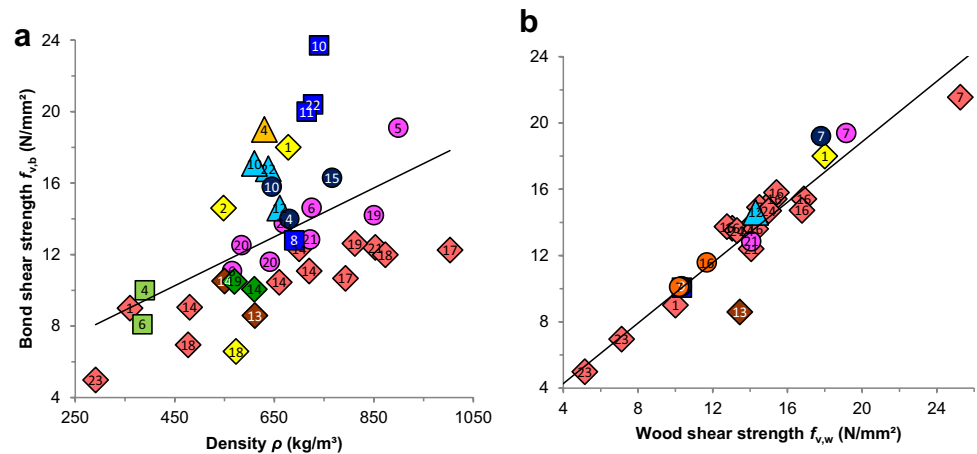


Fig. 1 Wood failure percentage vs. bondline block shear strength relationships (mean values) of hardwood GLTs from literature. 1: Alamsyah et al. (2007), 2: Alamsyah et al. (2008), 3: Herawati et al. (2010), 4: Frihart et al. (2015), 5: López-Suevos and Richter (2009), 6: Castro and Paganini (2003), 7: Chugg et al. (1961), 8: Aicher and Ohnesorge (2011), 9: Brandmair et al. (2012), 10: Lüdtke et al. (2015), 11: Schmidt et al. (2010), 12: Knorz et al. (2014), 13: Nadir and Nagarajan (2014), 14: Tan et al. (1992), 15: von Ruckteschell and Aicher (2012), 16: Bedel and Gautier (1972), 17: Bhkari et al. (2016), 18: Zisi and Aicher (2015a), 19: Zisi and Aicher (2015b)

Fig. 2 Bondline block shear strength $f_{v,b}$ relationships (mean values) with hardwood GLT properties (density ρ , wood shear strength $f_{v,w}$) from literature: **a** $f_{v,b}$ vs. $\rho \approx \rho_{12...15}$; for references see also caption of Fig. 1: 1, 2, 4–6, 8, 10–15, 17–19; 20: Belfas et al. (1993), 21: Nunes et al. (2016), 22: Jiang et al. (2014), 23: Komariah et al. (2015). **b** $f_{v,b}$ vs. $f_{v,w}$; refs. (see also Figs. 1, 2a): 1, 7, 9, 12, 13, 16, 18, 21; 24: Bourreau et al. (2013)



10–15%. In one case (Tan et al. 1992) where the data were given for a MC of 19%, an adjustment to 15% was made.

The test data comprise important hardwood species of the northern hemisphere, such as beech (*Fagus sylvatica*), ash (*Fraxinus excelsior*), oak (*Quercus robur/petraea*; *Q. rubra*) and poplar (i.a. *Populus tremuloides*), yet the majority of species stems from tropical or subtropical areas. Some other well-known species represented in the data are teak (*Tectona grandis*), meranti (*Shorea spp.*), rubberwood (*Hevea brasiliensis*), mangium (*Acacia mangium*), angélique (*Dicorynia spp.*) and limba (*Terminalia superba*). The adhesives of the bond data belong to seven families represented in the test series as follows: (phenol)-resorcinol-formaldehydes (PRF/RF, 56%), emulsion polymer isocyanates (EPI, 13%), melamine-urea-formaldehydes (MUF/UF, 11%), one-component polyurethanes (1C-PUR, 6%), polyvinyl acetates (PVAc, 6%), epoxies (EP, 5%) and casein (2%).

It should be pointed out that the presented results are biased in the sense that for each wood species per publication only one data point was chosen, representing the test series reaching the highest mean value of bond shear strength. The results were chosen independent of any further evaluations by the authors of the respective references. Hence, Figs. 1 and 2 comprise mainly results of satisfactorily performing bonds. The exemption of results with (very) low bond strengths from considerations regarding bond performance is considered reasonable as in any case pre-evaluations of suitable adhesive-wood-production configurations are indispensable for structural GLTs. Apart from the literature results, Fig. 1 also shows the kinked requirement line for mean values according to EN 386 (2001) and EN 14080 (2013), see below.

The reported mean bond strength values, see Fig. 1, cover a huge range from 5 to 24 N/mm², whereby the vast majority (> 87%) of mean wood failure percentages exceed the minimum wood failure percentage (for softwood) required by EN of $WF = 45\%$. Without focusing on any specific result,

it is evident that the requirement, derived for bondlines of softwood GLTs, is by far too moderate for most of the hardwood species bondlines. A fitted regression line reveals that overall a very weakly correlated trend towards lower wood failure percentages with increasing bond shear strength exists, which is acknowledged rather differently in some international standards.

Figure 2a reveals on the one hand the vast density range of the evaluated hardwood test series denoted by mean values of about 300–1000 kg/m³ and, on the other hand the apparently rather weakly correlated linear relationship between bond shear strength and density ($\rho = \rho_{12...15}$ in kg/m³):

$$f_{v,b} = 0.014 \rho + 4.095 \left(\frac{N}{mm^2} \right); R^2 = 0.25. \quad (1)$$

Figure 2b highlights an important result of the analyzed literature data, namely the strong correlation of bond and wood shear strength:

$$f_{v,b} = 0.912 f_{v,w} + 0.628 \left(\frac{N}{mm^2} \right); R^2 = 0.88. \quad (2)$$

With regard to literature results and here investigated interrelationships of bond shear strength and wood failure vs. wood shear strength it is important to recall that a bondline between two plane wooden adherends is not a straightly confined adhesive layer with a similarly plane wood-adhesive interface. In contrast, it represents a complex multi-layered continuum with fuzzy edges due to porosity of the wood leading to adhesive infiltration into the cell walls and/or lumens depending on adhesive type. This so-called wood interphase is neighbored by pure wood and the bulk adhesive layer whereby further subdivisions are possible (Marra 1992; Frihart 2009). For most structural wood adhesives the bulk adhesive is stronger in shear and tension perpendicular to fiber than wood and similarly is the adhesive-penetrated wood interphase, provided a sufficient adhesive-wood

compatibility exists and the bonding parameters, i.a. assembly and pressing time, cramping pressure and curing conditions were adequate. Given these bondline features, a block shear test under dry material conditions and for test purposes rather poor confinement of the fracture plane as compared to a fracture mechanics Mode I and/or II test (see e.g. River 2003), will lead to pronounced or entire wood failure at a strength level close to that of the pure wood material. At elevated wood moisture content, the fracture appearance and wood failure changes for many adhesives (see below).

Concerning the influence of adhesive, literature provides evidence that specific adhesive brands and families deliver for some hardwood species significantly lower to unsatisfactory bond shear strength and/or wood failure results. For oak (*Quercus robur/petraea*), this was proven in an adhesive evaluation project with 12 brands from five families (PRF with 3 brands, MUF (3), 1C-PUR (3), 2C-EP (1) and EPI (2)), all approved and certified in Europe for structural softwood bonding. Hereby, two adhesives (EP and PRF) delivered very low minimum and mean wood failure results in combination with low shear strength values and finally extreme delamination percentages (Aicher and Stapf 2007). For the wood species ash (*Fraxinus excelsior*), Knorz et al. (2014) obtained statistically significant, yet not extremely lower (-9%) bond shear strength values at the mean shear strength level for 1C-PUR bonds vs. the weighted mean strength level of several PRF and MUF resins, differing strength-wise only marginally. Regarding tropical hardwood species, Belleville et al. (2015) found for *Tectona grandis* and *Eucalyptus camaldulensis* significantly lower shear strength results for bondlines made with epoxy as compared to 1C-PUR and PVAc.

The reasons for the highly diverging suitability of specific adhesive brands and/or families for hardwood bonding are manifold. They are bound to a complex interaction of the wood and adhesive features, especially such as (i) wood porosity, density, surface hardness, extracts and wettability and (ii) the chemical build-up, molecular size distribution and curing mechanisms of the adhesive. Sometimes incompatibilities are well understood and may be compensated by means of specifically designed primers (e.g. López-Suevos and Richter 2009; Luedtke et al. 2015; DIBt Z-9.1-765 2016b). However, often no immediate answers exist for the aptness and durability of an adhesive vs. a specific hardwood bonding task. This is especially true when bond durability and integrity in the presence of elevated moisture and/or temperature and hereby induced bondline eigenstresses are concerned (e.g. Frihart 2009). In the latter case, even bonds of adhesives with well-developed wood interphase and high wood failure in dry material and moderate temperature conditions may eventually shift to an adhesive failure associated with very little wood failure if at all. In consequence, this leads in Europe at present to the situation that adhesives for

structural hardwood bonding have to be qualified as regards species and brand by delamination tests according to EN 302-1.

Shear strength of wood parallel to fiber, apart from effects of species, density, size and defects, is not an intrinsic material property but depends rather on the angle of the shear plane vs. the end grain face coordinates in radial and tangential direction, or, more generally, vs. the annual ring orientation of the cross-section determined by the sawing pattern. This fact and its immediate implications on bond shear strength of face glued laminations has been quantified for coniferous wood (Norway spruce) and respective bonds by Bröker et al. (1987) where shear planes aligned parallel to the radial-longitudinal plane provided consistently 40 and 20% higher wood and bond shear strength values, respectively, as compared to tangential-longitudinal planes. For hardwoods, literature does not provide similarly consistent data. Ongoing investigations at the MPA University of Stuttgart strongly indicate a significant influence of the shear plane orientation in the RT plane for several European and tropical hardwood species and respective face bonds, too. Contrary to coniferous species, in the case of hardwoods, higher ($\approx 20\%$) strength values are obtained for the LT shear plane. However, despite the fact that an influence from the sawing pattern on the absolute shear strength values can be identified, this occurrence does not affect the here presented bond strength (ratio) conclusions as the effect of the shear plane is compensated by the specifically employed matched specimen approach.

Finally it has to be recalled that the block shear test principle followed rather similarly by all known test standards for GLT (see below) and its specific experimental realization has a significant influence on the apparent shear strength values of bondlines of softwoods (Steiger et al. 2010). This fact, unquestioned, may be assumed for hardwood bondlines and pure wood shear strengths, too. The present test methods apply in principle a compressive shearing force parallel to the regarded bond/wood plane. With increasing applied load, secondary stresses perpendicular to the shearing area occur, leading to a complex stress situation strongly dependent on the actually used test setup, respective bearing widths and eventual lateral stabilizing supports. To overcome these test method related deficiencies a new compression shear test setup with a fiber/shear plane—force angle of 14 degrees was proposed by Steiger et al. (2010), similar as specified in EN 408 (2010) for solid wood and GLT, based on work by Feldborg (1991). This test setup with less potential handling inaccuracies and significantly reduced stresses perpendicular to the shear area delivers a considerably lower scatter of the bond strength results. As the new test method also leads to lower strength levels, depending on wood density, further calibration work is needed. In the context of this paper, the bias of an eventually not entirely correct absolute strength

level resulting from established block shear test methods is however not influential as finally no absolute shear strength values are regarded within the proposed matched specimen procedure.

3 Standardized block shear requirements

In the following, the minimum requirements of major international standards on bond shear strength and wood failure percentage related to hardwood GLTs are briefly presented. The comparison provides insight into fundamentally divergent test and especially evaluation approaches, leading in most cases to very different absolute values deemed necessary to assure sufficient bond strength and integrity. It is further revealed that the requirements differ pronouncedly with regard to initial type testing (ITT) also termed product qualification testing at first assessment of a new product and/or production process and at continuous factory production control (FPC) to assure constancy of product performance. Further the requirements differ in terms of whether single or mean values or both shall be taken into consideration. In detail, the provisions of the GLT standards from Europe (EN 386 2001; EN 14080 2013), Malaysia (MS 758 2001), the US (ANSI A190.1-2012 2013) and from Japan (MAF Notification No. 1152 2007) are presented.

3.1 European and malaysian specifications

The EU standard EN 14080 (2013) for GLT and GST addresses exclusively softwood species for certified products. Beyond that the standard's scope indicates that some provisions might apply to hardwood beams as well. The specified bondline block shear test has been adopted unchanged from EN 392 (1995) and the requirements conform to the former EU glulam standard EN 386 (2001), then comprising both softwood and hardwood GLTs. The EN 386 provisions did not differentiate between ITT and FPC and differences between softwoods and hardwoods were specified exclusively for the lower tail of single values. In detail, the EN 386 requirements on wood fiber percentage WF (in %) and bond shear strength $f_{v,b}$ (in N/mm^2) for individual (i) hardwood (D) specimens are:

$$WF_{i,D} \geq 74\% \quad \text{and} \quad f_{v,b,i} = f_{v,b,i,D,min} = 6 \, N/mm^2, \quad (3a,b)$$

$$WF_i \geq 153.3 - 13.3 f_{v,b,i} \quad \text{if} \quad 6 \, N/mm^2 < f_{v,b,i} < 10 \, N/mm^2, \quad (3c,d)$$

$$WF_i \geq WF_{i,D,min} = 20\% \quad \text{if} \quad f_{v,b,i} \geq 10 \, N/mm^2. \quad (3e,f)$$

A comparison of Eqs. (3a–f) with the specifications in EN 14080 and EN 386 for individual softwood (C) specimens, where

$$WF_{i,C} = 100\% \quad \text{and} \quad f_{v,b,i,C,min} = 4 \, N/mm^2 \leq f_{v,b,i} \leq 6 \, N/mm^2 \quad (3g,h)$$

reveals for softwoods a significantly reduced minimum strength level combined with a considerably increased requirement for wood failure percentage. Beyond $f_{v,b,i} = 6 \, N/mm^2$, the same specifications as for hardwood GLTs (Eqs. 3c–f) apply.

The requirements of EN 386 for the mean values of the block shear sample of hardwood and softwood GLTs (then adopted in EN 14080 for softwood GLTs only) are:

$$WF_{mean} \geq 90\% \quad \text{and} \quad f_{v,b,mean} = f_{v,b,mean,min} = 6 \, N/mm^2, \quad (4a,b)$$

$$WF_{mean} \geq 144 - 9 f_{v,b,mean} \quad \text{if} \quad 6 \, N/mm^2 < f_{v,b,mean} < 11 \, N/mm^2, \quad (4c,d)$$

$$WF_{mean} \geq WF_{mean,min} = 45\% \quad \text{if} \quad f_{v,b,mean} > 11 \, N/mm^2. \quad (4e,f)$$

Malaysia has adopted the EN 392 (1995) GLT shear test and the respective EN 386 (2001) requirements almost unchanged in MS 758 (2001) although dealing exclusively with hardwoods. In an extension, the relaxed EN 386 provisions for softwoods on the lower limit for individual values (Eqs. 3g–h) were opened in MS 758 for hardwood species of lighter density timbers. The Malaysian timber category of light hardwoods (LHW) covers a density range from 400 to 720 kg/m^3 at MC ~ 15% including a total of 48 trade (standard) names but considerably more species (MTIB 2009, 2010). Well-known species grouped in light hardwoods are for instance meranti of all colors (dark red, light red, white, yellow).

It can be seen from Eqs. (3a–h) and (4a–f) that (required) wood failure percentage WF and bond shear strength $f_{v,b}$ are considered as equally important interrelated bond quality parameters. Hereby a linear relationship between the dependent quantity WF and the independent variable $f_{v,b}$ is assumed for a wide shear strength range. The assumption of a linear relationship $WF(f_{v,b})$ is questionable (see above) and not followed in North American and Japanese standards. This critique vs. the prescription of very detailed WF percentages is further linked to the rather difficult precise determination of wood failure, especially within the frame of FPC, allowing minor inaccuracies to trigger the bond quality assessment unduly.

A further strong objection vs. the bond quality evaluation method according to Eqs. (3a–f) and (4a–f) results from the fact that the strength and wood failure percentage requirements are stated as absolute numbers irrespective of density, strength class and growth specifics of any hardwood species. It is apparent that a bond quality requirement being explicitly or implicitly fully detached from density which in the case of hardwoods can differ on the mean level dependent

on species up to about 700 kg/m³ is technically incorrect as there is a positive relationship between bondline strength and density, although weakly correlated, as revealed above.

3.2 North American specifications

Totally different from the present EU respectively Malaysian approach, the North American (US) verification of bond shear strength as stated in ANSI A190.1-2012 (2013) addresses, irrespective of softwoods or hardwoods, individual species or species groups whereby reference is made to the respective clear wood shear strength. The bond strength requirement is exclusively defined on the mean strength level as the ratio of bond vs. wood shear strength

$$r_{v,mean} = \frac{f_{v,b,mean}}{f_{v,w,mean}} \geq 0.9 \quad (5)$$

where $f_{v,w,mean}$ is the average clear wood shear strength parallel to grain as specified in ASTM D2555 (2016) and $f_{v,b,mean}$ is the mean block shear value of the specimens tested in the respective ITT or FPC series according to AITC Test T107 (2007).

The required minimum hardwood failure percentage specified differently for ITT and FPC is exclusively dependent on two wood density levels but not on bond shear strength. For non-dense (nd) hardwoods (see ASTM D245 (2006)), as for softwoods, the requirements are

$$WF_{mean} \geq WF_{mean, min, nd, ITT} = 80\% \quad \text{and} \quad (6a,b)$$

$$WF_{mean} \geq WF_{mean, min, nd, FPC} = 70\%$$

whereas for dense (d) hardwoods.

$$WF_{mean} \geq WF_{mean, min, d, ITT} = 60\% \quad \text{and} \quad (7a,b)$$

$$WF_{mean} \geq WF_{mean, min, d, FPC} = 50\%.$$

The US bondline quality assessment relating bond to wood shear strength of the specific wood species represents with regard to methodology an improved approach as compared to the EU procedures as the high correlation of bond and wood shear strength when considered at a large scale (Eq. 2) is acknowledged. Despite the improved bond strength assessment principle according to Eq. (5), the method has one significant draw-back, as the bias depends on the degree of conformance of the wood shear strength of the specifically bonded wood laminations with the mean clear wood shear strength value of the respective species given in ASTM D2555 (2016). Therefore, in case the employed timber has a density which is above the species average and hence tends to result in higher bond shear strengths, the fulfillment of the requirement gets easier and may eventually lead to acceptance of lower quality bonds. In contrast, for a timber quality below the species' average, meeting the requirements

necessitates an increasingly better bond performance to overcome the inferior wood substrate behavior.

The reduction of the required wood failure percentage with increasing density results from the understanding that higher densities lead to less mechanical anchoring of the adhesive in the wood substrate and hence, to less pull-out of wood fibers from the stronger wood matrix. This however could not be substantiated by the here presented test results (see below).

3.3 Japanese specifications

The Japanese GLT standard (see MAF Notification No. 1152 2007) differentiates with regard to wood species six groups, whereof three comprise hardwoods (see Table 1), either exclusively (groups 1 and 2) or mixed with coniferous species (group 5). For each species group, different bond shear strength and wood failure limits applicable to individual specimens, see Table 1, are specified. The tests can be performed with deliberate shearing lengths in the range of 25 to 55 mm. The shear strength qualification limit decreases from wood species group 1 comprising higher density hardwoods such as for example beech (*Fagus crenata*) to group 5, for example *Parashorea*, by 40%. The requirements on wood failure percentages differ between the species groups marginally and are 10% lower for the higher density groups 1 and 2 as compared to the lower density group 5.

To highlight the pronounced difference between the Japanese and the European specifications, exemplarily bondlines from wood species group 1 are considered where WF_i according to Table 1 must at least equal 60%. Inserting the minimum admissible strength value of group 1, $f_{v,b,i} = f_{v,b,i,min} = 9.6 \text{ N/mm}^2$ in Eq. (3c), the minimal WF_i required by EN 386 is only 26%, and thereby less than half of the Japanese specification. For bond strength values $\geq 10 \text{ N/mm}^2$ the EN 386 and MAF Notification WF requirements then differ by a factor of three.

Table 1 Japanese minimum requirements on bond shear strength and wood failure of hardwood GLTs acc. to MAF Notification No 1152 (2007)

	Wood species group		
	1 ^a	2 ^b	5 ^c
Minimum requirements for individual specimens	1 ^a	2 ^b	5 ^c
Bond shear strength $f_{v,b,i,min}$ in [N/mm ²]	9.6	8.4	6.0
Wood failure percentage $WF_{i,min}$ in [%]	60		65

^a*Acer mono*, *Betula maximowicziana*, *Fagus crenata*, *Quercus crispula*, *Zelkova serrata*, *Dipterocarpus spp*

^b*Fraxinus mandshurica*, *Fraxinus spaethiana*, *Ulmus davidiana*

^c*Parashorea*, *Pentacme*, *Shorea spp*

4 Materials

The specimen material for the experimental test program stemmed from industrially manufactured GLTs of eight different EU and tropical (TR) hardwoods. The four EU hardwoods comprised the three technically and stand volume-wise most important European species, consisting of oak (*Quercus robur/petraea*), beech (*Fagus sylvatica*) and sweet chestnut (*Castanea sativa*), and further ash (*Fraxinus excelsior*), for the majority of which national or EU technical GLT approvals exist. The tropical species were light red meranti (*Shorea spp.*), for which a German technical GLT approval exists, teak (*Tectona grandis*), keruing (*Dipterocarpus spp.*) and melagangai (*Potoxylon melagangai*). Table 2 provides condensed information on the GLTs concerning wood origin, lamination and GLT sizes and numbers, strengths (classes), adhesives, technical specifications and manufacturers. Further, the bandwidth of densities and shear strengths of clear wood of the respective species according to literature is specified to enable an assessment (see below) as to what extent the employed material can be regarded as representative for the respective species.

All GLT beams had been stored for several weeks in a heated non-climatised test hall prior to cutting of the specimens. The average moisture content (MC) of all GLT beams/species determined by oven dry method from lamination specimens prior to testing (see below) was $9.8 \pm 1.3\%$, with beech and keruing showing the lowest and highest means of 8.3 and 11.5%, respectively. The extreme values regarding all specimens ranged from 7.2 to 13.3%. So, the moisture contents of the specimens / beams conformed well to service class 1 conditions, characterized by moisture contents in the materials corresponding to a temperature of 20 °C and a relative humidity of the surrounding air only exceeding 65% for a few weeks per year (EN 1995-1-1 2004). As compared to the usual mean moisture content of GLT of about 12% at production, owed to the requirements of EN 14080 on the permissible lamination moisture content range, the investigated beams/specimens were about two percent (absolute) dryer due to storage in the heated test hall.

5 Test and evaluation methods

To capture the relationships of bond shear vs. wood shear strength and wood density, the tests were performed per species with closely matched bond and “pure” wood specimens. Per species, segments with a length of 300 mm were cut from different GLT beam locations. The number of segments varied per beam from 2 to 5, depending on number, length and cross-sectional size of the beams per species. Hereby attention was paid to two issues: (1) between adjacent beam

segments, as many as possible finger joints should occur to increase best possible interlamination differences between the respective segment build-ups in order to enlarge their variation of the relevant properties, for example density, shear strength and (2) no finger joint at all should be in a beam segment to achieve a high degree of material homogeneity for the matched specimens taken from a segment. From the beam segments then three cross-sectional slabs D, B and W, each with a thickness $t = 50$ mm (parallel to beam and fiber axis) were cut (see Fig. 3). Additionally a slab DEL of thickness 75 mm was taken for delamination tests not reported here.

Slab D, after weighing with regard to global density determination, was sawn up by a thin saw blade of 3 mm thickness to obtain the individual laminations for density and moisture content (oven-dry method) measurement. Slabs B and W were used for bondline and wood shear tests, respectively. The tests and evaluations were performed according to EN 14080 (2013) with strips of 50 mm width cut from the slabs (Fig. 3) and further applied schematically to the pure wood specimens, which were shear-loaded at mid-thickness of the laminations. Wood failure percentage of the bondline specimens was evaluated visually, supported by a magnifying lens at both fractured crack surfaces and determined as the average value rounded conservatively to the next lowest 10% increment.

The sample size of bond shear specimens per species was in general 92 with two exceptions (melagangai: 41, teak (2 adhesive—hardener mixtures): 2×72). The number of associated wood shear and density specimens exceeded the bond sample sizes per species by about 10%.

This matched specimen sampling and testing avoids any detrimental pre-damage effects which might occur when determining both quantities $f_{v,b}$ and $f_{v,w}$ successively from the same cross-sectional slab strip. Due to the rather short shearing length of the immediately adjacent bond and wood shear specimens, the strength of the wood specimens may be assumed equal to the shear strength of the adherents.

6 Results

6.1 Wood density and shear strength

Table 3 contains a compilation of the wood density and shear strength results per each of the investigated species. The obtained means of the densities characterize most of the GLT laminations as being representative for the respective species as specified in Table 2. This is especially true for the EU species ash, beech and chestnut whereas the oak material with a mean and characteristic density of 750 and 670 kg/m³, respectively, was somewhat ($\approx 10\%$) heavier than the literature average. In the case of the TR

Table 2 Technical data on investigated hardwood GLTs from eight different species and relevant clear wood properties

Wood trade name [species] (country)	GLT producer (country)	GLT technical specification A: techn. approval S: standard TD: techn. data sheet	Characteristic (5%-quantile) GLT strengths bending $f_{m,k}$ (shear $f_{v,k}$) N/mm ² (N/mm ²)	Lamination strength class or GLT group (and/or grade)[thickness]		GLT cross section A (length l) [No. of beams]	Clear wood property acc. to literature		Adhesive
				Outer [mm]	Inner [mm]		Density $\rho_{12...15}$ kg/m ³	Shear strength $f_{v,w}$ N/mm ²	
ash [<i>Fraxinus excelsior</i>] (Switzerland)	Neue Holzbau AG, (Switzerland)	TD ¹	40 (4.5) ^a	T33 ^b (-)	T24	140 × 400 (5) [2]	450... ⁸ 720 ...860	9.0... ⁸ 12.0 ...14.6	PRF
beech [<i>Fagus sylvatica</i>] (Germany)	Hess Timber GmbH & Co. KG (Germany)	A ² and S ³	32 (3.4)	- LS13 ^c [20]	- T16.9 (LS10) ^c [22]	100 × 240 (5) [3]	540... ⁹ 720 ...910	6.5... ⁹ 8.0 ...19.0	MUF
sweet chestnut [<i>Castanea sativa</i>] (Spain)	Sierolam S.A. (Spain)	A ⁴	30 (4.2)	T22.3 (LS13) [20]	T16.9 (LS10) ^c [20]	100 × 260 (5.5) [4]	590... ⁸ 620 ...680	8.0... ⁸ 11.0 ...9.5	MUF
oak [<i>Quercus robur/petraea</i>] (France)	Elaborados y Fabricados Gamiz S.A. (Spain)	A ⁵	33 (4.0)	T28 (LS13+) ^d [20]	T23 (LS10) [20]	100 × 200 (6) [2]	430... ⁹ 690 ...960	6.0... ⁹ 11.0 ...13.0	MUF
keruing [<i>Dipterocarpus spp.</i>] (Malaysia)	Woodsfield Glulam Manufacturing Snd (Malaysia)	S ⁶	39 (≈4.5) ^e	SG5 ^f (HS) ^g [30]	SG5 ^f (HS) ^g [30]	80 × 400 (7.5) [6]	690... ¹⁰ ...945	9.2... ¹⁰ ...12.3	PRF
meranti light red [<i>Shorea spp.</i>] (East Kalimantan)	PT Samtraco (Indonesia)	A ^{7,h}	36 (4.0)	$f_{m,k} = 50$ N/mm ² (LS13+) [20]	$f_{m,k} = 50$ N/mm ² (LS13+) [20]	80 × 120 120 × 120 120 × 240 (5) [7]	385... ¹⁰ ...755	6.3... ¹⁰ ...11.0	MUF
melagangai [<i>Potoxylon melagangai</i>] (Malaysia)	Woodsfield Glulam Manufacturing Snd (Malaysia)	S ⁶	41 (≈4.5)	SG3 ^f (HS) [15]	SG3 ^f (HS) [15]	80 × 360 (7.2) [5]	590... ¹⁰ ...850	14.0 ... ¹⁰ ...11.0	PRF
teak [<i>Tectona grandis</i>] (Columbia)	Hess Timber GmbH & Co. KG (Germany)	S ³	> 32 (<3.5)	$f_{m,k} = 51.4$ N/mm ² (LS10K, LS13K) [20.5]	$f_{m,k} = 51.4$ N/mm ² (LS10K, LS13K) [20.5]	95 × 266.5 (3) [2]	520... ⁸ 660 ...700 (750) ¹⁰	8.3... ⁸ 9.5 (...14.5) ¹⁰	MUF ^k

Table 2 (continued)

1: n^aH (2016) producer declaration; 2: DIBt Z-9.1-679 (2014); 3: EN 14080 (2013); 4: ETA-13/0642 (2013); 5: ETA-13/0642 (2013); 6: MS 758 (2001); 7: DIBt Z-9.1-577 (2016a); 8: Wagenführ (2007); 9: Kollmann (1955); 10: MTIB (2010); 11: Altmüller (2007)

^aDerived from specified design value (see n^aH 2016) by factor of 1.5

^bTJ(J,Z) represents the 5%-quantile (characteristic) lamination tensile strength $f_{t,0.01,k}$

^cVisual hardwood grade(s) acc. to DIN 4074-5 (2008)

^dLS13+: grade LS13 acc. to DIN 4074-5 (2008) plus extra requirements in respective tech. spec

^eest. from EN 338 (2016) as D50 acc. to EN 1912 (2012 +AC2013)

^fStrength group acc. to ¹⁰

^gHardwood structural grade HS = HSG acc. to MS 1714 (2003), equiv. to BS 5756 (2007)

^hTermed in ⁷ as dark red meranti

ⁱCharact. lamination bending strength acc. to ⁷

^jCharact. lamination bending strength acc. to ¹¹

^kSame resin, yet different hardeners for GLT beams 1 and 2

woods, keruing conformed exactly to the mean density of the species specified in literature, whereas the light red meranti was somewhat lower (− 7%) and the plantation grown teak material was as regards density roughly 10% below average. Considering melangai, as well, the density differences of the tropical species were within ± 10% of the references.

Contrary hereto, the wood shear strength results of all species, except for melangai, exceeded the literature values significantly. Disregarding one extreme deviation (+ 140% for beech), the reference shear strength data of all investigated EU and TR species are exceeded at the mean strength level by a factor in the range of 1.16 ... 1.3 ... 1.54. The reason for the considerably higher wood shear strength values may in some cases be partly owed to higher densities of the investigated material. Apart from that, no further obvious reasons regarding the deviations vs. the reference data (Kollmann 1955; Wagenführ 2007) could be detected as the references do not specify traceable research work. Thus, the stated differences are most likely owed to the fact that the reference data do not mirror the median and scatter of the material heterogeneity sufficiently. This may be underlined exemplarily by the species ash where Knorz et al. (2014) obtained 1.2 times higher wood shear strength values at 10% lower mean density as compared to Wagenführ (2007). The stated inconsistencies with literature data underline the potential bias risk when making reference in bond strength evaluation to fixed species-specific strength data.

The correlation of wood shear strength with density determined via linear regression is rather poor for each of the investigated species. For the four EU hardwoods, the range of coefficients of correlation is $R^2 = 0.10 \dots 0.19 \dots 0.24$, whereas for the tropical hardwoods, the R^2 scatter is somewhat less and at a higher level of $0.22 \dots 0.29 \dots 0.33$. The wood shear strength vs. density correlation of all species with their respective specimens taken as one sample gives ($\rho = \rho_{12}$ in kg/m³):

$$f_{v,w} = 0.013 \rho + 5.305 \left(\frac{N}{mm^2} \right), \quad R^2 = 0.24. \quad (8)$$

It is interesting to note that the slope of the presented $f_{v,w} - \rho$ relationship and its poor coefficient of correlation resemble the results presented in Eq. (1) for the literature evaluation of bond shear strength vs. density very closely.

The rather low correlation of wood shear strength with wood density differs from generally higher correlations of other (clear wood) strength property—density relationships. A major reason therefore, not discussed here in depth, is bound to the specific stress—wood micro/meso-structure interaction. In case of tension and compression parallel to the fiber, the increased mass, denoted by thicker cell walls and more latewood, results in a stronger and larger

Fig. 3 Cutting pattern, dimensions and test scheme of block shear (bond, wood) and density specimens

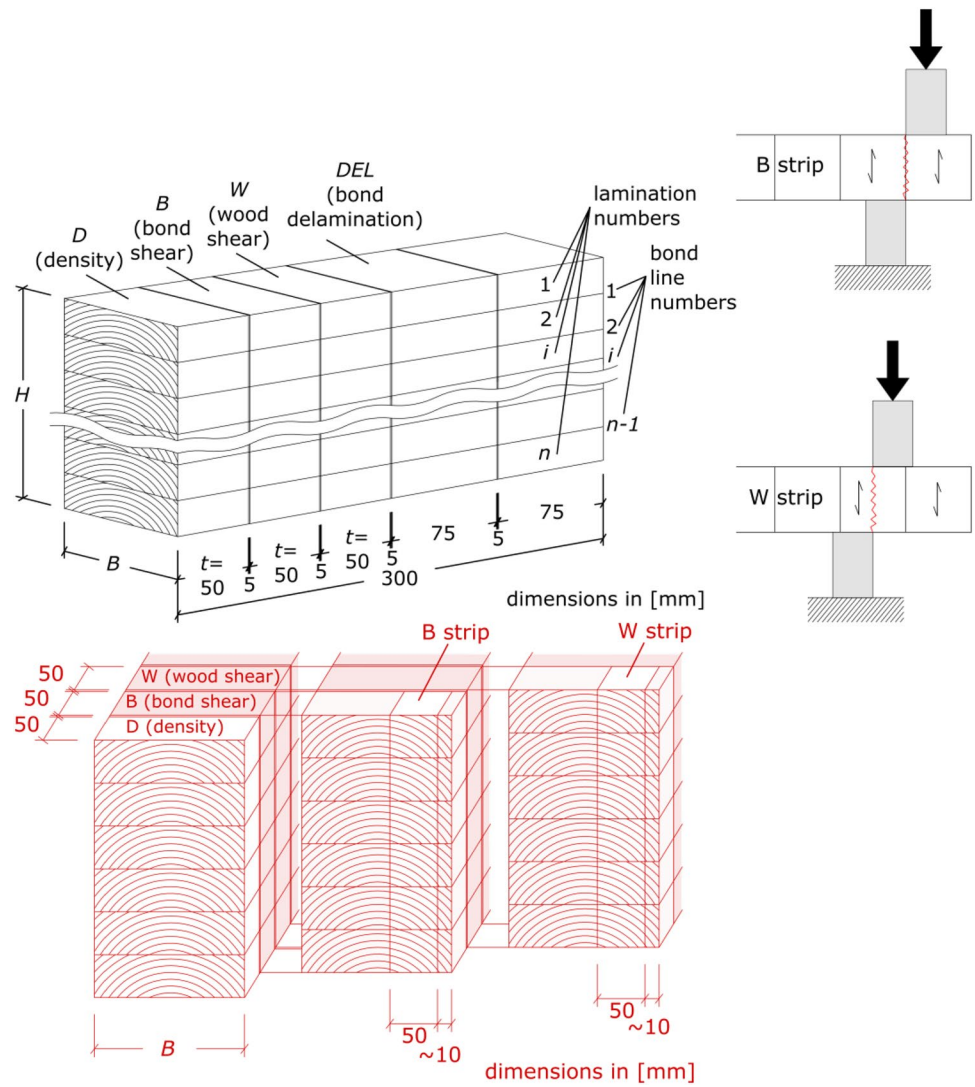


Table 3 Wood density and block shear strength of laminations adjacent to investigated hardwood GLT bondlines

Wood property	European hardwoods				Tropical hardwoods			
	Ash	Beech	Sweet chestnut	Oak	Keruing	Melagangai	Meranti, l.r.	Teak
Density of all laminations								
ρ_{12} (kg/m ³)								
M	695	742	596	752	804	797	528	587
COV	10%	7%	9%	7%	8%	8%	16%	9%
Min	542	618	471	655	641	653	367	458
x_{05}	574	652	510	670	693	689	393	497
Wood shear strength								
$f_{v,w}$ (N/mm ²)								
M	17.4	19.1	13.5	14.7	13.2	13.9	10.1	13.7
COV	10%	13%	13%	14%	12%	12%	16%	13%
Min	10.2	11.2	8.8	8.7	10.2	10.2	5.6	5.0
x_{05}	14.2	14.6	10.6	11.2	10.6	11.1	7.6	10.4

Fig. 4 Wood failure percentage vs. bond shear strength results for GLTs from European hardwood species; further requirements acc. to EN 386 and newly suggested are given. **a** beech, **b** oak, **c** ash, **d** sweet chestnut

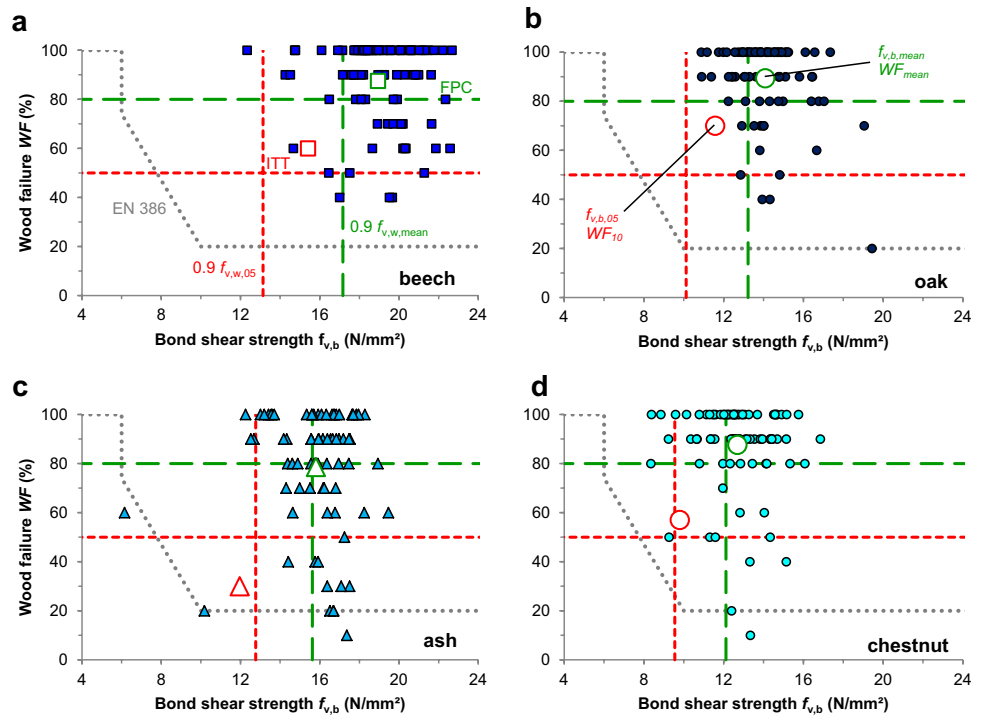
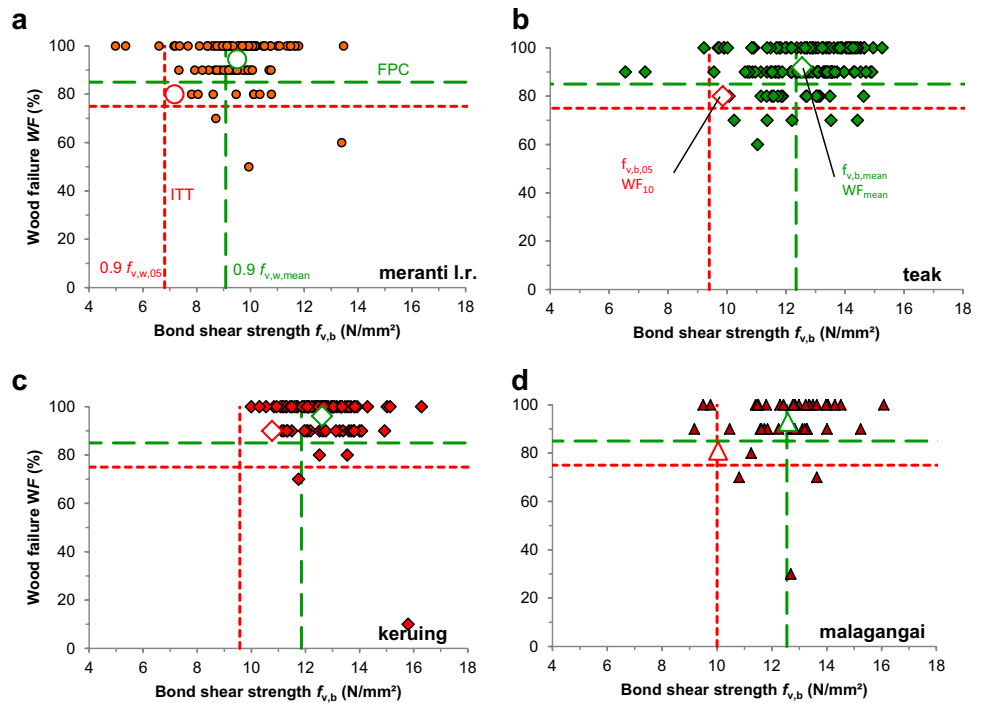


Fig. 5 Wood failure percentage vs. bond shear strength of GLTs from four tropical hardwoods species; further requirements acc. to EN 386 and newly suggested are given. **a** meranti l.r., **b** teak, **c** keruing, **d** melagangai



strength-relevant net cross-section. Contrary, in shear parallel to fiber, the density increase does not lead to immediate improvement of several strength-relevant growth characteristics, such as for example the early-latewood transition and interface region in case of ring and semi-ring porous hardwoods.

6.2 Bond shear strength and wood failure

Figure 4 a–d show the results for bond shear strength $f_{v,b}$ and wood failure percentage WF of all specimens of the four investigated EU hardwood species and Fig. 5 a–d give analogously the results for the four tropical hardwood species.

Table 4 Bond shear strength and wood failure percentage of investigated hardwood GLT bondlines

Bondline properties	European hardwoods				Tropical hardwoods			
	Ash	Beech	Sweet chestnut	Oak	Keruing	Melagangai	Meranti, l.r.	Teak
Bondline shear strength								
$f_{v,b}$ (N/mm ²)								
M	15.8	18.9	12.7	14.1	12.6	12.6	9.5	12.5
COV	12%	11%	13%	11%	9%	12%	14%	12%
Min	6.1	12.3	8.3	10.9	10.0	9.2	5.0	6.6
x_{05}	12.0	15.4	9.8	11.6	10.8	10.0	7.2	9.8
Wood failure percentage								
WF (%)								
M	79	88	88	89	96	93	94	92
COV	31%	20%	21%	18%	11%	14%	10%	8%
Min	10	40	10	20	10	30	50	60
x_{10}	30	60	57	70	90	81	80	80

Additionally, the figures contain graphical representations of the EN 386 $WF - f_{v,b}$ requirement and of the new proposals (see below). Table 4 compiles the statistical evaluations of quantities $f_{v,b}$ and WF per species. With regard to the teak GLT beams bonded with two different adhesive—hardener mixtures no statistically significantly different results were observed; hence the specimens of both bonding configurations were evaluated as one combined sample.

Irrespective of, in some instances, significant differences in the mean values of bond shear strength of the different species ranging from 9.5 N/mm² (l.r. meranti) to 19 N/mm² for beech, the relative bond strength scatter is very similar for all species. The rather moderate coefficients of variation (COV) range from minimally 9% for keruing to maximally 14% for l.r. meranti. No significant difference can be observed in the strength scatters of EU and TR hardwood bonds which both show an average $COV_{EU} = COV_{TR} = 12\%$.

Regarding the second important bond test result—wood failure percentage—some significant differences between the investigated EU and TR species and the bonds made hereof can however be observed. Rather small differences exist at the mean value level, where for the EU species the $WF_{mean,EU}$ values are in the range of 79% ... 86% ... 89%, and for the TR species the range is $WF_{mean,TR} = 93\% \dots 94\% \dots 96\%$. In contrast, the scatter of the WF results is obviously considerably different for the EU and TR species. In the case of the EU species, the scatter is strongly expressed (on average 20%), hereby disregarding the extreme WF scatter of the ash bonds where a $COV = 31\%$ was obtained. Conversely, the average WF -COV of the tropical species is just 11%. The pronounced differences in WF scatters obviously result in profound effects on the lower quantile values of the distribution. Differing from wood strength, where lower characteristic levels are in general specified as 5%-quantiles, here in the case of wood failure (percentages), the 10%-quantiles are addressed as being less sensitive to outliers which are more

frequent in WF - than $f_{v,b}$ -results. Regarding the EU species (except ash) and the TR woods, extremely different WF_{10} results of roughly 60% and 80%, respectively, are obtained.

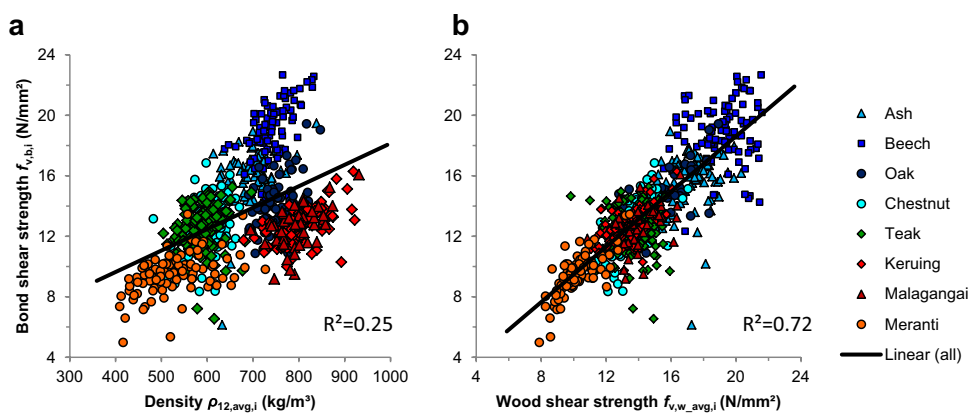
A linear regression analysis showed no correlation ($R \approx 0$) of bond shear strength and wood failure for any of the investigated species / adhesive samples. This result renders the provisions of EN 386 and MS 758, assuming a strong linear relationship for the lower bound, as questionable.

The observed significant differences in WF scatter dependent on species and growth region are not related to bond strength levels and respective scatters as revealed above. There are no indications that specific adhesive families or brands or production methods are causative. Some reasons emanate from the very different wood fiber texture of the regarded EU and TR species. While the species from the European regions are characterized predominantly (except beech) by climate dependent growth ring characteristics, the tropical species are throughout diffuse-porous. However, no apparent explanation exists why diffuse-porous beech wood, resembling in many micro-structural aspects tropical species, gives such different WF results as compared to the tropical species. These aspects will be addressed more deeply in further investigations.

6.3 Correlations of bond strength and wood density

The linear regression of bond strength $f_{v,b} = f_{v,b,i}$ with the averaged density $\rho_{12,avg} = \rho_{12,avg,i} = 0.5 (\rho_{12,avg,i} + \rho_{12,avg,i+1})$ of the respective bondline adherents (i, i + 1), results in very low coefficients of correlation R^2 in the range of 0.05...0.19...0.31 for both EU and TR hardwoods. Correlating $f_{v,b}$ with the lower density of both adherents gives a similar scatter of 0.06 ... 0.21 ... 0.35 with a marginally higher correlation average of $R^2 = 0.21$. Combining all species delivers for the bond strength vs. mean density relationship depicted in Fig. 6a a linear regression of

Fig. 6 Bond shear strengths of specimens of all investigated species dependent on matched adherent properties. **a** Bond strength vs. density; **b** bond vs. wood strength



$$f_{v,b} = 0.014 \rho_{12,avg} + 3.964 \left(\frac{N}{mm^2} \right), R^2 = 0.25 \quad (9)$$

which literally coincides with regard to equation coefficients and coefficient of correlation with those obtained for the literature data and given in Eq. (1). Similar to the single species results, the regression with the lower respective densities results in a slightly better correlation ($R^2 = 0.27$), yet the same slope of 0.014. It is interesting to note that the $f_{v,b,i} - \rho_{12,avg}$ data scatter graph of the here investigated species/specimens (Fig. 6a) resembles very closely the graph in Fig. 1, obtained for the literature data, there representing mean values and a considerably higher number of species.

It should be stated that the revealed weak correlations of bond shear strength and wood density in conjunction with the observed high wood failure percentages reflect an immediate consequence of the poor correlations of wood shear strengths with density.

6.4 Relations of bond and wood shear strength

If bond shear strength $f_{v,b} = f_{v,b,i}$ is related to the average or minimum wood shear strength of both respective adherents $i, i + 1$ $f_{v,w_avg} = f_{v,w_avg,i} = 0.5(f_{v,w,i} + f_{v,w,i+1})$ and $f_{v,w_min} = f_{v,w_min,i} = \min(f_{v,w,i}; f_{v,w,i+1})$, respectively, the linear regressions forward for the different species strongly diverging correlations. Independent of whether f_{v,w_avg} or f_{v,w_min} is used as the independent variable, the R^2 scatter for all investigated species spans the wide range of 0 ... 0.27 ... 0.57, with rather little systematic difference between EU and TR hardwoods. The average R^2_{mean} —values for EU and TR hardwoods are 0.24 and 0.30 in the case of the regression variable f_{v,w_avg} whereas $R^2_{mean} = 0.21$ and 0.33 for $f_{v,b}$ (f_{v,w_min}). Species with no correlations between bond and wood shear strength at all ($R^2 \approx 0$) were ash, beech and teak whereas rather pronounced correlations ($R^2 \approx 0.5$) were obtained for sweet chestnut, oak, l.r. meranti and keruing.

The considerable R^2 differences between species can neither be attributed to a significantly divergent scatter of wood

density, denoted for all samples (except l.r. meranti) by a COV of 7–10%, nor to significantly different COVs of wood shear strengths being in a very narrow range of 10–13% (exception l.r. meranti: 16%). Deepened investigations into the physical and chemical reasons for the encountered inter-species differences of bond vs. wood shear strength correlations, although highly desirable, were beyond the scope of the study. This, however, does not affect the chosen basis of the below derived bond strength assessment procedures and requirements.

Combining the specimens of all species to one sample, the strongly correlated linear relationship (Fig. 6b).

$$f_{v,b} = 0.914 f_{v,w_avg} + 0.335 \left(\frac{N}{mm^2} \right), R^2 = 0.72 \quad (10)$$

is obtained. The slope of 0.914 conforms exactly to the results (Eq. 2) obtained for the linear regression of bond vs. wood shear strength (sample means) of the literature data. A regression to the means of bond and wood shear strength of the here investigated species ($f_{v,b,mean} = 0.97 f_{v,w,mean} + 1.27$) gives an almost perfectly linear relationship $R^2 = 0.97$, which conforms well with the result obtained from the literature data evaluation (Fig. 2b and Eq. 2).

A more comprehensive perception of the shear strength relationships is obtained when not the absolute strength data, but rather the ratios of bond and wood shear strength are regarded. Table 5 specifies per species the ratios based on the mean (x_{50}) and 5%-quantile (x_{05}) values of bond and wood shear strength

$$\eta_{b,50} = \frac{f_{v,b,50}}{f_{v,w,50}}, \eta_{b,05} = \frac{f_{v,b,05}}{f_{v,w,05}} \quad (11a,b)$$

Further, the evaluations based on the individual ratios per bondline are given considering the two alternatives for the wood strength being either the average or the minimum shear strength of the respective adherents

$$\eta_{b,w_avg,i} = \frac{f_{v,b,i}}{f_{v,w_avg,i}}, \eta_{b,w_min,i} = \frac{f_{v,b,i}}{f_{v,w_min,i}} \quad (12a,b)$$

Table 5 Bond vs. wood shear strength ratios of investigated hardwood GLTs

Bond vs. wood shear strength ratio	European hardwoods				Tropical hardwoods			
	Ash	Beech	Sweet chestnut	Oak	Keruing	Melagangai	Meranti, l.r.	Teak
$f_{v,b,mean} / f_{v,w,mean}$	0.910	0.993	0.943	0.958	0.958	0.903	0.942	0.915
$f_{v,b,05} / f_{v,w,05}$	0.843	1.055	0.924	1.030	1.012	0.904	0.949	0.944
$f_{v,b,i} / f_{v,w,avg(i,i+1)}$								
M	0.914	0.989	0.937	0.950	0.958	0.902	0.928	0.917
COV	13%	13%	11%	8%	7%	12%	10%	14%
Min	0.356	0.665	0.643	0.737	0.722	0.664	0.624	0.439
x_{05}	0.686	0.774	0.767	0.819	0.852	0.723	0.770	0.696
$f_{v,b,i} / f_{v,w,min(i,i+1)}$								
M	0.972	1.096	1.019	1.038	1.027	0.962	1.014	1.007
COV	14%	21%	11%	13%	7%	11%	11%	25%
Min	0.357	0.705	0.716	0.767	0.870	0.741	0.811	0.479
x_{05}	0.712	0.763	0.834	0.829	0.915	0.785	0.833	0.682

It can be seen that the bond vs. wood shear strength ratio range yields for all investigated species on the mean level (Eq. 11a) 0.90 ... **0.94** ... 0.99, without any difference between EU and TR hardwoods. The respective averages are $\eta_{b,50,EU} = 0.95$ and $\eta_{b,50,TR} = 0.93$. Rather similar ratios are obtained at the 5%-quantile level, where for both EU and tropical hardwoods alike a ratio of $\eta_{b,05,EU} = \eta_{b,05,TR} = 0.96$ results. Yet it has to be acknowledged that at the 5%-quantile level, the scatter between different species gets larger with a higher $\eta_{b,05}$ -range from 0.84 to 1.06 for the EU hardwoods as compared to 0.9–1.01 for the tropical species. Looking at the ratios of the directly matched bond and wood adherent shear strengths, as expected, $\eta_{b,i,w_{avg},50}$ is identical to $\eta_{b,50}$ for each species. Different thereto, when the normalizing wood shear strength is the minimum value of both adherents, the strength ratios considering all EU and TR species rise at the mean level $\eta_{b,i,w_{min},50}$ to a range of 0.96 ... **1.02** ... 1.10 with closely conforming means for the EU and TR hardwoods of 1.03 and 1.00, respectively.

The absence of any density influence on the bond-wood shear strength ratio $\eta_{b,w_{avg},i}$ is proven in Fig. 7a, revealing $R^2 = 0$. Similarly, Fig. 7b proves the non-existing relationship ($R^2 = 0$) of $\eta_{b,w_{avg},i}$ vs. $f_{v,w_{avg},i}$. Regarding the bond-wood shear strength ratios at other probability levels, Fig. 8a presents the cumulative frequency distributions of ratios $\eta_{b,w_{avg},i}$ fitted for each species by a normal function. Figure 8b shows the lower tails of the test results as non-parametric cumulative frequencies.

The presented results excel the ratio of bond strength vs. wood shear strength of the related adherents as an excellent parameter for assessment of bond quality - regardless of species, growth specifics, adhesives and manufacturing details.

7 Proposals for GLT block shear assessment

New test procedures and requirements for block shear tests of hardwood GLTs are outlined. The proposals aim at the future European (EN) hardwood GLT standard but also for

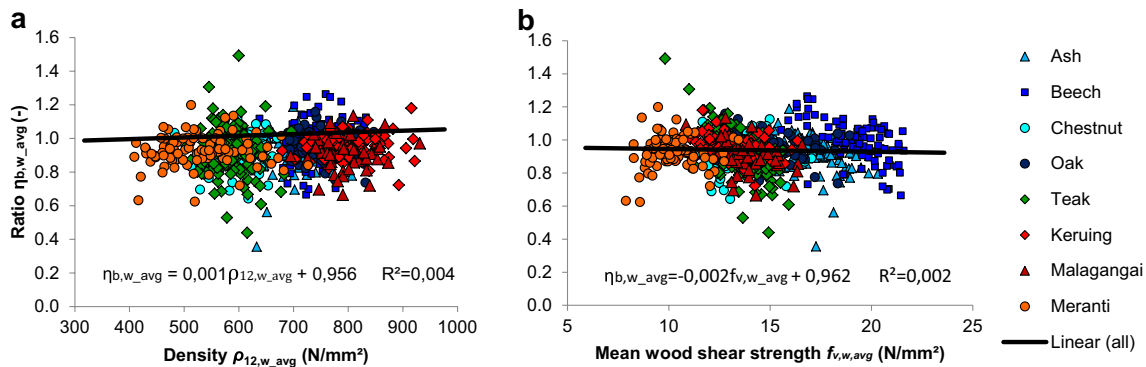
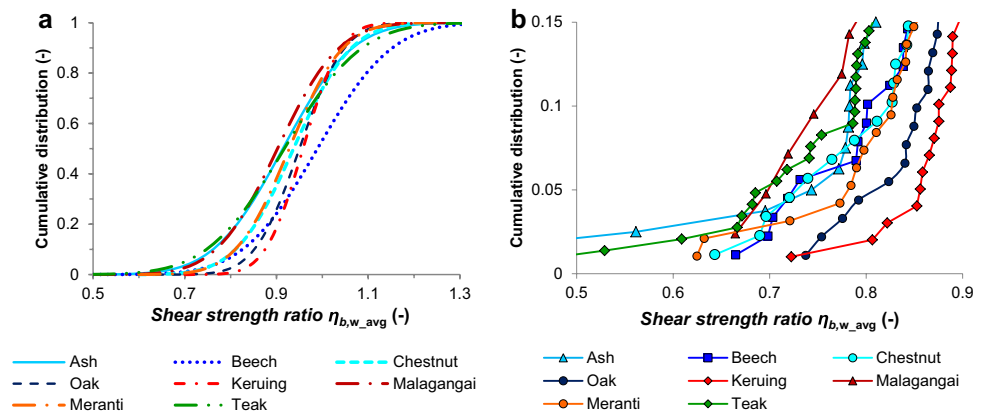


Fig. 7 Relationship of bondline-wood shear strength ratio with associated density and strength properties of investigated hardwood GLTs. **a** $\eta_{b,w_{avg}}$ vs. $\rho_{12,w_{avg}}$, **b** $\eta_{b,w_{avg}}$ vs. $f_{v,w_{avg}}$

Fig. 8 Cumulative distributions of bond-wood block shear strength ratios $\eta_{b,w,avg}$ from GLTs of eight investigated European and tropical hardwood species. **a** normal distribution fits to all data per species, **b** lower tail of cumulative frequencies



wider discussion on the ISO level. Specifically hardwood species with mean and characteristic densities in the range of about 350–750 kg/m³ and 300–680 kg/m³, respectively, are addressed. The block shear tests shall be carried out with adjacent cross-sectional GLT slabs with a thickness of 50 mm each. At one slab, all bondlines are tested in shear as specified today in EN 14080 and EN 386, whereas for the other slab the wood shear strength of each lamination shall be tested at mid-thickness. For ITT it seems reasonable to base the requirements on the lower quantiles (5, 10%) of the strength and wood failure percentage distributions of the test samples. In the case of FPC, where lower numbers of specimens are tested, the requirements are specified for the mean values.

The requirements on bond strength, actually addressing the ratio of bond vs. wood shear strength, are postulated irrespective of timber species and growth region (EU or TR) for ITT and FPC, respectively, as

$$r_{v,05,ITT} = \frac{f_{v,b,05}}{f_{v,w,05}} \geq 0.9 \text{ and } r_{v,mean,FPC} = \frac{f_{v,b,mean}}{f_{v,w,mean}} \geq 0.9. \tag{13a,b}$$

Regarding wood failure, a requirement which encompasses all species and growth regions within the defined density range is not justified by the presented test results and would finally lead to either too low or too high settings for individual species. Adequate ITT requirements for EU and TR species, then based on the lower 10%-quantiles, are

$$WF_{10} \geq WF_{10,EU,ITT} = 50\% \text{ and } WF_{10} \geq WF_{10,TR,ITT} = 75\% \tag{14a,b}$$

whereas in the case of FPC, the rather closely matching requirements

$$WF_{mean} \geq WF_{mean,EU,FPC} = 80\% \text{ and } WF_{mean} \geq WF_{mean,TR,FPC} = 85\% \tag{15a,b}$$

are deemed sensible.

The specified $f_{v,b}$ and WF requirements are presented graphically for the eight EU and TR species in Figs. 4 a–d and 5a–d. For each sample/species, the respective $f_{v,b,05} - WF_{10}$ and $f_{v,b,mean} - WF_{mean}$ data points are also given for the assessment of applicability of the requirements. Evidently, the proposed requirements are fulfilled throughout, except for the species ash, where especially the WF_{ITT} criterion is not met. The latter is not surprising as the ash bonds showed by far the highest WF result scatter ($COV = 30\%$), by far exceeding the $WF-COV_s$ of all other species. This indicates some possible bonding irregularities which, in practice, would necessitate further ITT assessment.

The proposed requirements differ methodically from the specifications in EN 14080 and EN 386, where absolute strength values and herewith precisely correlated WF percentages are prescribed without any consideration of inter and intra species dependent influences of wood shear strength. In a similar yet less expressed manner, significant differences exist vs. the present Japanese bond quality requirement philosophy prescribing species group dependent $f_{v,b}$ and WF settings for individual specimens.

In contrast, the presented proposal incorporates some important aspects of the ANSI A 190.1–2012 (2013) procedure as the bond vs. wood shear strength ratio is defined as 0.9, as well, on both the mean and 5% quantile levels. Notwithstanding that, a major difference vs. *ANSI* consists in the fact that the reference quantity, i.e. wood shear strength, is now determined from the actual GLT material whereby any intra-species bias is avoided. The relevancy of this approach was underlined by the differences between the obtained test and literature wood shear strength values. Further, the bond vs. wood shear strength ratios are now determined in ITT and FPC at different quantile levels of the tested samples. Apart from the bond strength requirements, the new proposal differs from *ANSI* also considerably with regard to the wood failure percentage specifications.

8 Conclusion

The block shear tests performed at dry material conditions ($MC \approx 10\%$) with glued laminated timber (GLT) beams made from eight different industrially important European (EU) and tropical (TR) hardwood species have proven consistently a rather constant ratio of 0.9 of bond vs. wood shear strength at the mean and 5%-quantile distribution level. Hereby both shear strength properties have to be determined from closely adjacent cross-sectional slabs.

In good agreement with literature, the correlation of bond and wood shear strength was very high when regarding the strength means ($R^2 = 0.97$) and 5%-quantiles ($R^2 = 0.84$), respectively, of the different species covering a rather wide wood shear strength range ($f_{v,w,50} = 10.1\text{--}19.1 \text{ N/mm}^2$). A slightly less pronounced though still high correlation ($R^2 = 0.72$) of bond and wood shear strength was obtained for the entirety of specimens of all species ($f_{v,w,i} = 5.0\text{--}23.5 \text{ N/mm}^2$). However, for the individual species investigated in this study, throughout rather low wood shear strength scatters ($COV \approx 13\%$) were obtained whereas highly divergent levels of bond and wood shear strength correlations had to be stated. Hereby the R^2 values stretched from zero, i.e. no correlation, in case of ash, beech and teak to marked correlations ($R^2 \approx 0.5$) for sweet chestnut, oak, l.r. meranti and keruing. Any deepened investigations into the physical and chemical reasons of the encountered inter-species differences in bond vs. wood shear strength correlations were beyond the scope of the presented study yet, important, do not oppose the derived requirement proposals based on mean and 5%-quantile strength ratios. Notwithstanding that, the mentioned species related differences deserve future research efforts.

Regarding wood failure, comparable results were obtained for all species at the mean level. Hereby, the European hardwoods resulted in throughout somewhat lower values as compared to the tropical species which showed on average a mean wood failure percentage of 95%. However, the scatter of the wood failure results was consistently about two times higher for the European as compared to the tropical species, then leading to distinctly lower EU quantile values. For all species, no correlation of bond strength with wood failure percentage was obtained and consistent with literature, density of the laminations was found poorly correlated with bond strength of individual species.

The research results render the bond block shear assessment specifications of hardwood GLTs as specified in EN 386, adopted unchanged in the Malaysian GLT code MS 758, as being methodologically inappropriate. Quantitatively, the requirements of said standards state even for low density hardwoods far too low, and hence unsafe, qualification limits.

Taking into consideration the new test results, literature data and the US (ANSI) and Japanese (MAF Notification) GLT provisions, a new approach to species-encompassing GLT bond quality judgement has been derived. The proposal is based as regards strength on a bond vs. wood shear strength ratio - to be evaluated at different sample distribution levels (x_{05} , x_{mean}) for the cases of initial type testing (ITT) and factory production control (FPC). The suggested qualification limit of the strength ratio is 0.9 for all species, formally reflecting the ANSI approach. Very different, however, the reference quantity “wood strength” is now determined from the same GLT, subject to bond strength evaluation, instead from generalized literature data, hereby avoiding likely bias due to intra species variations. Regarding wood failure, similar to the US and Japanese philosophy, based on the verified non-existent correlation of bond strength and wood failure, constant qualification limits are proposed at the 10%-quantile and mean level in the cases of ITT and FPC, respectively. Due to the experienced pronounced difference in wood failure scatter, the ITT requirements are stated markedly different as 50 and 75% for the European and tropical species, respectively, whereas for FPC the proposed requirements of 80–85% are closely matching.

It is important to mention that the reported results and the conclusions relate to dry hardwood material which in moderate extrapolation of the test conditions can be assumed in the range of 7 to 15% MC. In case of higher MCs, changes of the proposed strength ratios and wood failure percentages might be necessary.

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