European Journal of Wood and Wood Products (2025) 83:153
https://doi.org/10.1007/s00107-025-02296-y

ORIGINAL ARTICLE

Shear strength and stiffness of glued-laminated timber made from European ash (*Fraxinus excelsior* L.)

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Received: 3 December 2024 / Accepted: 17 June 2025 / Published online: 13 August 2025
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Abstract

The influence of size effects on the shear strength and stiffness of glued-laminated timber (GLT) made from European ash (*Fraxinus excelsior* L.) was assessed based on a comprehensive experimental campaign. The experiments were performed on full-scale GLT beams with rectangular cross-sections width × height = $b \times h = 120 \times 480\text{-}800$ mm^2, shear lengths L_v = 720-1500 mm, and ratios between the shear length L_v and the beam height h, i.e. $\alpha = L_v/h = 1.2\text{-}2.5$. The influence of the test configuration (3-point bending and asymmetric 4-point bending) was also assessed. The obtained shear strengths of European ash GLT had mean values $f_{v,\,mean}$ = 10.2 N·mm^{-2} (coefficient of variation CoV_{fv} = 14%) and 12.2 N·mm^{-2} (CoV_{fv} = 15%), for the 3-point and asymmetric 4-point bending test configurations, respectively. The shear strength showed some size dependency, with an exponent $1/m = 0.2$ 0.4 for a strength modification factor $(600/h)^{1/m}$ as a function of the beam height h. The shear modulus showed no size dependency and the obtained mean values were G_{mean} = 1162 N·mm^{-2} (CoV_G = 6%) and 1120 N·mm^{-2} (CoV_G = 6%), for the 3-point and asymmetric 4-point bending tests, respectively.

1 Introduction

1.1 Background

In construction practice, timber is very often used in the form of glued-laminated timber (GLT) beams, in Europe mostly made from softwood, namely Norway spruce (*Picea abies* (L.) H. Karst.). However, in Central Europe, 42 to 46% of the forest area comprises predominantly broadleaved trees and, during the last 30 years, the growing stock of broadleaved trees increased at a higher rate than that of coniferous trees (FOREST EUROPE 2020). In Switzerland, deciduous trees already make up 32% of the forest stock and with a tendency to increase due to climate change (Bundesamt für Umwelt BAFU 2023). Compared to common softwoods used for structural applications, hardwood from European beech (*Fagus sylvatica* L.), European ash (*Fraxinus excelsior* L.), and chestnut (*Castanea sativa* Mill.) exhibit significantly higher strength, but it is nevertheless being mostly used to produce energy and not as a structural material. This was, in part, due to lack of guidelines for the production and design of structural hardwood products. Design verifications regarding structural safety and serviceability for beam-type elements require the determination of bending and shear strengths, as well as the calculation of the expected deflections. For these verifications, the most important mechanical properties are the bending strength f_m, the shear strength f_v, the bending modulus of elasticity E_m, and the shear modulus G. The importance of shear strength is higher for hardwoods, given the lower f_v/f_m ratios compared to softwood strength classes (Lignatec 33/2021 and EN 14080:2013). While the experimental determination of bending strength and modulus of elasticity can be carried out relatively easily through 4-point bending tests (e.g., in accordance with EN 408:2010+A1:2012), it is significantly more difficult to determine values of shear strength and shear modulus that are adequate for structural design verifications.

The determination of shear properties, shear modulus G and shear strength f_v, has been the focus of decade-long discussions (Foschi and Barrett 1980; Madsen 1995; Lam et al. 1997; Riyanto and Gupta 1998; Yeh and Williamson 2001; Brandner et al. 2007, 2012; Steiger and Gehri 2011). In the

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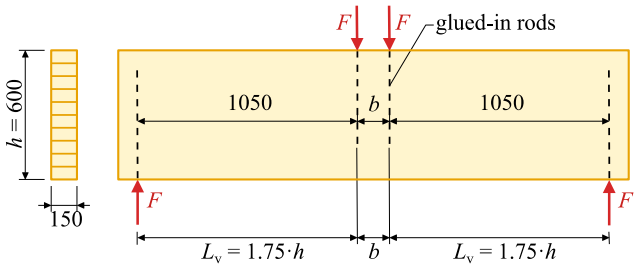


Fig. 1 3-point bending test configuration proposed by Gehri (2010) for the determination of shear properties of glued-laminated timber beams (dimensions in mm)

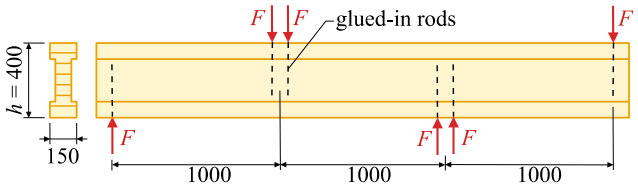


Fig. 2 Asymmetric 4-point bending tests performed by Ehrhart (2019) for the determination of shear properties of glued-laminated timber beams made from European beech (dimensions in mm)

ongoing revision of EN 1995-1-1:2004+A1:2008 *Eurocode 5*, the determination of shear strength has also been under active discussion, particularly regarding conversion factors required to convert results from small-scale tests into values that represent the behaviour of the material in a structure. As pointed out, e.g., by Ehrhart et al. (2020), the main issues with the experimental determination of the shear strength parallel to the grain are the: (i) influence of perpendicular-to-the-grain stresses; (ii) influence of volume and geometryrelated parameters, and; (iii) incidence of unrelated failure modes.

Regarding the influence of perpendicular-to-the-grain stresses, on small-scale specimens, the presence of tensile perpendicular-to-the-grain tensile stresses reduces the shear strength (Sandhaas 2012), whereas the presence of low perpendicular-to-the-grain compressive stresses increases (or at least it does not decrease) the shear strength (Mistler 1979; Spengler 1982). The incidence of unrelated failure modes, specifically in bending and compression perpendicular-to-the-grain, arises mostly in experiments on large-scale specimens and is due to the test and loadapplication configurations. Finally, the influence of volume-related parameters arises from shear being a brittle failure mode and, therefore, dependent on the theoretically higher probability of a strength-reducing feature occurring in a larger stressed volume.

1.2 Experiments on full-scale beams

Previous studies have concluded that realistic values of shear strength cannot be based on tests on small-scale specimens, such as those for instance prescribed by EN 408:2010, but should instead be based on full-scale beam tests (Schickhofer 2001; Yeh and Williamson 2001; Klöck 2005; Gehri 2010; Aicher and Ohnesorge 2011). Shear failures are brittle and, therefore, the shear strength depends on the size of the stressed volume. In these cases, it is common to relate the strength of a stressed volume V to a reference volume V_{ref} in the form of a power law $(V/V_{ref})^{1/m}$ (Weibull 1939). The exponent $1/m$ represents the sensitivity of the strength property to the influence of volume effects (higher values of the exponent $1/m$ make the strength property more sensitive to the stressed volume V). Stress states of pure shear are difficult to materialise experimentally and hardly occur in real structures; therefore the test configurations should mostly aim to represent the conditions to which the material is subjected in a real structure. As already mentioned, an issue with using bending tests to determine the shear strength has been the high number of bending failures that tend to occur. To overcome this, beams with I-shaped cross-sections have been used (Schickhofer 2001; Aicher and Ohnesorge 2011; Ehrhart 2019) and they were even included in the draft amendment to EN 408:2007/prA1:2007, even though they were finally not adopted in the versions published since (EN 408:2010 and EN 408:2010+A1:2012). The main shortcomings of these beams are the bigger preparation effort, a more complicated calculation of shear stresses and shear modulus, and stress concentrations in the web-flange transition.

Gehri (2010) proposed the test configuration shown in Fig. 1, which comprises a simple three-point bending test and a beam with a rectangular cross-section, allowing for an easy determination of shear strength and shear modulus. To ensure that the shear stresses are as constant as possible over the entire shear field, without significant perpendicular-to-the-grain stresses, the applied forces are introduced using glued-in rods (GiRs), namely the GSA® system developed by the company *neue Holzbau AG*, and not only through compressive perpendicular-to-the-grain stresses (Steiger and Gehri 2011). Since the shear strength of GLT made from hardwood is higher than that of softwood GLT, the requirements for the loadtransfer system are also higher, otherwise the shear strength of hardwood could not be captured experimentally. The shear fields proposed by Gehri (2010) have a ratio $\alpha = L_v/h = 1.75$, avoiding the bending failures that come with high values of α, while remaining within the range of validity of the classical beam theory, as shown by 3-point bending tests on European beech GLT beams Gehri et al. (2022).

Ehrhart (2019) performed shear tests under an asymmetric 4-point bending configuration, based on a test configuration developed by Basler et al. (1960), on GLT beams made from European beech (*Fagus sylvatica* L.) with an I-shaped cross-section (Fig. 2). In comparison with 3-point bending

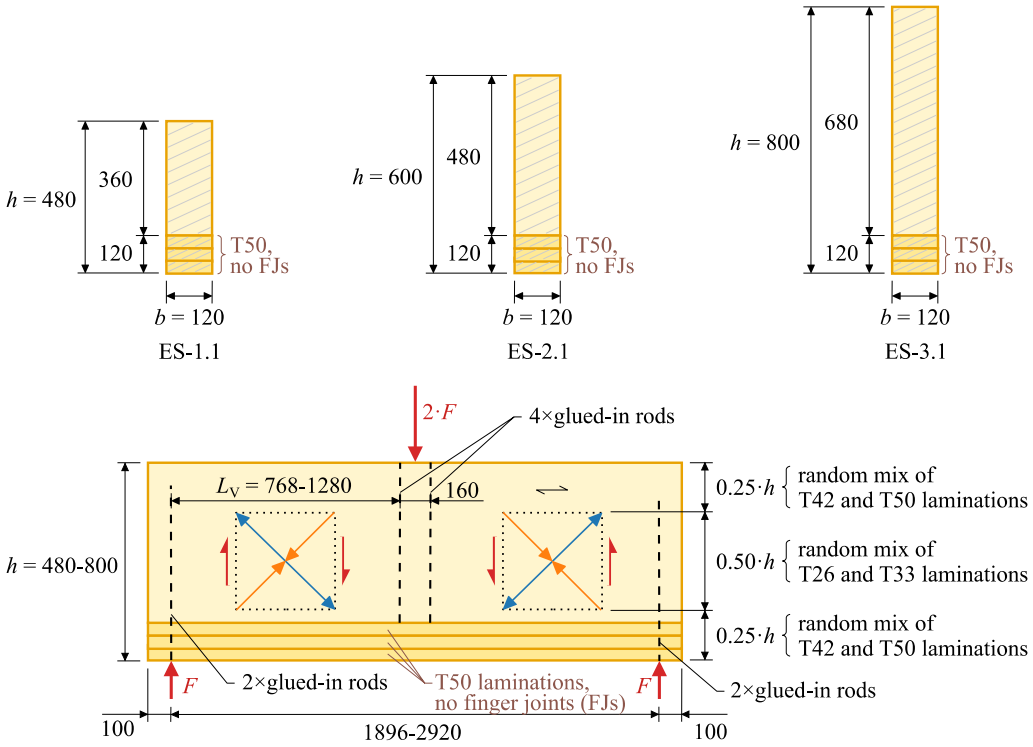


Fig. 3 3-point bending tests on European ash GLT—geometry of test specimens and test configuration (dimensions in mm, drawing not to scale)

Table 1 3-point bending tests on European ash GLT—geometry of test specimens and test configuration

Test configuration		Cross-section			Shear field		
		b	h	L_v	α	A_{shear}	Vol_v
		[mm]	[mm]	[mm]	[°]	[mm^2]	[m^3]
ES-1.1	(n = 3)	120	480	768	1.6	92,160	0.044
ES-2.1	(n = 3)	120	600	960	1.6	115,200	0.069
ES-3.1	(n = 3)	120	800	1280	1.6	153,600	0.123

tests, this configuration allows for longer shear fields for the same beam height and bending moment, which gives the possibility to study the influence of the various geometric parameters over broader ranges.

1.3 Objectives and scope

The objectives of this study were to: (i) determine the shear strength and shear stiffness properties for the investigated GLT material; (ii) obtain knowledge on the influence of the member size (geometrical parameters) and of the test configuration on the shear strength of GLT made from hardwood (European ash); (iii) develop tests methods for the experimental determination of the shear stiffness and strength parallel to the grain of GLT beams for research (where it is important to obtain only shear failures and it is possible to implement more complicated test set-ups) and for quality control during GLT production (where simple test set-ups are required); (iv) define the reference dimensions for cross-sections that meet the requirements for the two abovementioned fields of application; and (v) propose simple relationships to account for size effects, which can be implemented in design standards (e.g. SIA 265:2021 or EN 1995-1-1:2004+A1:2008).

2 Experimental research

2.1 Three-point bending tests

2.1.1 Materials and methods

The 3-point bending tests on European ash GLT beams (Fig. 3; Table 1) were performed at the Structural Engineering Research Laboratory of Empa, in Switzerland. The test specimens were produced by the company *neue Holzbau AG* and were made from European ash GLT. The layup of the GLT test specimens was as follows: in the middle part of the cross-Sect. (0.5·h, zone relevant for the shear behaviour), a random mix of boards of classes T26 and T33 was used;

in the outer parts of the cross-Sect. (0.25·h), a random mix of boards of classes T42 and T50 was used. The three outer laminations in the tension zone were made from boards of class T50, without finger joints to avoid premature bending failures (Fig. 3). The number after the letter "T" represents the characteristic, i.e. the 5% percentile, value of the tensile strength parallel to the grain of the boards. Given that the scope of the European standard EN 14080:2013 is limited to the production of GLT made from the most common softwood species and Poplar, the production of GLT made from hardwood is, in Switzerland, produced in accordance with specifically developed guidelines (Holzindustrie Schweiz 2021). The most important mechanical and physical properties of the strength classes of GLT made from European ash, European beech, and chestnut (*Castanea sativa* Mill.) and produced in accordance with the guidelines are given in the document Lignatec 33/2021. The finger joints were made using the 1component polyurethane (PUR) adhesive Henkel Loctite HB S109 and the GLT beams were produced using the 1component PUR adhesive Henkel Loctite HB S709, at a wood moisture content of 10% and using a primer. The mean density of the test specimens was ρ_{mean} = 640 kg·m^{-3} (coefficient of variation CoV_{ρ} = 3%) at an average moisture content ω_{mean} = 10%. The density of the test specimens was determined by measuring their outer dimensions and weighing them (the weight of the glued-in rods was discounted). The moisture content was determined using a hand-held resistance-type moisture meter. The load-application zones were reinforced with GiRs (Steiger et al. 2015; ETA-19/0752 2020; neue Holzbau 2020). The GiRs used in the test specimens are the commercial product known as "GSA®-Technology" and are covered by a European Technical Assessment ETA 19/0752 (the industry partner involved in the project, *neue Holzbau AG*, who also produced the GLT test specimens, is the manufacturer certified by the ETA 19/0752).

The adopted shape of the shear fields $\alpha = L_v/h = 1.6$ is based on 3-point bending tests on European beech GLT beams (Gehri et al. 2022), which for $\alpha = 1.56$ still showed largely identical strains in tension and compression in the shear fields. For smaller values of α, the compressive strains increased and the tensile strains decreased, showing that the forces were being transferred by the compression diagonal directly to the support.

The tests were performed under force control. The test specimens were loaded up to 40% of the estimated failure load, at an approximately constant loading rate, and the load was then held constant for 180 s, while the displacement sensors used to measure the displacements in the diagonals were removed. The load was then increased at an approximately constant loading rate, so that failure occurred between 300 ± 120 s (based on EN 408:2010+A1:2012).

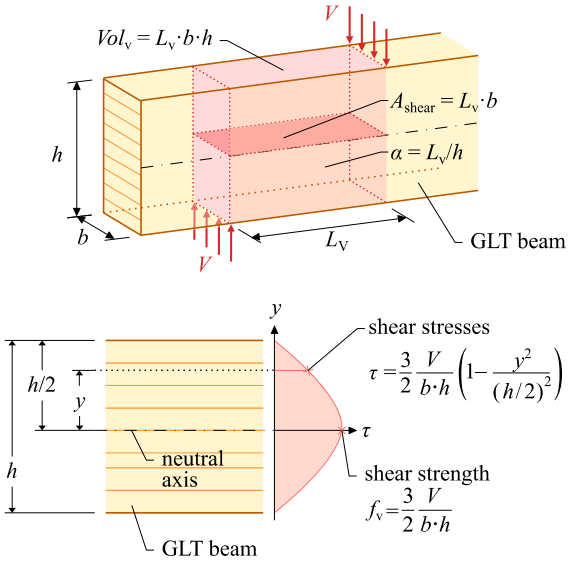


Fig. 4 Geometric parameters and distribution of shear stresses in timber beams subjected to bending

Table 2 Results of the 3-point bending tests on European ash GLT

Test configuration		Shear modulus		Shear strength	
		G_{mean}	CoV	$f_{v,mean}$	CoV
		[N·mm^{-2}]	[-]	[N·mm^{-2}]	[-]
ES-1.1	(n = 3)	1228	19%	10.7	18%
ES-2.1	(n = 3)	1117	15%	10.4	16%
ES-3.1	(n = 3)	1132	8%	9.6	10%
All	(n = 9)	1162	15%	10.2	14%

The average loading rates were between 0.5 and 1.5 kN·s^{-1}. The shear modulus G was determined based on the shear field test method prescribed in EN 408:2010+A1:2012, with square measurement fields with side lengths $h/2$ (Figs. 3 and 8). The shear strength f_v was calculated as $f_v = 3/2 \cdot F/(b \cdot h)$ (Fig. 4).

2.1.2 Results

The results of the 3-point bending tests on European ash GLT are presented in Table 2; Fig. 5. The mean shear modulus was G_{mean} = 1162 N·mm^{-2} (CoV_G = 6%) and showed no size dependency. The global mean shear strength was $f_{v,mean}$ = 10.2 N·mm^{-2} (CoV_{fv} = 14%). Some size dependency of the shear strength can be observed at the mean-value level, but the scatter of the results makes it less clear than for equivalent Norway spruce GLT beams (Gehri et al. 2022). The mean shear strength f_v can be described as a function of the beam height h by Eq. 1.

$$f_v = 34 \cdot h^{-0.19} = 10.2\left(\frac{h_{ref}=600}{h}\right)^{0.19} \quad (1)$$

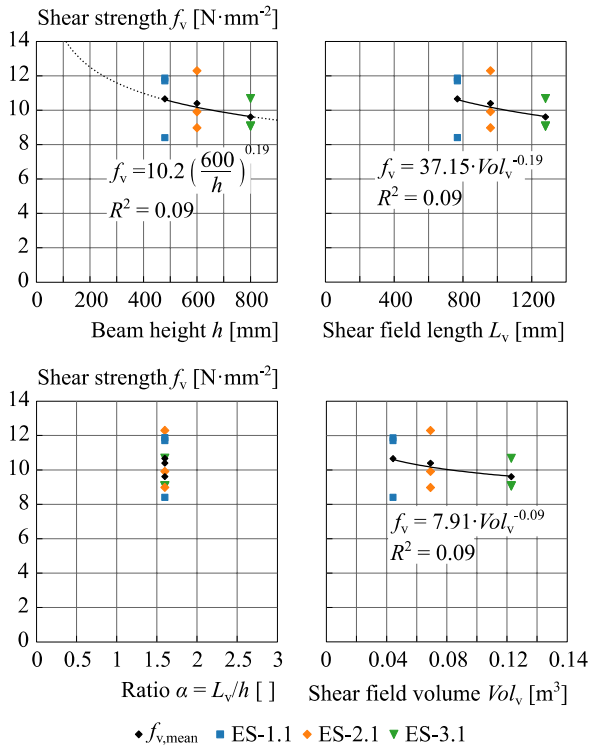


Fig. 5 Results of the 3-point bending tests on European ash GLT—shear strength f_v as a function of the beam height h, length of the shear field L_v, ratio $\alpha = L_v/h$, and volume of the shear field Vol_v

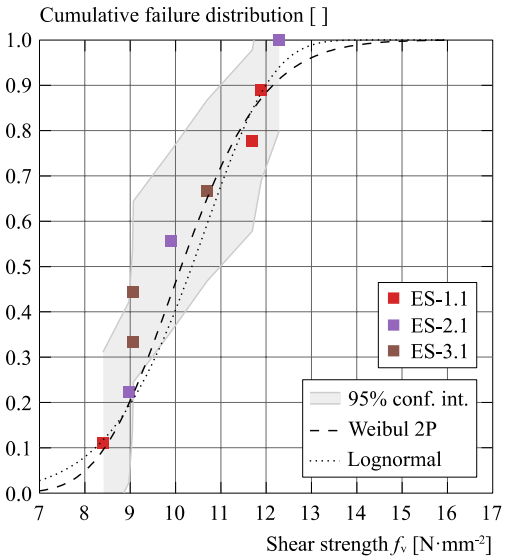


Fig. 6 Cumulative failure distribution of the shear strength observed in the 3-point bending tests (all test specimens pooled together)

The similar mean values and the variation of the shear strength (Table 2; Fig. 5) introduce a high uncertainty in the fitted exponent $1/m = 0.19$, which has a very wide 95% confidence interval [-0.36, 0.74].

The cumulative failure distribution of shear strength is shown in Fig. 6. The characteristic 5%-percentile values

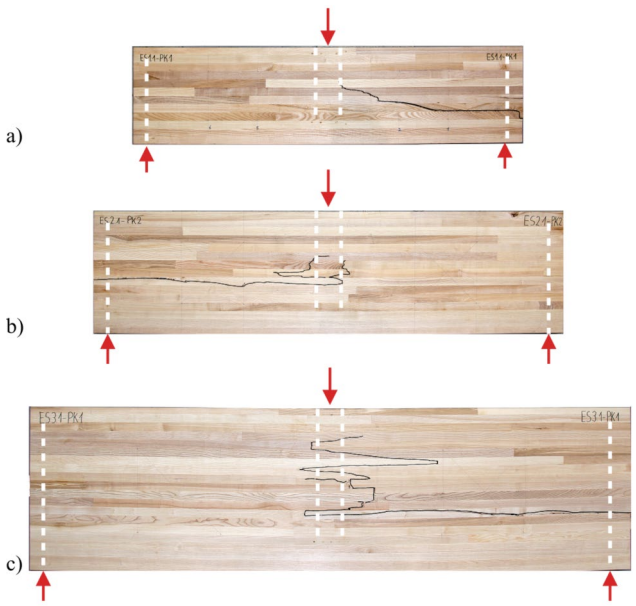


Fig. 7 Typical failures observed in the 3-point bending tests: **a** test specimen ES-1.1 (no. 1); **b** ES-2.1 (no. 2); **c** ES-3.1 (no. 1). The location of the glued-in rods and the applied forces are also shown

derived according to the standard EN 14358:2016 are: (i) $f_{v,0.05} = 7.5$ N·mm^{-2}, if all results are pooled together; (ii) $f_{v,0.05,h=480\ mm} = 5.7$ N·mm^{-2}, for the beams with $h = 480$ mm; (iii) $f_{v,0.05,h=600\ mm} = 6.2$ N·mm^{-2}, for the beams with $h = 600$ mm; and (iv) $f_{v,0.05,h=800\ mm} = 7.1$ N·mm^{-2}, for the beams with $h = 800$ mm. The mean values $f_{v,mean}$ and the characteristic 5%-percentile values $f_{v,0.05}$ of shear strength show different trends in relation to the beam height h. The mean value $f_{v,mean}$ decreases with increasing beam height h (Table 2; Fig. 5), whereas the characteristic 5%-percentile values increase. However, given the small sample size for each beam height ($n = 3$) and the comparatively high coefficient of variation, these results must be taken with caution.

Typical failures are shown in Fig. 7. The position of the longitudinal shear cracks was above the neutral axis in approximately 70% of the tests and below the neutral axis in approximately 30% of the tests (Gehri et al. 2022). For beam heights $h = 480$ and 600 mm, the shear cracks occurred within $0.25 \cdot h$ above the neutral axis (i.e. in the zone under longitudinal compressive stresses), which corresponds to shear stresses higher than $0.75 \cdot \tau_{max}$, with $\tau_{max} = 1.5 \cdot V/(b \cdot h)$. For the three beams with height $h = 800$ mm, the shear cracks occurred within $0.15 \cdot h$ and $0.20 \cdot h$ above and below the neutral axis, respectively, which corresponds to shear stresses higher than $0.84 \cdot \tau_{max}$, with $\tau_{max} = 1.5 \cdot V/(b \cdot h)$. Therefore, all shear cracks occurred in the middle part ($0.5 \cdot h$) of the cross-section. The mean maximum bending stresses reached when the shear failures occurred were $\sigma_{m,max,mean} = 70.9$ N·mm^{-2} ($CoV_{\sigma max} = 15\%$) and no bending failures happened.

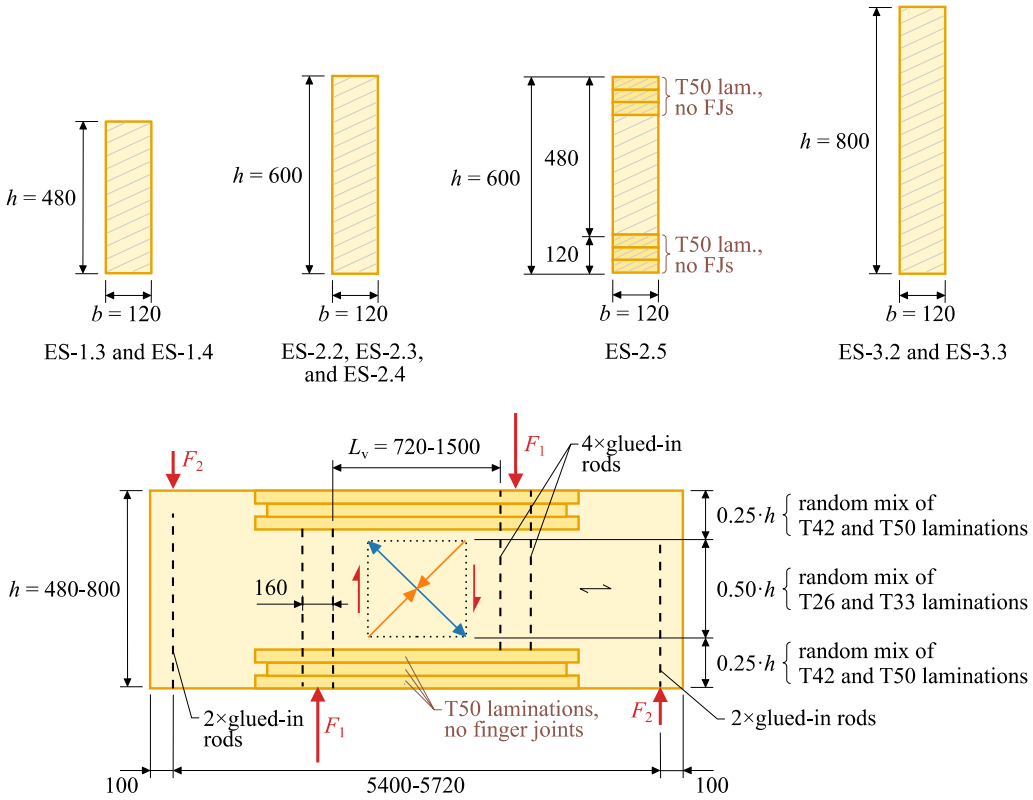


Fig. 8 Asymmetric 4-point bending tests on European ash GLT—geometry of test specimens and test configuration (dimensions in mm, drawing not to scale)

Table 3 Asymmetric 4-point bending tests on European ash GLT—geometry of test specimens and test configuration

Test configuration		Cross-section			Shear field		
		b	h	L_v	α	A_{shear}	Vol_v
		[mm]	[mm]	[mm]	[°]	[mm^2]	[m^3]
ES-1.3	(n = 3)	120	480	768	1.6	92,160	0.044
ES-1.4	(n = 3)	120	480	960	2.0	115,200	0.055
ES-2.2	(n = 3)	120	600	720	1.2	86,400	0.052
ES-2.3	(n = 5)	120	600	960	1.6	115,200	0.069
ES-2.4	(n = 3)	120	600	1200	2.0	144,000	0.086
ES-2.5	(n = 3)	120	600	1500	2.5	180,000	0.108
ES-3.2	(n = 3)	120	800	960	1.2	115,200	0.092
ES-3.3	(n = 3)	120	800	1280	1.6	153,600	0.123

2.2 Asymmetric 4-point bending tests

2.2.1 Materials and methods

The asymmetric 4-point bending tests on European ash GLT beams were also performed at Empa's Structural Engineering Research Laboratory. The test specimens (Fig. 8; Table 3) were made from ash GLT. The layup of the GLT test specimens was as follows: in the middle part of the cross-section ($0.5 \cdot h$ zone relevant for the shear behaviour), a random mix of boards of classes T26 and T33 was used; in the outer parts of the cross-Sect. ($0.25 \cdot h$), a random mix of boards of classes T42 and T50 was used. In the test configuration ES-2.5, the three outer laminations in the tension zone were of made from boards of class T50, without finger joints (Fig. 8). Since it is the middle part of the cross-section that is relevant for the shear behaviour, the results of the 3-point bending tests (Subsection 2.1) and of the asymmetric 4-point bending tests are directly comparable. The finger joints were again produced using the 1component polyurethane (PUR) adhesive Henkel Loctite HB S109 and the GLT beams were produced using the 1component PUR adhesive Henkel Loctite HB S709, at a wood moisture content of 10% and using a primer. The mean density of the test specimens was ρ_{mean} = 664 kg·m^{-3} (CoV_ρ = 3%) at an average moisture content ω_{mean} = 10%. The

Table 4 Results of the asymmetric 4-point bending tests on GLT made from European ash

Test configuration		Shear modulus		Shear strength	
		G_{mean}	CoV	$f_{v,mean}$	CoV
		[N·mm^{-2}]	[–]	[N·mm^{-2}]	[–]
ES-1.3	(n = 3)	1097	5%	11.5	13%
ES-1.4	(n = 3)	1108	4%	12.3	12%
ES-2.2	(n = 3)	1105	4%	13.9	10%
ES-2.3	(n = 5)	1124	12%	13.9	12%
ES-2.4	(n = 3)	1124	4%	12.6	10%
ES-2.5	(n = 3)	1092	3%	12.5	4%
ES-3.2	(n = 3)	1172	6%	9.8	3%
ES-3.3	(n = 3)	1134	5%	10.3	11%
All	(n = 26)	1120	6%	12.2	15%

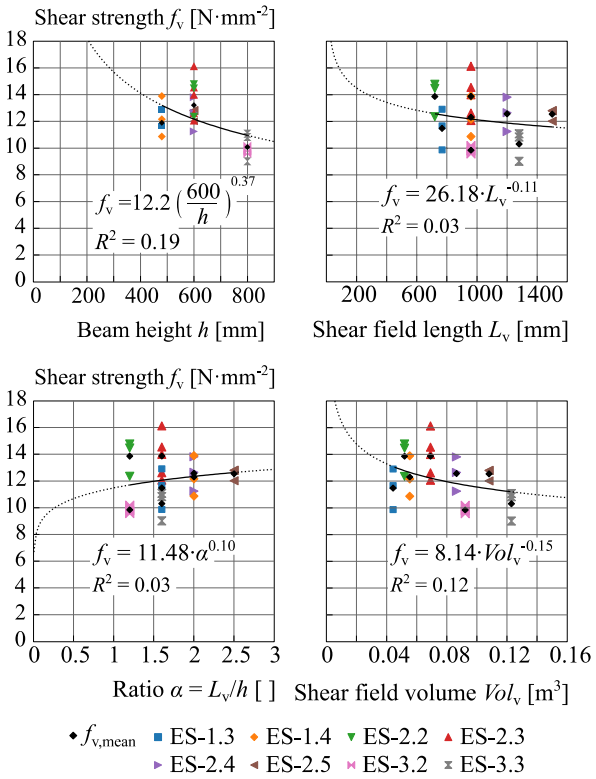


Fig. 9 Results of the asymmetric 4-point bending tests on GLT made from European ash—shear strength f_v as a function of the beam height h, length of the shear field L_v, ratio $\alpha = L_v/h$, and volume of the shear field Vol_v

load-application zones were reinforced with GiRs (Steiger et al. 2015; ETA-19/0752 2020; neue Holzbau 2020). The asymmetric 4-point bending configuration allows for higher $\alpha = L_v/h$ ratios without premature bending failures, but for comparison with the results of the 3-point bending tests, test specimens with a ratio $\alpha = L_v/h = 1.6$ were included for all beam heights (Table 3). For the beams with the reference height $h = 600$ mm and ratio $\alpha = L_v/h = 1.6$, five tests were performed, instead of only three, to have a better understanding of the variability of the test results.

The tests were performed under force control. As in the 3-point bending tests, the test specimens were loaded up to 40% of the estimated failure load, at an approximately constant loading rate, and the load was then held constant for 180 s. The test specimen was then unloaded and the displacement sensors used in the diagonals to determine the displacements in the shear field were removed. The load was then increased at an approximately constant loading rate, so that failure occurred between 300 ± 120 s (based on EN 408:2010+A1:2012). The average loading rates were between 1.0 and 2.5 kN·s^{-1}. This test configuration was more difficult to implement, because both reaction forces (supports 1 and 2) had to be measured and vertical displacements of both load-application points had to be the same, to ensure symmetry of applied loads and support reactions. The shear modulus G was determined based on the shear field method, with square measurement fields with side lengths $h/2$. The shear strength f_v was calculated as $f_v = 3/2 \cdot (F_1 F_2)/(b \cdot h)$ (Fig. 8).

2.2.2 Results

The results of the asymmetric 4-point bending tests on European ash GLT are presented in Table 4; Fig. 9. The mean shear modulus was G_{mean} = 1120 N·mm^{-2} (CoV_G = 6%) and showed no size dependency. The global mean shear strength was $f_{v,mean}$ = 12.2 N·mm^{-2} (CoV_{fv} = 15%). Some sizedependency of the shear strength can be observed at the mean-value level, but the scatter of the results makes it less clear than for the equivalent Norway spruce GLT beams. The mean value of the shear strength can be described as a function of the beam height h (Eq. 2).

$$f_v = 126.8 \cdot h^{-0.37} = 12.2\left(\frac{h_{ref}=600}{h}\right)^{0.37} \quad (2)$$

The similar mean values and the coefficient of variation of the shear strength (Table 2; Fig. 5) introduce a high uncertainty in the fitted exponent $1/m = 0.37$, which has a wide 95% confidence interval [0.05, 0.68]. Whereas, as expected, a clear reduction of shear strength f_v is observed from $h = 600$ mm to 800 mm, an increase from $h = 600$ mm to 480 mm is not observed.

The cumulative failure distributions of shear strength are shown in Fig. 10, where the lower strengths of the test specimens with a beam height $h = 800$ mm are easily identifiable. The characteristic 5%-percentile values derived according to the standard EN 14358:2016 are: (i) $f_{v,0.05}$ = 10.9 N·mm^{-2}, if all results are pooled together; (ii) $f_{v,0.05,h=480\,mm}$ = 8.9 N·mm^{-2}, for the beams with $h = 480$ mm; (iii) $f_{v,0.05,h=600\,mm}$ = 10.9 N·mm^{-2}, for the beams with

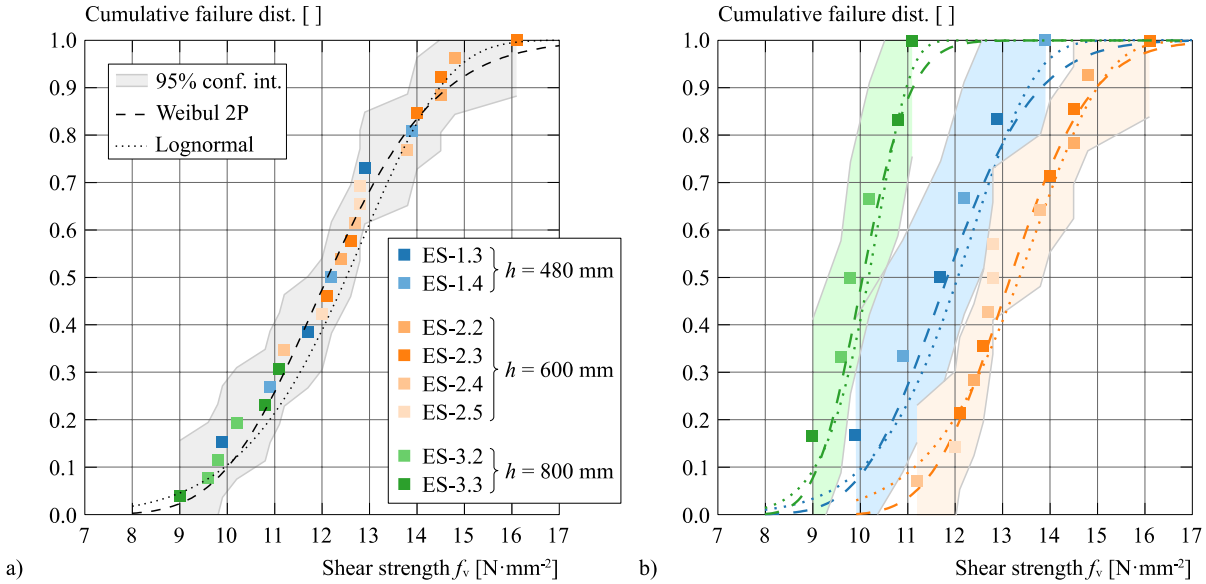


Fig. 10 Cumulative failure distributions of the shear strength in the asymmetric 4-point bending tests: **a** all test specimens pooled together; **b** specimens of the same height h pooled together

h=600 mm; and (iv) $f_{v,0.05,h=800\ mm}$ = 8.4 N·mm^{-2}, for the beams with h=800 mm.

Typical failures are shown in Fig. 11. The position of the longitudinal shear cracks was above the neutral axis in approximately 60% of the tests and below the neutral axis in approximately 40% of the tests (Fig. 8). All but one shear crack occurred within ±20% of the beam height from the neutral axis, which corresponds to shear stresses higher than 0.84·τ_{max}, with τ_{max}=1.5·V/(b·h) (Gehri et al. 2022). Therefore, all but one shear crack occurred in the middle part (0.50·h) of the cross-section. The exception was a test specimen of the configuration ES-2.3, in which the shear crack occurred 0.30·h above the neutral axis, but the corresponding shear strength was very close to the average shear strength of the ES-2.3 configuration.

The mean maximum bending stresses reached when the shear failures occurred were $\sigma_{m,max,mean}$=47.3 N·mm^{-2} ($CoV_{\sigma max}$ = 29%), and no bending failures happened.

3 Discussion

3.1 Test configurations

From a production quality-control point of view, e.g. to check if a specified or declared material property (which in effect means a system value linked to a controlled procedure) is met, the simpler 3-point bending test configuration is adequate and provides all the necessary information for quality assessment. The asymmetric 4-point bending test allows for a broader range of geometric parameters, namely higher α=L_v/h ratios, given the higher shear forces for the same bending moment. It is better suited to study the shear behaviour of timber beams but it is also significantly more complicated to perform. Reinforcement with GiRs is necessary to ensure a uniform shear field and to apply the required high forces perpendicular to the grain, in particular for hardwood GLT.

3.2 Reference size of test specimens

The test results showed that it is possible to test beams with cross-sectional dimensions of up to 120 × 800 mm^2 for European ash GLT, but the applied forces are quite high (up to 1150 kN). Since the bending properties are given for a reference beam height h=600 mm (e.g. EN 14080:2013, SIA 265:2021), it makes sense to adopt this dimension as the reference height, i.e. h_{ref} = 600 mm, also for shear properties.

3.3 Shear modulus

As expected, the shear modulus showed no size dependency. The stiffness of the tension and compression diagonals in the shear fields showed, however, some dependency on the ratio α=L_v/h. The obtained mean values were G_{mean} = 1162 N·mm^{-2} (CoV 6%) and 1120 N·mm^{-2} (CoV 6%), for the 3-point and asymmetric 4-point bending tests, respectively (Fig. 12). This is in good agreement with the value G_{mean} = 1000 N·mm^{-2} specified in the publication Lignatec 33/2021, which was published recently in Switzerland, to disseminate results from research projects on the use of hardwood into design practice.

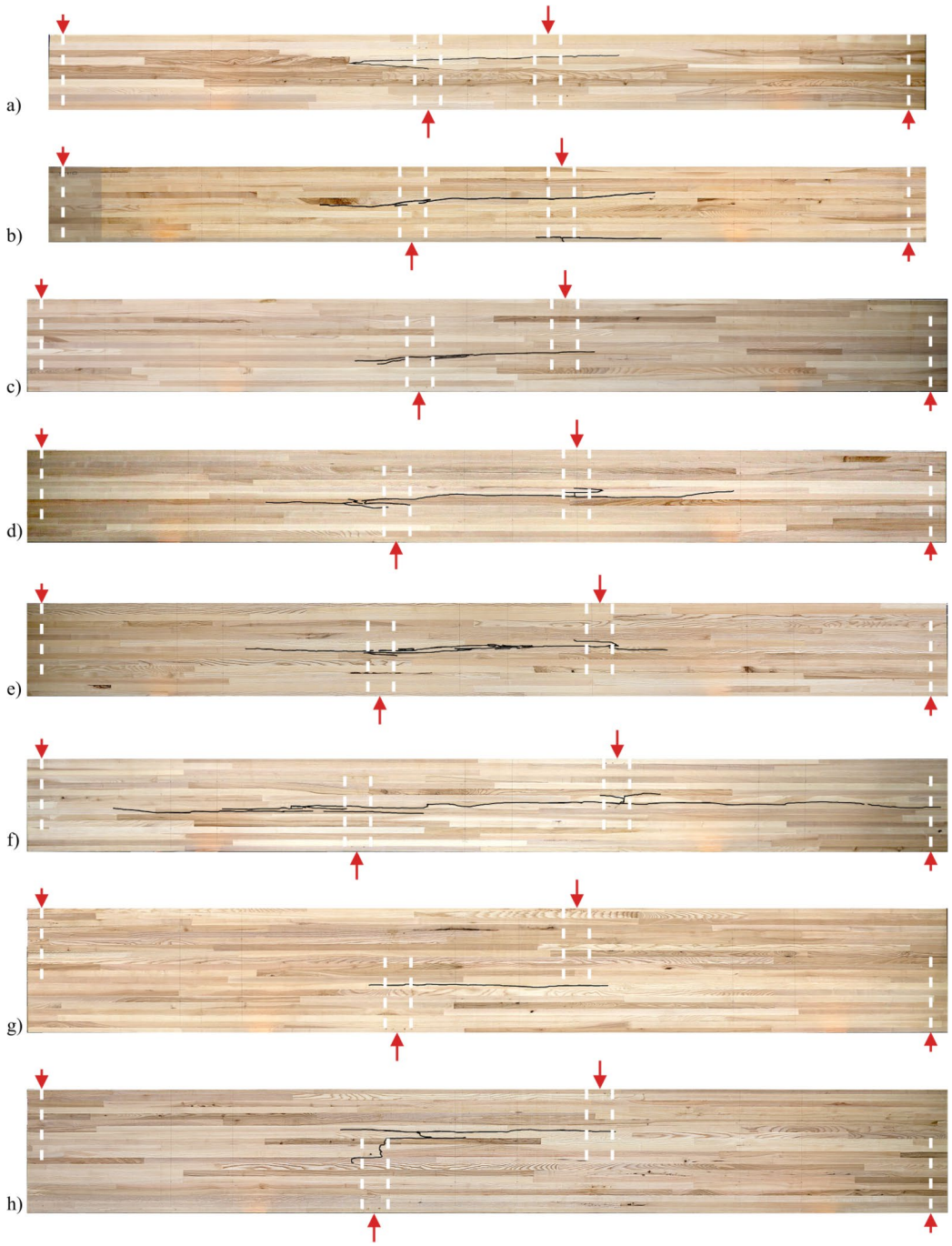


Fig. 11 Typical failures observed in the asymmetric 4-point bending tests: **a**) test specimen ES-1.3 (no. 2); **b** ES-1.4 (no. 3); **c** ES-2.2 (no. 1); **d** ES-2.3 (no. 3); **e** ES-2.4 (no. 2); **f** ES-2.5 (no. 2); **g** ES-3.2 (no. 2); **h** ES-3.3 (no. 2). The location of the glued-in rods and the applied forces are also shown

3.4 Shear strength

The obtained shear strengths of European ash GLT had mean values $f_{v,mean}$ = 10.2 N·mm^{-2} (CoV_{fv} = 14%) and 12.2 N·mm^{-2} (CoV_{fv} = 15%), for the 3-point and asymmetric 4-point bending tests, respectively (Fig. 13; Table 5). This difference can be partially explained by the fact that in the 3-point bending tests two shear fields are effectively being tested simultaneously, since failure occurs on only one of the two shear fields, whereas in the asymmetric 4-point bending tests only one shear field is tested. Therefore, shear strength data calculated from 3-point bending tests is right censored, since the shear field that did not fail has a higher shear strength than the neighboring shear field that failed. Fitting

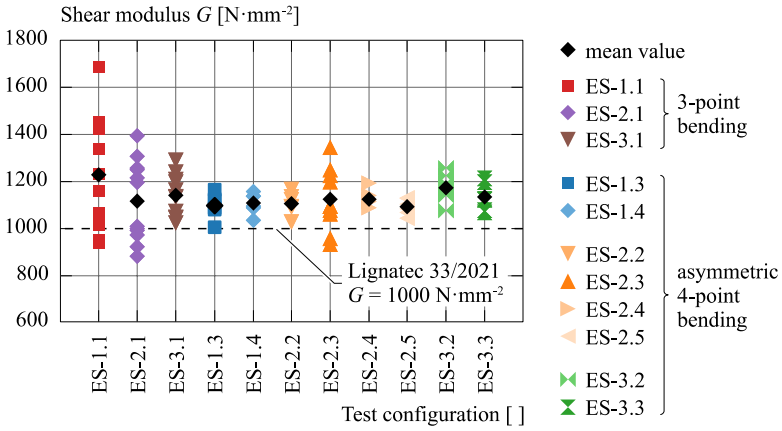


Fig. 12 Shear modulus, based on the shear field test method of EN 408:2010+A1:2012, obtained in the 3-point bending and asymmetric 4-point bending tests on GLT made from European ash

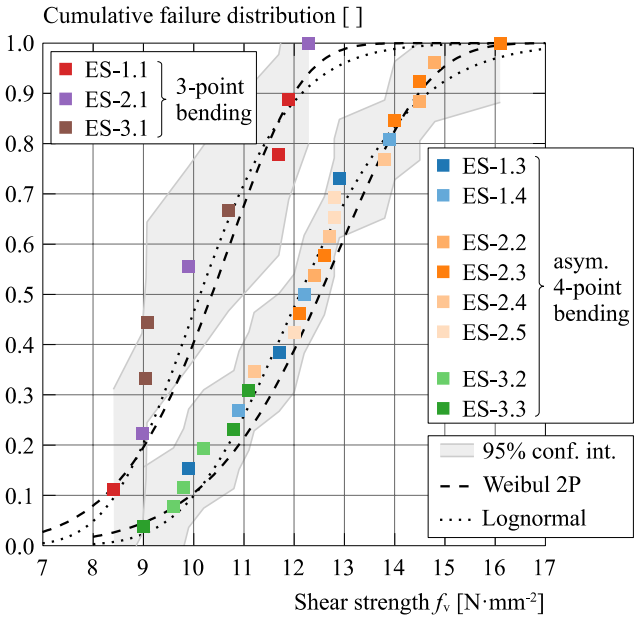


Fig. 13 Cumulative failure distributions of the shear strength in the 3-point bending and asymmetric 4-point bending tests on GLT made from European ash

a lognormal distribution to the right censored shear strength data calculated from the 3-point bending tests gives a mean value of the shear strength $f_{v,mean}$ = 12.1 N·mm^{-2}, using SciPy's (version 1.11.1) statistical functions *CensoredData* and *lognorm.fit* (Virtanen et al. 2020). For comparison, the corresponding value determined in 3-point bending tests on GLT made from Norway spruce was $f_{v,mean}$ = 4.0 N·mm^{-2} (CoV_{fv} = 19%) (Gehri et al. 2022). The obtained coefficients of variation (Tables 2 and 4) seem realistic: average of 14% for the 3-point bending tests and 15% for the asymmetric 4-point bending tests. The JCSS Probabilistic Model Code (JCSS 2006) specifies a coefficient of variation of 25% for the shear strength of softwood structural timber and Brandner et al. (2012) report an average coefficient of variation of 15% based on a literature survey.

The test configuration showed a marked influence on the position of the failure cracks. Failure cracks in the 4-point bending tests were evenly distributed within ±0.2·h from the neutral axis, whereas in the 3-point bending tests the failure cracks occurred mostly within 0.25·h above the neutral axis. Photos of some test specimens showing typical failure modes (Figs. 7 and 11) allow concluding that the reinforcement with glued-in rods did not confine crack growth. In the 3-point bending tests, the failure cracks reach the end surface of the beams (Fig. 7). This did not occur in the asymmetric 4-point bending tests, because the end surfaces were too far away from the central shear field.

The shear strength also showed some size dependency (obtained strength modification factors are presented in Fig. 9), even though not as evident as in preliminary tests on Norway spruce GLT (Gehri et al. 2022). The sensitivity of the shear strength to volume-related effects is accounted for by the exponents 1/m of the modification factor $(600/h)^{1/m}$ for the mean shear strength. For 3-point bending and asymmetric 4-point bending tests, the obtained exponents are 1/m=0.19 and 0.37, respectively (Fig. 14). Due to the observed coefficients of variation and limited number of replicas, the confidence intervals of these exponents are quite wide. In the asymmetric 4-point bending tests, a clear reduction of shear strength f_v is nevertheless observed from h=600 mm

Table 5 Shear strengths determined in the 3-point bending tests and in the asymmetric 4-point bending tests on GLT made from European ash

Test configuration		Mean value	Coeff. of variation	5%-percentile values			
				h=480, 600, and 800 mm			h=600 mm
		$f_{v,mean}$	CoV(f_v)	$f_{v,0.05,empirical}$	$f_{v,0.05,lognormal}$	$f_{v,0.05,Weibull}$	$f_{v,0.05,EN14358}$
		[N·mm^{-2}]	[-]	[N·mm^{-2}]	[N·mm^{-2}]	[N·mm^{-2}]	[N·mm^{-2}]
ES-3P	(n = 9)	10.2	14%	8.6	8.0	7.6	6.2
ES-4P	(n = 26)	12.2	15%	9.7	9.5	8.8	10.9

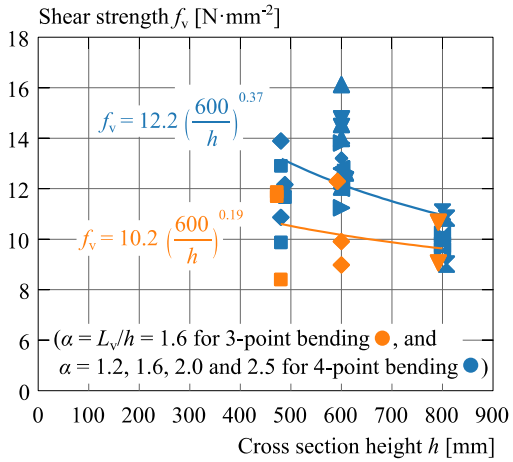


Fig. 14 Shear strength as a function of the beam height h of the cross-section for the 3-point bending tests and the 4-point bending tests on GLT made from European ash

to 800 mm: $f_{v,h=600,mean}$ = 13.3 N·mm^{-2} ($CoV_{fv,h=600}$ = 10%) and $f_{v\,h=800,mean}$ = 10.1 N·mm^{-2} ($CoV_{fv,h=800}$ = 8%). However, an increase from h = 600 mm to 480 mm is not observed. This might be related to the limited number of tests with h = 480 mm (n = 6) compared to h = 600 mm (n = 14), the similar mean values of the shear strength $f_{v,h=480,mean}$ = 11.9 N·mm^{-2} and $f_{v,h=600,mean}$ = 13.3 N·mm^{-2}, and the similar coefficients of variation $CoV_{fv,h=480}$ = 12% and $CoV_{fv,h=600}$ = 10%, lead to a great overlap of the results for these beam heights.

Ehrhart (2019) obtained an exponent 1/m = 0.42 for both the mean and 5%-percentile values of shear strength, but based on 3-point bending tests on European beech GLT beams with I-shaped cross-sections and h_{web} < 240 mm. Ehrhart et al. (2020) then proposed a modification factor $(400/h)^{0.4}$ to account for volume-related effects in the 5%-percentile values of shear strength of European beech GLT. The design guideline Lignatec 33/2021 specifies a modification factor $(600/h)^{0.25}$ for the design shear strength value of European beech and European ash GLT. This exponent 1/m = 0.25 is approximately the average of the 1/m values determined from the 3– and asymmetric 4-point bending tests performed in this study. The same design guideline specifies a conservative reference design shear strength $f_{v,d}$ = 3.2 N·mm^{-2} for a reference height h = 600 mm and all strength classes.

Given that in the 3-point bending tests two shear fields are effectively being tested simultaneously, as mentioned above, if it is assumed that the shear field volume Vol_v is the total volume of the two shear fields (i.e., $Vol_v = 2 \times b \times h \times L_v$), since both are equally stressed. Under this assumption, the effect of the stressed volume in the reduction of the shear strength becomes more evident and considering the results from the 3- and asymmetric 4-point bending tests, all pooled together, leads to a fitted exponent 1/m = 0.19 (Fig. 15).

3.5 Size effects in design standards and guidelines

In Eurocode 5 (EN 1995-1-1:2004+A1:2008), the design shear strength is based on the characteristic 5%-percentile values derived from tests according to EN 408:2010 and prescribed, e.g. for softwood GLT, in EN 14080:2013 as $f_{v,g,k}$ = 3.5 N·mm^{-2} for all strength classes. As already mentioned, the strength values derived from EN 408:2010 are not adequate for typical structural applications and hence, a strength modification factor k_{cr} was introduced already in the first Amendment to Eurocode 5 (EN 1995-1-1:2004+A1:2008). This modification factor was supposed to account for the negative influence of cracks and the

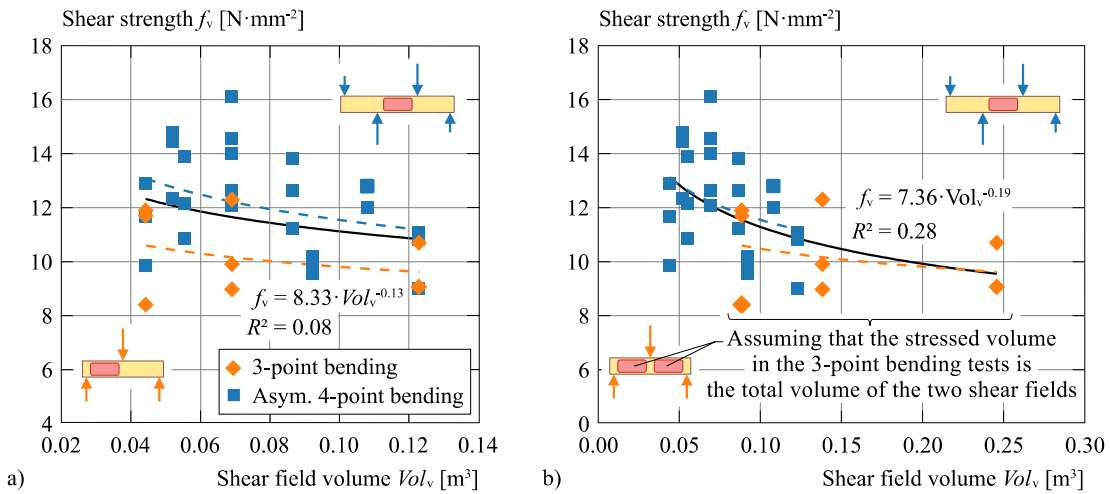


Fig. 15 Shear strength as a function of the shear field volume Vol_v observed in the 3-point bending and asymmetric 4-point bending tests on GLT made from European ash: **a** assuming that the shear field volume Vol_v in the 3-point bending tests is only that of the shear field that failed (i.e., $Vol_v = b \times h \times L_v$, Fig. 3); **b** assuming that the shear field volume Vol_v in the 3-point bending tests is the total volume of the two shear fields (i.e., $Vol_v = 2 \times b \times h \times L_v$)

recommended value was $k_{cr} = 0.67$. Since it was a "nationally determined parameter", countries were able to set their own values of k_{cr}, which led to widely varying approaches. During the systematic reviews of EN 1995-1-1 *Eurocode 5*, there were many comments and requests regarding clarification and harmonisation of k_{cr}, to discretise it into more well-defined factors accounting for the influence of specific parameters on the shear strength. The revised shear strength verifications in the latest draft of *Eurocode 5* (FprEN 1995-1-1:2024) include a modification factor k_{var} that allows to account for the influence of cracks and, in addition, a modification factor $k_{h,v}$ to account for volume-related effects on the 5%-percentile value of shear strength of softwood products. For softwood structural timber (EN 14081-1:2019), structural finger jointed timber (EN 15497:2014), and glued solid timber (EN 14080:2013), the prescribed modification factor is $1.0 < k_{h,v} = (150/h)^{0.2} < 1.3$, i.e. the reference beam height is $h_{ref} = 150$ mm and the exponent is $1/m = 0.2$. This latter value is based on 3-point bending tests on spruce beams with Ishaped cross-sections and $h_{web} < 300$ mm performed by Brandner et al. (2012). For softwood GLT (EN 14080:2013), the modification factor is $0.9 < k_{h,v} = (600/h)^{0.1} < 1.1$, i.e. the reference height is $h_{ref} = 600$ mm and the exponent is $1/m = 0.1$. For beech and ash GLT, the design guideline Lignatec 33/2021 prescribes a modification factor $(600/h)^{0.25} < 1.2$ to account for volume-related effects on the design value of shear strength, i.e. the same reference height $h_{ref} = 600$ mm, but a 2.5 times higher exponent $1/m = 0.25$. As mentioned before, this exponent $1/m = 0.25$ is approximately the average of the $1/m$ values determined from the 3– and asymmetric 4-point bending tests performed in this study.

4 Conclusion

The shear strength and stiffness of glued-laminated timber (GLT) made from European ash (*Fraxinus excelsior* L.), and the influence of the size of the tested specimens, was assessed based on a comprehensive experimental campaign. The experiments were performed on full-scale GLT beams with rectangular cross-sections $b \times h = 120 \times 48$-800 mm^2, shear lengths L_v = 720-1500 mm, and ratios between the shear length L_v and the beam height h of $\alpha = L_v/h = 1.2$-2.5. The influence of the test configuration (3-point bending and asymmetric 4-point bending) was also assessed.

The obtained shear strengths of European ash GLT beams had mean values $f_{v,mean} = 10.2$ N·mm^{-2} ($CoV_{fv} = 14\%$) and 12.2 N·mm^{-2} ($CoV_{fv} = 15\%$), for the 3-point and asymmetric 4-point bending test configurations, respectively. The shear strength showed some size dependency, with exponents $1/m = 0.2$ and 0.4 for a strength modification factor $(600/h)^{1/m}$ as a function of the beam height h, for the 3-point and asymmetric 4-point bending test configurations, respectively. Due to the observed coefficients of variation and limited number of replicas, the confidence intervals of these exponents are quite wide. In the asymmetric 4-point bending tests, a clear reduction of shear strength f_v was observed from $h = 600$ mm to 800 mm: $f_{v,h=600,mean} = 13.3$ N·mm^{-2} ($CoV_{fv,h=600} = 10\%$) and $f_{v,h=800,mean} = 10.1$ N·mm^{-2} ($CoV_{fv,h=800} = 8\%$).

Only shear failures occurred, and the failure cracks involved mostly timber, even though some failure cracks followed, for limited lengths, the glue lines. The shear modulus showed no size dependency, and the obtained mean values were $G_{mean} = 1162$ N·mm^{-2} ($CoV_G = 6\%$) and 1120 N·mm^{-2} ($CoV_G = 6\%$), for the 3-point and asymmetric 4-point bending tests, respectively.

From a production quality-control point of view, the simpler 3-point bending test configuration is adequate and provides all the necessary information for quality assessment. The asymmetric 4-point bending test allows for a broader range of geometric parameters, but it is also significantly more complicated to perform, so mostly appropriate for research. Reinforcement with glued-in steel rods is necessary to ensure a uniform shear field and to apply the required high forces perpendicular to the grain, in particular for hardwood GLT.

Since the bending properties are given for a reference beam height $h = 600$ mm (e.g. EN 14080:2013, SIA 265:2021), it makes sense to adopt this dimension as the reference height, i.e. $h_{ref} = 600$ mm, also for shear properties.

Acknowledgements The authors gratefully acknowledge the financial support from the *Wald- und Holzforschungsförderung Schweiz* (WHFF-CH) of the Swiss *Bundesamt für Umwelt* (BAFU) (Federal Office for the Environment) and of the Swiss Cantons.

Author contributions Pedro Palma planned and carried out the experiments, performed the data analyses, and prepared the article.René Steiger obtained the funding, planned and carried out experiments, and supervised the project.Thomas Strahm designed and produced the test specimens.Ernest Gehri conceived the original idea and supervised the project.All authors reviewed the article.

Funding Open Access funding provided by Lib4RI – Library for the Research Institutes within the ETH Domain: Eawag, Empa, PSI & WSL.

Data availability No datasets were generated or analysed during the current study.

Declarations

Conflict of interest The authors declare no competing interests.

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