World Conference on
Timber Engineering
Oslo 2023

SHEAR TESTS ON FULL-SCALE EUROPEAN ASH GLUED LAMINATED TIMBER BEAMS

Pedro Palma [1] , René Steiger [2] , Thomas Strahm [3] , and Ernst Gehri [4]

ABSTRACT: The influence of volume 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 $b \times h = 120 \times 480$ - $800\ \text{mm}^2$, shear lengths $L_v = 720$ - 1500 mm, and shear length/height ratios $\alpha = L_v/h = 1.2$ - 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 had mean values $f_{v,\text{mean}} = 10.2$ ($CoV_{fv} = 14\%$) and $12.2\ \text{N}\cdot\text{mm}^{-2}$ ($CoV_{fv} = 15\%$), for the 3-point and asymmetric 4-point bending test configurations. The shear strength showed some size dependency, with $k = 0.2$-0.4 for a strength modification factor $(h/600)^{-k}$ as a function of the beam height h.

KEYWORDS: shear strength, shear modulus, glued laminated timber, hardwood, experimental research, size effect

1 INTRODUCTION

1.1 BACKGROUND

The determination of shear properties, namely shear modulus G and shear strength f_v, is a decade-long discussion [1–8]. In the ongoing revision of EN 1995-1-1:2004 *Eurocode 5* [9], the determination of shear strength has also been under active discussion, namely 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. [10], the main issues in the determination of the shear strength parallel to the grain are the: i) influence of perpendicular-to-the-grain stresses; ii) influence of volume- and geometry related parameters and; iii) the incidence of unrelated failure modes.

Regarding the influence of perpendicular-to-the-grain stresses, the presence of tensile perpendicular-to-the-grain tensile stresses reduces the shear strength, whereas the presence of low perpendicular-to-the-grain compressive stresses increases (or at least it does not decrease) the shear strength [11,12]. Most of these tests, however, were carried out on small clear specimens [13]. The incidence of unrelated failure modes, namely in bending and compression perpendicular-to-the-grain arises mostly in tests on large-scale specimens and is due to the test and load-application configurations. Finally, the influence of volume-related parameters arises from shear being a brittle failure mode and, therefore, dependent on the theoretical higher probability of a strength-reducing feature occurring in a larger stressed volume [8].

1.2 FULL-SCALE BEAM TESTS

Previous studies have concluded that realistic values of shear strength cannot be based on tests on small-scale specimens, such as those prescribed by EN 408:2010 [14], but should instead be based on full-scale beam tests [5,15–18]. Shear failures are brittle and, therefore, the shear strength depends on the stressed volume. In this cases, it is common to relate the strength to a reference volume V_{ref} (or dimension) in the form of a power law $(V/V_{\text{ref}})^{-k}$. 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 reality. 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 and at a certain point they were even included in the draft amendment to EN 408:2007/prA1:2007 [19], even though they were finally not adopted. 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 [17] proposed the test configuration in Figure 1. This configuration comprises a simple three-point bending test and a beam with 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),

---

[1] Pedro Palma, Empa, Structural Engineering Research Lab, Switzerland, pedro.palma@empa.ch.

[2] René Steiger, Empa, Structural Engineering Research Lab, Switzerland.

[3] Thomas Strahm, neue Holzbau AG, Lungern, Switzerland.

[4] Ernst Gehri, Prof. emeritus ETH Zürich, Dr. h. c., Switzerland.

https://doi.org/10.52202/069179-0018

namely the GSA® system developed by *neue Holzbau* AG, and not through "conventional" compressive perpendicular-to-the-grain stresses [7]. Since the shear strength of hardwood is higher than that of softwood glued laminated timber (GLT), the requirements for the load-transfer system are also higher, otherwise the shear strength of hardwood could not be captured experimentally. The shear fields proposed by Gehri [17] have a ratio $\alpha = L_v/h = 1.75$, avoiding the bending failures that come with high values of α and still remaining within the classical beam theory with $\alpha > 1.5$.

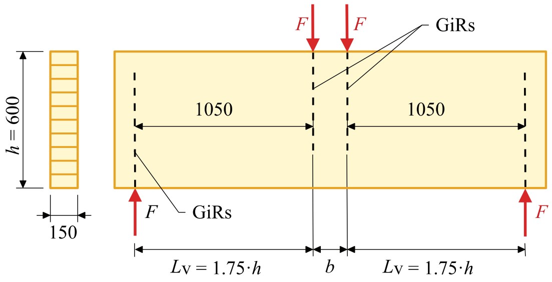

Figure 1: *Three point bending tests configuration proposed by Gehri [17] (dimensions in mm, drawing not to scale).*

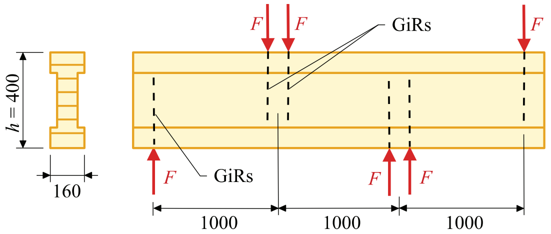

Figure 2: *Asymmetric four point bending tests performed by Ehrhart et al. [10] for the determination of shear properties (dimensions in mm, drawing not to scale).*

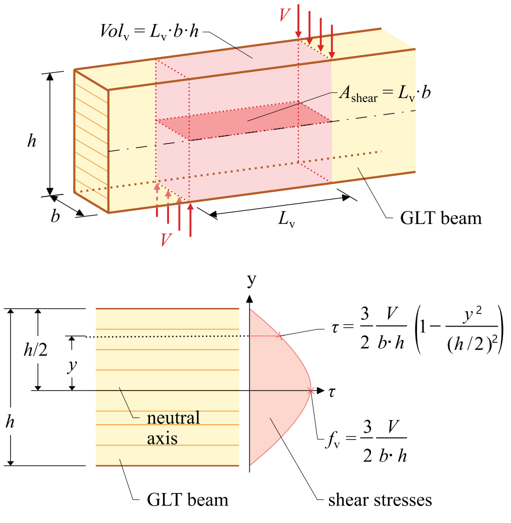

Figure 3: *Geometric parameters and distribution of shear stresses.*

Ehrhart et al. [10] performed shear tests on beams with an I-shaped cross section under an asymmetric four-point bending configuration, based on a test configuration developed by Basler et al. [20], (Figure 2). In comparison with 3-point bending 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.

For structural engineering practice, the values of shear strength must be adjusted for the actual climatic and loading conditions and geometry of the structural member. It is therefore of interest to study the influence of geometric parameters on the shear strength (Figure 3), namely those that are easily available to the designer, since the shear strength of GLT is not correlated (or slightly negatively correlated) to the strength classes (EN 14080:2013) [21]. The most straightforward parameter is the beam height h, since the volume under the higher shear stresses around the neutral axis is correlated to the beam height. The shear length L_v is also a parameter of interest, since it is proportional to the shear crack area (Figure 3).

In addition, the volume of the shear field Vol_v is a relevant parameter (Figure 3), but it is not always easy to determine, since it depends on the loading configuration and might be disturbed by perpendicular-to-the-grain stresses. Therefore, test configurations should ensure that shear stresses are as constant as possible over the entire shear field, without significant perpendicular-to-the-grain stresses. This is possible if the applied forces are introduced using GiRs, as mentioned above and described in detail by Steiger and Gehri [7].

1.3 OBJECTIVES AND SCOPE

The objectives of the study presented in this paper were to:

- obtain knowledge on the influence of the member size (geometrical parameters) and of the test configuration on the shear strength of hardwood (European ash) GLT and of a small sample of softwood (Norway spruce);
- 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 GLT production (where simple test set-ups are required);
- define the reference dimensions for cross-sections that meet the requirements for the two abovementioned fields of application;
- propose simple relationships to account for size effects in design standards (SIA 265:2021 and EN 1995-1-1:2004).

The experimental research presented in this paper was conducted on full-scale glued laminated timber (GLT) beams made of European ash (*Fraxinus excelsior* L.). For comparison purposes, tests were also performed on GLT made of Norway spruce (*Picea abies* (L.) H. Karst.).

https://doi.org/10.52202/069179-0018

2 EXPERIMENTAL RESEARCH

2.1 THREE-POINT BENDING TESTS ON ASH GLT

2.1.1 Materials and methods

The 3-point bending tests on European ash (*Fraxinus excelsior* L.) GLT beams (Figure 4 and Table 1) were performed at the Structural Engineering Research Lab of Empa (Switzerland). The test specimens were made from European ash GLT of strength class GL48c "special", with T33 laminations and three T50 outer laminations, without finger joints, in the tension zone. The mean density of the test specimens was $\rho_{\mathrm{mean}} = 640\ \mathrm{kg\cdot m^{-3}}$ (coefficient of variation $CoV_\rho = 3\%$) at an average moisture content $\omega_{\mathrm{mean}} = 10\%$. The load-application zones were reinforced with GiRs (GSA® system).

The tests were performed under force control. 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 $f_v = 3/2\cdot F/(b\cdot h)$.

2.1.2 Results

The results of the 3-point bending tests on European ash GLT are presented in Table 2 and Figure 5. The mean shear modulus was $G_{\mathrm{mean}} = 1162\ \mathrm{N\cdot mm^{-2}}$ ($CoV_G = 6\%$) and showed no size dependency. The global mean shear strength was $f_{v,\mathrm{mean}} = 10.2\ \mathrm{N\cdot mm^{-2}}$ ($CoV_{fv} = 14\%$). 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 the equivalent Norway spruce GLT beams. The shear strength can be described as a function of the beam height h by

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

The position of the longitudinal shear cracks in the beam height was above the neutral axis in approximately 70% of the tests and below the neutral axis in approximately 30% of the tests [22].

For beam heights $h = 480$ and 600 mm, the shear cracks occurred within 25% of the beam height 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 15 and 20% of the beam height above and below the neutral

***Table 1:** Three point bending tests on European ash GLT: geometry of test specimens and test configuration.*

		Cross-section		Shear field		
Test configuration	Width	Height	Length	Ratio $\alpha = L_v/h$	Area	Vol.
	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	92160	0.044
ES-2.1 (*n*=3)	120	600	960	1.6	115200	0.069
ES-3.1 (*n*=3)	120	800	1280	1.6	153600	0.123

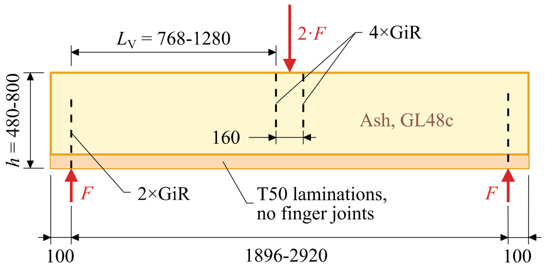

***Figure 4:** Three-point bending tests on European ash GLT: geometry of test specimens and test configuration (dimensions in mm, drawing not to scale).*

***Table 2:** Three point bending tests on European ash GLT: geometry of test specimens and test configuration.*

Test configuration		Shear modulus		Shear strength	
		G_{mean}	CoV	$f_{v,\mathrm{mean}}$	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*=12)	1162	15%	10.2	14%

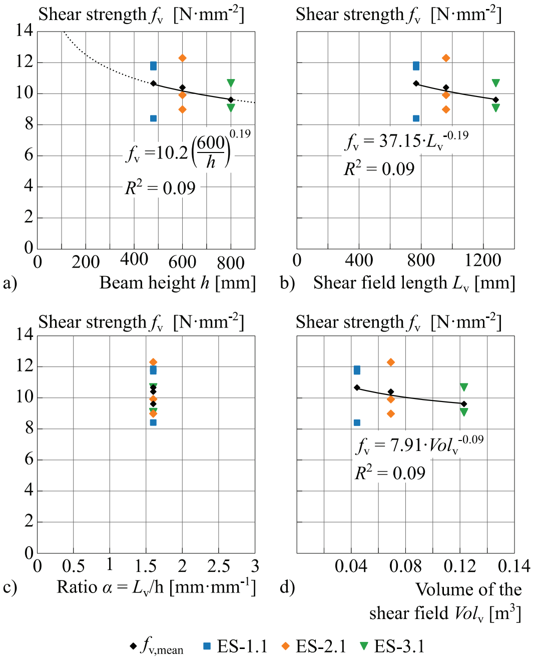

***Figure 5:** Results of the 3-point bending tests on Norway spruce GLT – shear strength f_v as a function of the: a) beam height h; b) length of the shear field L_v; c) ratio $\alpha=L_v/h$; and d) volume of the shear field Vol_v.*

axis, respectively, which corresponds to shear stresses higher than $0.84\cdot\tau_{\max}$, with $\tau_{\max} = 1.5\cdot V/(b\cdot h)$. The mean maximum bending stresses reached when the shear failures occurred were $\sigma_{\mathrm{m,max,mean}} = 70.9$ N·mm^{-2} ($CoV_{\sigma\max} = 15\%$) and no bending failures happened.

2.2 ASYMETRIC 4-POINT BENDING TESTS ON EUROPEAN ASH GLT

2.2.1 Materials and methods

The asymmetric 4-point bending tests on European ash (*Fraxinus excelsior* L.) GLT beams were also performed at the Structural Engineering Research Lab of Empa. The test specimens (Figure 6 and Table 3) were made from ash GLT of strength class GL40c, except test specimens ES-2.5, which were made from ash GLT of strength class GL48c "special", with T33 inner laminations and three T50 outer laminations, without finger joints, in the tension zones. The mean density of the test specimens was $\rho_{\mathrm{mean}} = 664$ kg·m^{-3} ($CoV_{\rho} = 3\%$) at an average moisture content $\omega_{\mathrm{mean}} = 10\%$. The load-application zones were reinforced with GiRs (GSA® system).

The tests were performed under force control. This test configuration was more difficult to implement, namely 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 $f_v = 3/2\cdot(F_1\text{-}F_2)/(b\cdot h)$ (see Figure 6).

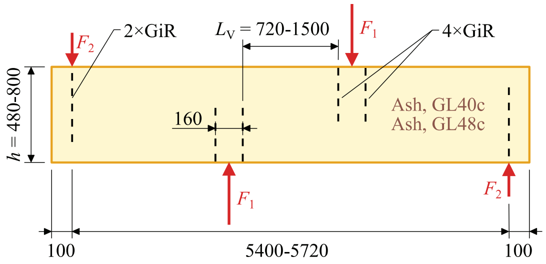

Figure 6: *Asymmetric 4-point bending tests on European ash GLT: geometry of test specimens and test configuration (dimensions in mm, drawing not to scale).*

Table 3: *Three point bending tests on European ash GLT: geometry of test specimens and test configuration.*

	Cross-section		Shear field			
Test configuration	Width b [mm]	Height h [mm]	Length L_v [mm]	Ratio $\alpha = L_v/h$ α [ ]	Area A_{shear} [mm^2]	Vol. Vol_v [m^3]
ES-1.3 (*n*=3)	120	480	768	1.6	92160	0.044
ES-1.4 (*n*=3)	120	480	960	2.0	115200	0.055
ES-2.2 (*n*=3)	120	600	720	1.2	86400	0.052
ES-2.3 (*n*=5)	120	600	960	1.6	115200	0.069
ES-2.4 (*n*=3)	120	600	1200	2.0	144000	0.086
ES-2.5 (*n*=3)	120	600	1500	2.5	180000	0.108
ES-3.2 (*n*=3)	120	800	960	1.2	115200	0.092
ES-3.3 (*n*=3)	120	800	1280	1.6	153600	0.123

2.2.2 Results

The results of the asymmetric 4-point bending tests on European ash GLT are presented in Table 4 and Figure 7. The mean shear modulus was $G_{\mathrm{mean}} = 1120$ N·mm^{-2} ($CoV_G = 6\%$) and showed no size dependency. The global mean shear strength was $f_{\mathrm{v,mean}} = 12.2$ N·mm^{-2} ($CoV_{f\mathrm{v}} = 15\%$). 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 the equivalent Norway spruce GLT beams. The shear strength can be described as a function of the beam height h by

$$f_v = 34\cdot h^{-0.37} = 12.2\left(\frac{600}{h}\right)^{0.37}. \qquad (2)$$

The position of the longitudinal shear cracks in the beam height was above the neutral axis in approximately 60% of the tests and below the neutral axis in approximately 40% of the tests [22]. All but one shear crack occurred within ±20% of the beam height from the neutral axis, which corresponds to shear stresses higher than $0.84\cdot\tau_{\max}$, with $\tau_{\max} = 1.5\cdot V/(b\cdot h)$

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

3 DISCUSSION AND CONCLUSIONS

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. The asymmetric 4-point bending test allows for a broader range of geometric parameters, namely higher $\alpha = L_v/h$ 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 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 160×800 mm^2 for Norway spruce GLT and 120×800 mm^2 for European ash GLT, but the applied forces are quite high (up to 550 and 1150 kN, respectively). Since the bending properties

Table 4: *Asymmetric 4-point bending tests on European ash GLT: geometry of test specimens and test configuration.*

Test configuration		Shear modulus G_{mean} [N·mm^{-2}]	CoV [ ]	Shear strength $f_{\mathrm{v,mean}}$ [N·mm^{-2}]	CoV [ ]
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%

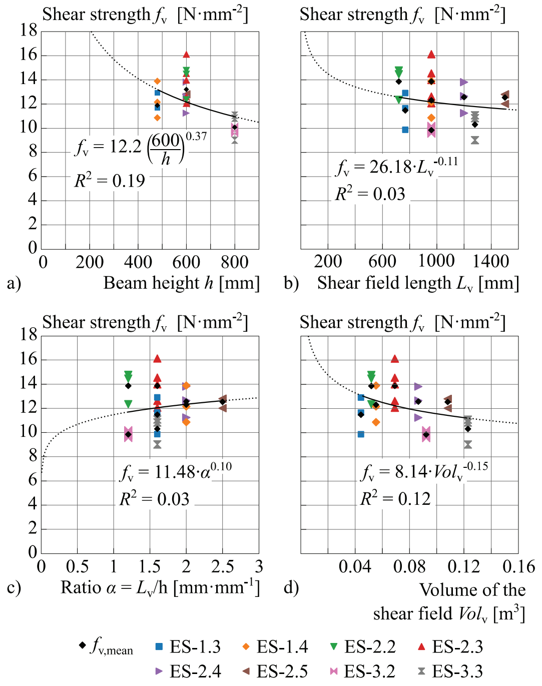

Figure 7: *Results of the asymmetric 4-point bending tests on European ash GLT – shear strength f_v as a function of the: a) beam height h; b) length of the shear field L_v; c) ratio $\alpha = L_v/h$; and d) volume of the shear field Vol_v.*

Table 5: *Shear strengths in the 3-point bending tests on Norway spruce GLT, 3-point bending tests on European ash GLT, and asymmetric 4-point bending tests on ash GLT.*

Test config.	Mean value $f_{\mathrm{v,mean}}$ [N·mm^{-2}]	Coef. of variation $CoV(f_v)$ [ ]	5%-percentile $f_{\mathrm{v,mean}}$ [N·mm^{-2}]	$f_{\mathrm{v,mean}}$ [N·mm^{-2}]	$f_{\mathrm{v,mean}}$ [N·mm^{-2}]
FI-3P	4.0	19%	3.2	2.6	2.9
ES-3P	10.2	14%	8.6	7.6	8.0
ES-4P	12.2	15%	9.6	8.8	9.5

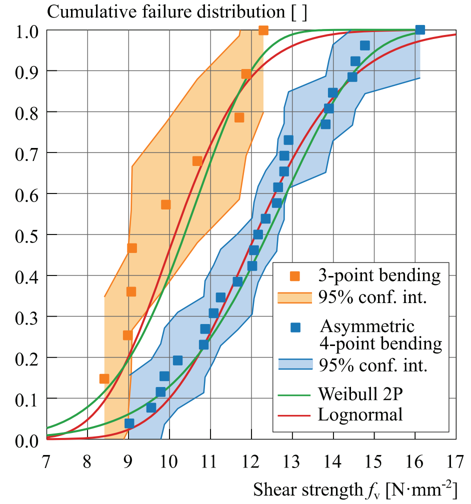

Figure 8: *Cumulative failure distributions of the shear strength in the 3-point bending tests on Norway spruce GLT, 3-point bending tests on European ash GLT, and asymmetric 4-point bending tests on ash GLT.*

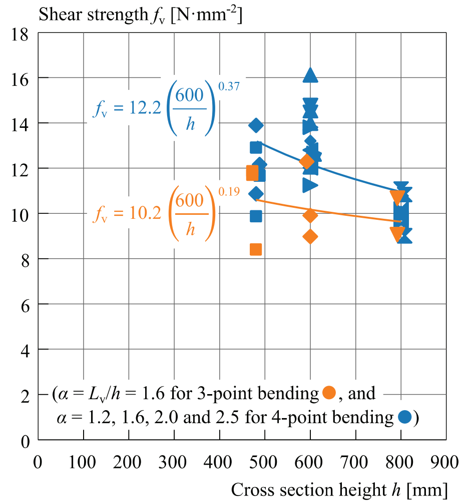

Figure 9: *Shear strength as a function of the beam height h of the cross section for the 3-point bending tests on Norway spruce GLT, 3-point bending tests on European ash GLT, and 4-point bending tests on ash GLT.*

are given for a reference beam height $h = 600$ mm (e.g. EN 14080:2013 [21], SIA 265:2021 [23]), it makes sense to adopt this dimension as the reference height, i.e. $h_{\text{ref}} = 600$ mm, also for the shear properties.

3.3 Shear modulus *G*

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 $\alpha = L_v/h$. The obtained mean values were $G_{\text{mean}} = 1162$ (CoV 6%) and 1120 N·mm^{-2} (CoV 6%), for the 3-point and asymmetric 4-point bending tests, respectively. This is in good agreement with the value $G_{\text{mean}} = 1000\ \text{N·mm}^{-2}$ specified in the publication Lignatec 33/2021 [24], which had been issued recently in Switzerland, to disseminate results from research projects on the use of hardwood in design practice.

3.4 Shear strength f_v

The obtained shear strengths of European ash GLT had mean values $f_{v,\text{mean}} = 10.2$ (CoV 14%) and 12.2 N·mm^{-2} (CoV 15%), for the 3-point and asymmetric 4-point bending tests, respectively (Figure 8 and Table 5). For Norway spruce, the corresponding value determined in 3-point bending tests was $f_{v,\text{mean}} = 4.0\ \text{N·mm}^{-2}$ ($CoV_{fv} = 19\%$) [22]. The test configuration showed a marked influence on the shear strength and on the position of the failures cracks. Failure cracks in the 4-point bending tests were evenly distributed within $\pm 0.2 \cdot h$ from the neutral axis, whereas in the 3-point bending tests the failure cracks occurred mostly within $0.25 \cdot h$ above the neutral axis.

The shear strength also showed some size dependency (obtained strength modification factors are presented in Figure 9), even though not as evident as in the preliminary tests on Norway spruce GLT. The exponent k of the strength modification factor $(h/600)^{-k}$ for the 3- and asymmetric 4-point bending tests is $k = 0.19$ and 0.37, respectively. The latter is close to the value $k = 0.4$ proposed by Ehrhart et. al. [10] for European beech (*Fagus sylvatica*) GLT, but that was based on 3-point bending tests on beams with I-shaped cross sections and $h_{\text{web}} < 240$ mm. The publication Lignatec 33/2021 [24] specifies a value of $k = 0.25$ for beech and ash GLT, which is approximately the average of the k values determined in the 3– and asymmetric 4-point bending tests. The same publication, for European beech and European ash, also specifies a conservative reference design shear strength $f_{v,d} = 3.2\ \text{N·mm}^{-2}$ for $h = 600$ mm and all strength classes.

3.5 Size effects in design standards

In Eurocode 5 (EN 1995-1-1:2004 [9]), the design shear strength is based on the characteristic 5th-percentile values derived from tests according to EN 408:2010 [14] and prescribed, e.g. for softwood GLT, in EN 14080:2013 [21] as $f_{v,g,k} = 3.5\ \text{N·mm}^{-2}$ for all strength classes. As already mentioned, the strength values derived from EN 408:2010 [14] 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) [25]. This modification factor was supposed to account for the negative influence of "cracks" and the recommended value was $k_{\text{cr}} = 0.67$. 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}, namely to discretise it into more well-defined factors accounting for the influence of specific parameters on the shear strength. A revision of the verification of shear strength is ongoing within Working Group 3 of CEN/TC 250/SC 5 *Eurocode 5: Design of timber structures*. The latest draft of the revised verifications [26] includes a modification factor $k_{h,v}$ to account for the effect of size on the shear strength of softwood GLT that is a function of $(600/h)^{-0.2}$, i.e. sets $k_{h,v} = 0.2$ as proposed by Brandner et. al. [8] (based on 3-point bending tests on spruce beams with I-shaped cross sections and $h_{\text{web}} < 300$ mm). That value is in good agreement with the value $k = 0.19$ determined in the 3-point bending tests on ash GLT. In the latest draft of prEN 1995-1-1 [26], the influence of cracks on the shear strength may still be accounted for by means of a specific factor k_{var}.

ACKNOWLEDGEMENT

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

REFERENCES

[1] R. Foschi, J. Barrett, Consideration of size effects and longitudinal shear strength for uncracked beams, in: Proc. CIB-W18 Meet. 13, Otaniemi, Finland, 1980: pp. 13-6–2, 9 p.

[2] B. Madsen, Shear strength of Douglas Fir timbers, in: Proc. CIB-W18 Meet. 28, Copenhagen, Denmark, 1995: pp. 28-6–2, 37 p.

[3] F. Lam, H. Yee, J.D. Barrett, Shear strength of Canadian softwood structural lumber, Can. J. Civ. Eng. 24 (1997) 419–430. https://doi.org/10.1139/l96-119.

[4] D. Riyanto, R. Gupta, A comparison of test methods for evaluating shear strength of structural lumber, For. Prod. J. 48 (1998) 83–90.

[5] B. Yeh, T. Williamson, Evaluation of glulam shear strength using a full-size four-point test method, in: Proc. CIB-W18 Meet. 34, Venice, Italy, 2001: pp. 34-12–2, 13 p.

[6] R. Brandner, E. Gehri, T. Bogensperger, G. Schickhofer, Determination of modulus of shear and elasticity of glued laminated timber and related

examinations, in: Proc. CIB-W18 Meet. 40, Bled, Slovenia, 2007.

[7] R. Steiger, E. Gehri, Interaction of shear stresses and stresses perpendicular to the grain, in: Proc. CIB-W18 Meet. 44, Alghero, Italy, 2011: pp. 44-6–2, 14 p.

[8] R. Brandner, W. Gatternig, G. Schickhofer, Determination of shear strength of structural and glued laminated timber, in: Proc. CIB-W18 Meet. 45, CIB, Växjö, Sweden, 2012: pp. 45-12–2, 16 p.

[9] EN 1995-1-1:2004. Eurocode 5: Design of timber structures – Part 1-1: General – Common rules and rules for buildings, European Committee for Standardization (CEN), Brussels, 2004.

[10] T. Ehrhart, R. Steiger, M. Lehmann, A. Frangi, European beech (Fagus sylvatica L.) glued laminated timber: Lamination strength grading, production and mechanical properties, Eur. J. Wood Wood Prod. 78 (2020) 971–984. https://doi.org/10.1007/s00107-020-01545-6.

[11] H.-L. Mistler, Die Tragfähigkeit des am Endauflager unten rechtwinklig ausgeklinkten Brettschichtträgers, Technische Hochschule Karlsruhe, Karlsruhe, Germany, 1979.

[12] R. Spengler, Festigkeitsverhalten von Brettschichtholz unter zweiachsiger Beanspruchung - Teil 1 - Ermittlung des Festigkeitsverhaltens von Brettelementen aus Fichte durch Versuche, 1982.

[13] C. Sandhaas, Mechanical behaviour of timber joints with slotted-in steel plates, Doctoral thesis, Delft University of Technology (TU Delft), 2012.

[14] EN 408:2010+A1:2012. Timber structures. Structural timber and glued laminated timber. Determination of some physical and mechanical properties, European Committee for Standardization (CEN), Brussels, 2012.

[15] G. Schickhofer, Evaluation of glulam shear strength using a full-size four-point test method, in: Proc. CIB-W18 Meet. 34, Venice, Italy, 2001: pp. 34-12–6, 383–409.

[16] W. Klöck, Statistical analysis of the shear strength of glued laminated timber based on full-size flexure tests, Otto-Graf-J. 16 (2005) 225–244.

[17] E. Gehri, Shear problems in timber engineering – Analysis and solutions, in: Proc. 11th World Conf. Timber Eng. WCTE2010, Trentino, Italy, 2010: p. 6.

[18] S. Aicher, D. Ohnesorge, Shear strength of glued laminated timber made from European beech timber, Eur. J. Wood Wood Prod. 69 (2011) 143–154. https://doi.org/10.1007/s00107-009-0399-9.

[19] EN 408:2007/prA1:2007. Timber structures. Structural timber and glued laminated timber. Determination of some physical and mechanical properties, European Committee for Standardization (CEN), Brussels, 2007.

[20] K. Basler, B.-T. Yen, J.A. Mueller, B. Thürlimann, Web buckling tests on welded plate girders., Fritz Engineering Laboratory, Lehigh University, 1960.

[21] EN 14080:2013. Timber structures – Glued laminated timber and glued solid timber – Requirements, European Committee for Standardization (CEN), Brussels, 2013.

[22] P. Palma, R. Steiger, T. Strahm, E. Gehri, Shear stiffness and strength of European ash glued laminated timber, in: Int. Netw. Timber Eng. Res. INTER – Meet. Fifty-Five, Timber Scientific Publishing, Bad Aibling, Germany, 2022: pp. 225–241.

[23] SIA 265:2021. Holzbau, Schweizerischer Ingenieur- und Architektenverein (SIA), Zürich, 2021.

[24] Lignatec 33/2021. Verklebte Laubholzprodukte für den statischen Einsatz, Lignum, Holzwirtschaft Schweiz, Zürich, Schweiz, 2021.

[25] EN 1995-1-1:2004/A1:2008. Eurocode 5: Design of timber structures – Part 1-1: General – Common rules and rules for buildings, European Committee for Standardization (CEN), Brussels, 2008.

[26] F. Kupferle, CEN/TC 250/SC 5/WG 3 N 388. Revised INF ENQ Draft clauses: Verification of shear strength., (2022).