Glued Laminated Timber: Shear Test of Gluelines

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Abstract

Shear tests of bondlines are required for quality control measures carried out in glulam plants. The test procedures are typically described in more than one standard. In most of the standards the method of applying shear stress to the glueline is only given by a single schematic scheme. The actual construction of the test equipment as well as the procedure of testing influences the resulting stress in the bondline. The acting stress is not pure shear but rather a combination of shear and normal stresses. In cases where the acting shear stress and tensile stress perpendicular to the grain are simultaneous, the shear strength values can drop dramatically, whereas compression stresses perpendicular to the grain lead to an overestimation of the shear strength of the bondline. This paper gives an overview of existing methods for block shear testing of wood. Starting from an explanation of the multiaxial stress situation by static equilibrium analysis, parameters are identified which influence the test results. To avoid the statically indeterminate loading situation, a prototype of a shear test device has been developed aimed at ensuring a clearly defined state of shear loading of the specimens. Extensive test results on the comparison of the prototype device with the established one, in terms of shear strengths and percentages of wood failure, are presented and discussed.

Introduction

Shear tests of the bondlines are required for quality control purposes in glulam plants. The test procedures are given in various standards [e.g., EN 392:1995 (CEN 1995a), ASTM D 905-03:2003 (ASTM 2003), and ISO 12579:2006 (ISO 2006)]. In the EN and ISO standards 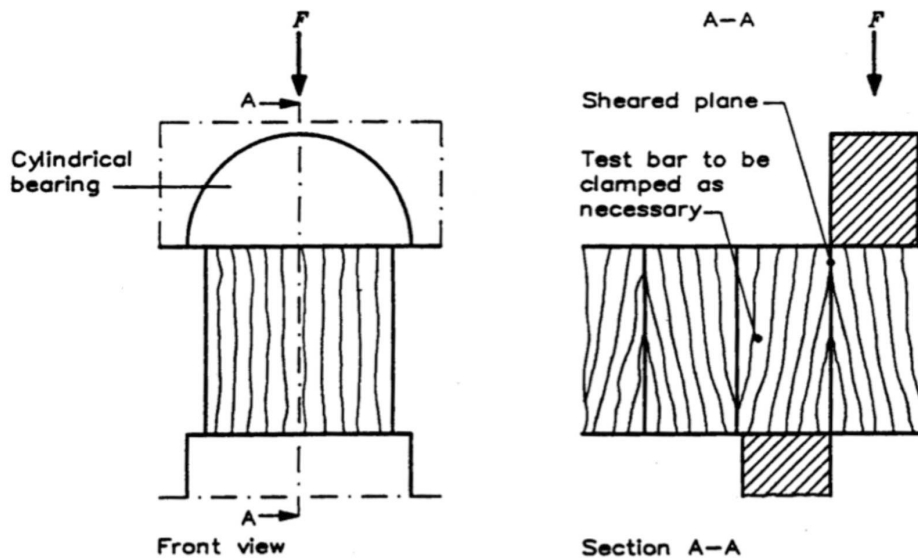the method of applying shear stress to the glueline is only described with a single schematic (**Fig. 1**). On the basis of this schematic, a variety of test equipment has been produced and is used by laboratories, glulam manufacturers, and producers of adhesives.

Depending on the actual construction of the test equipment as well as the procedure of testing, the resulting stress in the bondline is neither uniformly distributed nor pure shear but rather a combination of shear and normal stresses. Simultaneously acting shear stress and tensile stress perpendicular to the grain lead to a dramatic drop in shear strength. On the other hand, compression stresses perpendicular to the grain lead to an overestimation of the shear strength of the bondline. In the past, this test method did not test the capacity of the bondline correctly. However, this issue was addressed in several stages of the development of EN 392 [(CEN 1990) as an example] but has not been completely solved yet. To overcome this problem, a prototype of a shear test device was developed, which ensures a clearly defined state of shear loading on the specimens.

Block Shear Tests of Gluelines: Principles According to Different Standards

European Standards

In Europe the requirements for glued-laminated timber are given in the standard EN 14080:2005 (CEN 1995b). The bonding strength of bondlines shall be assessed as a bondline integrity test according to one of the test procedures defined in EN 386:2001 (CEN 2001). The EN 386:2001 asks for delamination tests according to EN 391:2001 and block shear tests according to EN 392:1995. The shear strength $f_{v,a}$ of each bondline shall be at least 6 N/mm². For coniferous wood, lower individual values of shear strength (down to 4 N/mm²) shall be regarded as acceptable if the wood failure reaches a certain percentage (**Table 1**).

Figure 1. ~ *Method of applying shear stress to a glueline according to EN 392:1995 (CEN 1995).*

Table 1. ~ *Minimum wood-failure percentages relating to the shear strength (EN 386:2001).*

	Average values			Individual values		
Shear strength $f_{v,a}$ [N/mm²]	6	8	$f_{v,a} \geq 11$	$4 \leq f_{v,a} < 6$	6	$f_{v,a} \geq 10$
Minimum wood failure percentage[†]	90%	72%	45%	100%	74%	20%

For values in between, linear interpolation shall be used.

[†]For average values the minimum wood failure percentage is: $144 - 9 \times f_{v,a}$.

For the individual values the minimum wood failure percentage for shear strengths $f_{v,a} \geq 6$ N/mm² is: $153.3 - 13.3 \times f_{v,a}$.

The block shear test is to be carried out according to EN 392:1995 (CEN 1995a). This standard is intended to be for continuous quality control of bondlines. The principle schematic for the shearing tool is given (**Fig. 1**): The shearing force shall be applied self-aligning via a cylindrical bearing so that the specimen is loaded at the end grain with a stress-field uniform in width direction and the distance between the glueline and the sheared plane nowhere exceeds 1 mm. The width b and the thickness t (in longitudinal direction) of the specimen shall be 40 to 50 mm each, with loaded surfaces to be smooth and parallel to each other as well as perpendicular to the grain direction.

The shear(ing) strength $f_{v,a}$ is derived from

$$f_{v,a} = k\frac{F_u}{A} \qquad [1]$$

with A = sheared area = $b \times t$, F_u = ultimate load and k being a modification factor for test pieces where the thickness in the grain direction of the sheared area is less than 50 mm.

American Standards

In the United States glulam producers follow quality control guidelines ANSI/AITC 190.1-2002 (AITC 2002) and ANSI/AITC 200-2004 (AITC 2004). Shear testing of gluelines is covered by AITC Test T107. Here, concerning shear block tests, reference is made to the American Standard ASTM D 905-03 (ASTM 2003). In Section 4.1, the ASTM D 905 standard makes the user aware of the fact that "this test method cannot be assumed to measure the true shear strength of the adhesive bond" because "many factors interfere or bias the measurement including the strength of the wood, the specimen, the shear tool design themselves, and the rate of loading". In Section 4.1.2, it is mentioned that "stress concentrations at the notches of the specimen tend to lower the measured strength". The shearing tool to be used shall have a self-aligning seat, ensuring uniform lateral distribution of the load. The shearing tool and the shape and the dimensions of the specimen are shown in **Fig. 2**. Shear strength of solid wood has to be derived following the rules of ASTM D 143 (ASTM 2000). Both test method are similar but they result in different apparent strengths due to differences in specimen shape and shear tool design (Okkonen and River 1989). ASTM D 143 uses single-notched specimens and a shear tool with 1/8-inch offset; ASTM D 905 uses double-notched specimens and a shear tool without an offset.

ISO Standards

Within the ISO standards series, ISO 12578 (ISO 2007) deals with the component performance and the requirements for the production of glulam. The formulations in this standard are quite similar to the European pendant EN 386:2001. In analogy to the latter, one possibility for controlling bondline integrity and strength is to perform block shear tests. Here reference is made to the standard ISO 12579 (ISO 2006). ISO 12579 provides a combination of rules and specimen types taken from EN 392 and ASTM D 905. Concerning the apparatus to be used for the shear tests, the standard provides only a schematic sketch similar to EN 392 (**Fig. 1**). In ISO 6238:2001 (ISO 2001) one can find an example of a shearing tool for
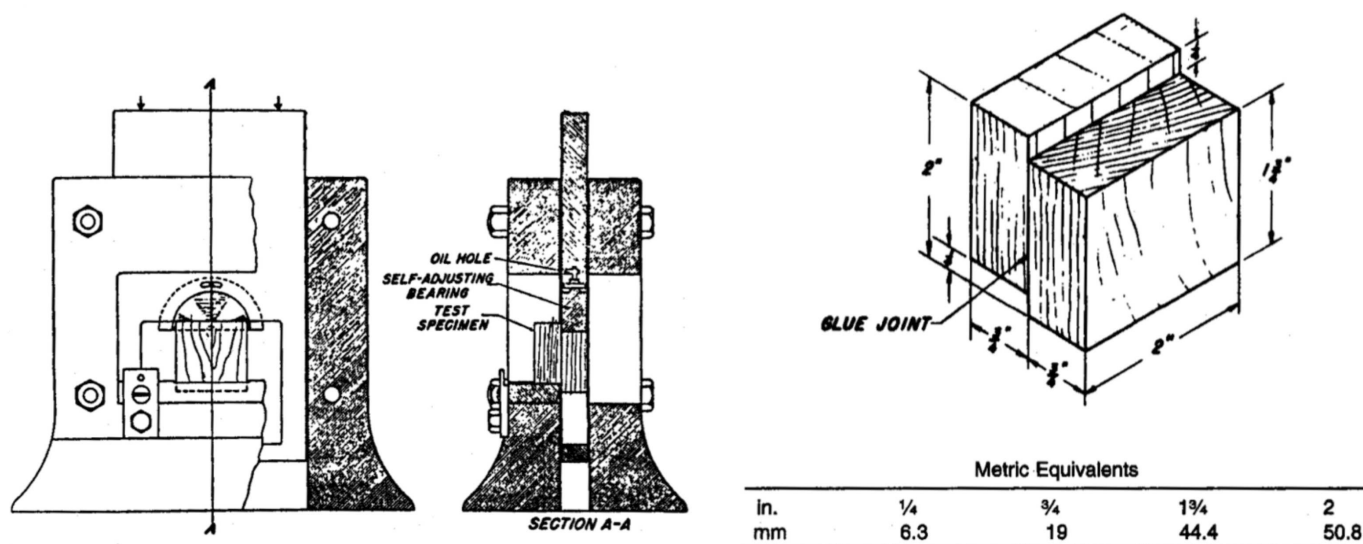
Figure 2. ~ *ASTM D 905-03 shearing tool and test specimen to derive shear strength of bondlines (ASTM 2003).*

compressive shear block tests being identical to the one shown in Fig. 6 of ASTM D 905-03.

Shortcomings of the Block Shear Test Method

The block shear test method has the advantage of being simple with regard to the preparation of the test specimen, the test equipment needed, the overall procedure, and the analysis of the test results. But nevertheless there are several shortcomings to be mentioned:

- The test method suffers from a non-uniform shear-stress distribution with a stress concentration near the corner, as was shown by experimental and theoretical stress analysis (Coker and Coleman 1935, Radcliffe and Suddarth 1955). Hence the derived shear strength using **Eq.** [**1**] is only nominal.

- The test results are influenced by the actual materialization of the principal sketch of EN 392 (**Fig. 1**) as well as by the person carrying out the test (see below). In **Figure 3**, as an example, three different types of test devices are shown. It can easily be seen that the way of applying forces and thus the resulting stress situation in the bondline differ.

- During the shear test, the specimen is subjected to a shear strain. Most of the existing shearing devices hinder this strain. This results in unknown side effects on the test results.

- Test results derived using different test devices cannot be compared directly. Strictly said, the method only serves the glulam producer as a kind of warning sign if the test values drop below a certain threshold.

Analysis of Static Equilibrium

The state of static equilibrium in specimens tested according to EN 392:1995 is shown in **Figure 4**. Being not aligned but rather eccentric (with a gap e depen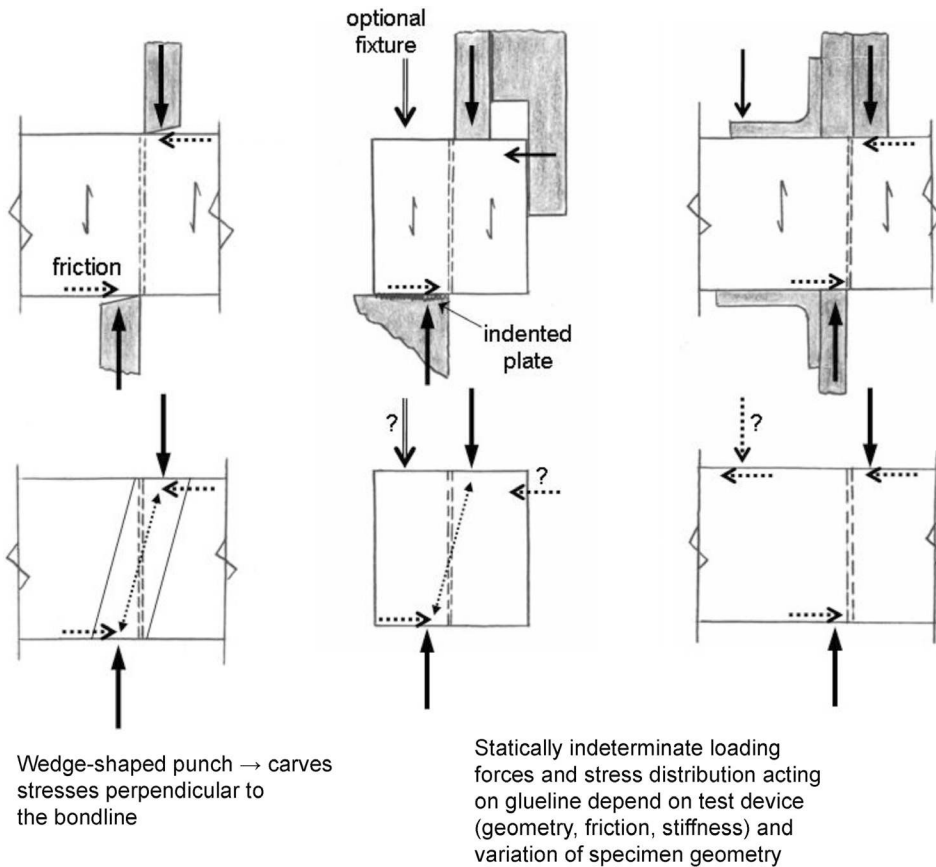ding on the dimensions of the stamps l_A of the actual test equipment) the acting shearing forces A_v cause a moment $A_v \times e$, which has to be compensated by a counteracting moment $h \times A_h$. Both the eccentricity e and the counteracting moment are indeterminate, depending on the actual shearing device.

Actually there is a state of compression at an angle to the grain: $(\alpha \approx \arctan (A_h/A_v) = \arctan (3/13.5) = 12.5°)$ and a counteracting moment is built up when the zone of maximum compression stress is deformed. The deformation leads to an uplift of the test bar. If the uplift is prevented, for example by holding down the test bar, significant bending stresses are added to the acting shearing stresses and the specimen tends to fail early at a low level of shear stress. This situation actually happened in a Swiss glulam plant, where the person responsible for the shear tests of gluelines retired and was replaced by another person. After this replacement there was a drop in test results. This drop could not be explained because there was no change in production parameters. Analyzing the situation in detail it was found that the new person was younger and more powerful than his predecessor, holding down the test bar with more power.
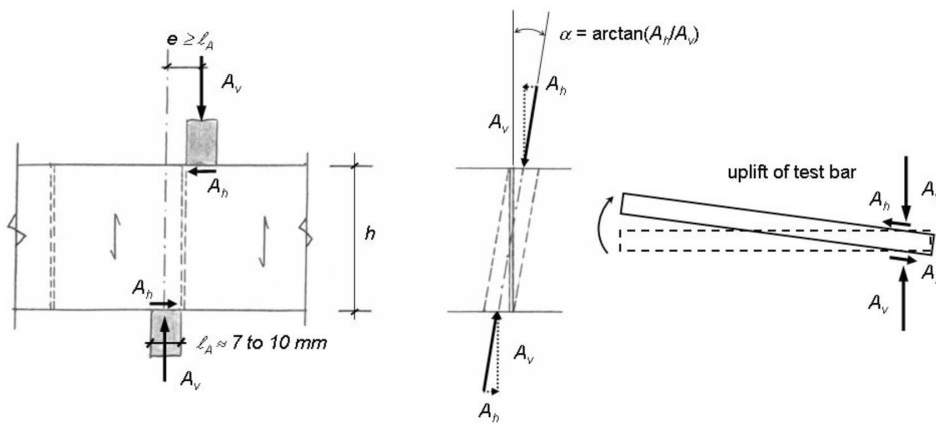
Optimized Block Shear Test

Approach

As it is well known and shortly summarized below, one can derive shear strength by carrying out compression tests not parallel to the grain but rather with a certain inclination. Panel shear-tests to derive shear-strength parallel to the grain according to EN 408:2003 (CEN 2003), for example are based on that. There, an oblique angle between the loading direction and the longitudinal axis of the specimen (which is actually the grain direction) of 14° is used. The procedure, however, is rather tedious and not suitable for the quality control of bondlines, since tapered steel plates have to be glued to the specimens. But the idea of carrying out a compression test at an oblique angle to the grain can be used to improve the block shear test method.

Figure 3. ~ *Three examples of shearing tools used by different labs and glulam producers.*

Wedge-shaped punch → carves stresses perpendicular to the bondline

Statically indeterminate loading forces and stress distribution acting on glueline depend on test device (geometry, friction, stiffness) and variation of specimen geometry

Figure 4. ~ *Static equilibrium in specimens tested according to EN 392:1995.*

Compression and Tension Stresses at an Angle to the Grain

Different angles α between loading directions and grain can be modeled, e.g., by the Hankinson-formula (Hankinson 1921), which was also found independently by Kollmann (1934) on the basis of scientific findings in crystal physics by Hörig (1931). However, the Hankinson formula does not provide any information on failure modes to be expected with varying angles α.
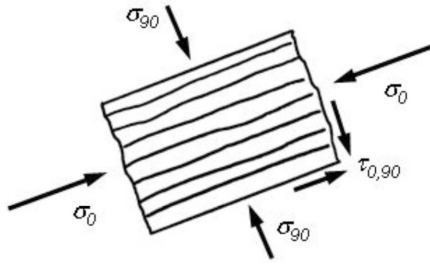
Stüssi (1946, 1949) showed that for isotropic materials, a relation between normal stresses σ and shear stresses τ is determined by stress equilibrium of a plane strain element subjected to a stress σ_α inclined by an angle α with reference to the grain direction. The principal stresses σ_1 and σ_2 are:
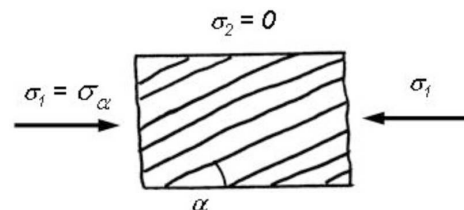
$$\sigma_1 = \sigma_\alpha \qquad\qquad [2]$$

$$\sigma_2 = 0 \qquad\qquad [3]$$

Respective stresses parallel and perpendicular to the grain and shear stresses can be calculated according to the theory of the strength of materials:

$$\sigma_0 = \sigma_\alpha \times \cos^2\alpha \qquad [4]$$

$$\sigma_{90} = \sigma_\alpha \times \sin^2\alpha \qquad [5]$$

$$\tau_{0,90} = \sigma_\alpha \times \cos\alpha \times \sin\alpha \qquad [6]$$

Depending on the actual angle α between the loading and the grain direction there are three different failure modes possible:

- Compression failure parallel to the grain:

$$\sigma_\alpha = \frac{\sigma_0}{\cos^2\alpha} \qquad [7]$$

- Shear failure:

$$\sigma_\alpha = \frac{\tau_{0,90}}{\sin\alpha \cdot \cos\alpha} \qquad [8]$$

- Compression failure perpendicular to the grain:

$$\sigma_\alpha = \frac{\sigma_{90}}{\sin^2\alpha} \qquad [9]$$

Solving Airy's stress function, Ylinen (1963) found that these formulas are valid for orthotropic materials as well. The dependency of compression strength from the angle between grain and load direction is shown in **Fig. 5**. It can be concluded that:

- The shear strength $f_{v,0,90}$ can be derived from compression tests at an oblique angle α to the grain based on **Eq.** [**8**]:

$$f_{v,0,90} = f_{c,\alpha} \times \cos\alpha \times \sin\alpha \qquad [10]$$

- Shear failures can to be expected for $\alpha_1 \leq \alpha \leq \alpha_2$ with $\alpha_1 \approx 13°$ and $\alpha_2 \approx 34°$. [Analyzing test results by Kraemer, Baumann, and Stüssi it can be shown, that this assumption is valid (Gehri and Steurer 1979)].

Prototype of a New Shearing Tool

Owing to the fact that high compression stresses perpendicular to the grain result in higher shear stresses, an angle α in the range of α_1 is to be preferred. In analogy to the EN 408:2003 rules (CEN 2003), for panel shear tests an angle α of 14° is chosen (**Fig. 6**, left), being equal to a slope of 1:4. Prototype tests and calculations showed that smaller slopes of e.g., 1:5 or 1:6, would not be possible since the specimens might be crushed due to exceeding compression stresses parallel to the grain in the loading zone. With a slope of 1:4 for coniferous specimens, shear strengths up to 10 to 12.5 N/mm^2 were recorded resulting in compression stresses parallel to the grain from 40 to 50 N/mm^2. When testing deciduous specimens this problem is even bigger since these species, with increasing
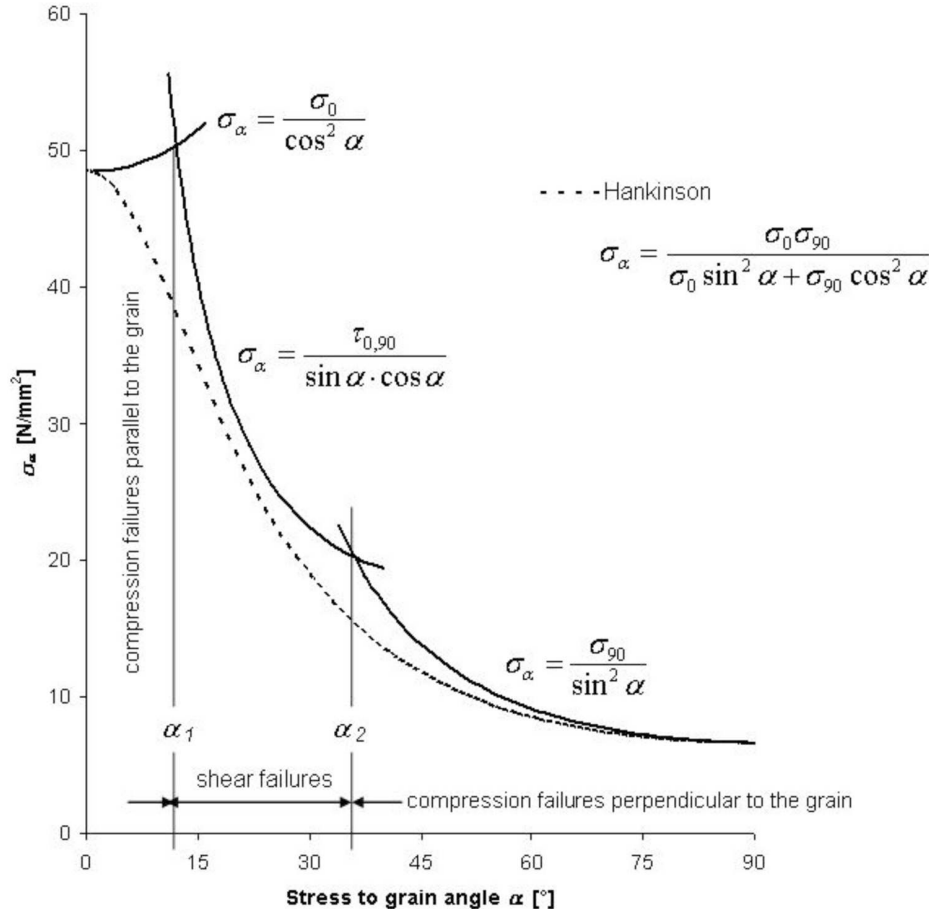
Figure 5. ~ *Influence of the angle between loading and grain direction on compression strength according to Stüssi (Stüssi 1946, Stüssi 1949).*

quality, show a stronger increase in shear strength than in compression strength parallel to the grain.

As is shown in **Fig. 6** (right) and experimentally proven (Keylwerth 1951), a shearing strain occurs during the shearing test. This shearing strain may not be hindered or blocked but rather be made possible. That is why the upper and the lower plungers are coupled to the loading parts by pivot bearings. To account for the specifications given by EN 392:1995 (cylindrical bearing, see Fig. 1) one of the plungers has a two-way pivot bearing.

Application of New Shearing Tool
Comparison of Existing and New Test Device

A test series was conducted to compare shear strengths and percentages of wood failure derived from tests with either the established device used at Empa or the new one (**Fig. 7**) (Steiger and Risi 2009).

Comparability of test results was made possible by testing pairs of edge bars and center bars taken from two slices cut from front ends of glulam beams directly after finishing the production in the glulam plant. Eight glulam producers supplied the test bars cut from three to four different glulam beams each. The bars contained 8 to 10 bondlines of different types of adhesives and had a cross-section of 50×50 mm^2. Due to geometrical restrictions when trimming the block shear specimens, not all bondlines could be tested. The actual sample sizes are reported in **Table 2.** In total, about 600 block shear tests were carried out in the course of the main test series.

The block shear specimens were tested to shear failure using either the established shear test device or the new

$$f_{v,a} = \frac{F_u \cos \alpha}{A}$$
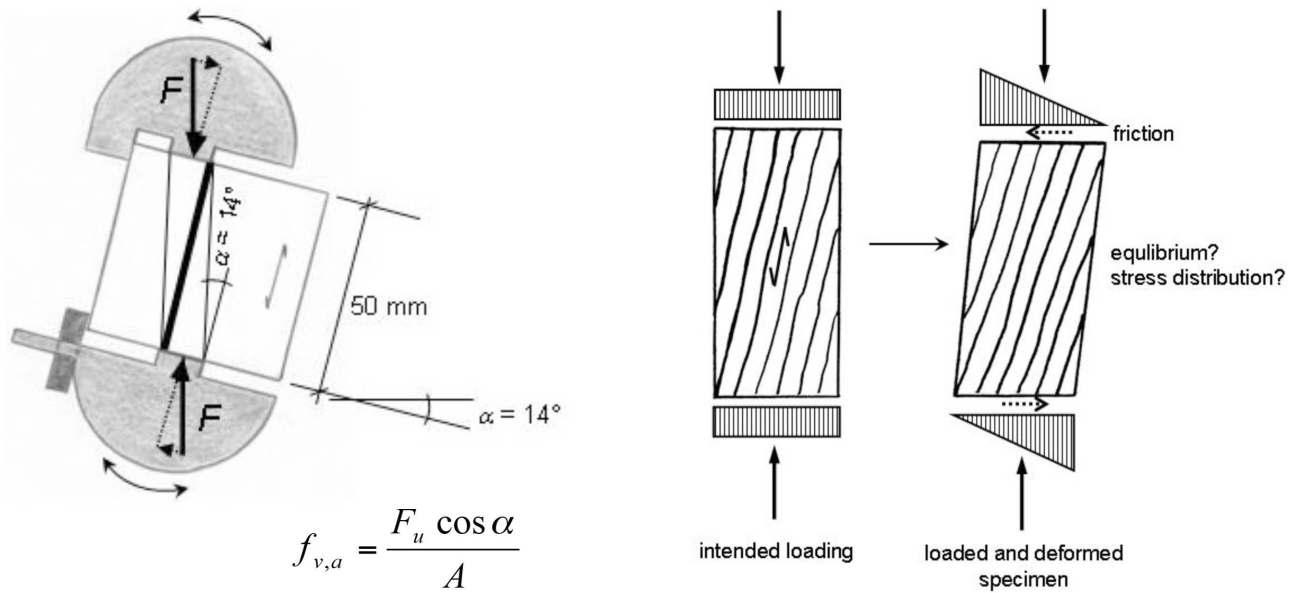
Figure 6. ~ *Loading scheme of the new shearing tool (left) and respective stress distribution in the specimen (right).*

Figure 7. ~ *EN 392 type shearing tool used at Empa (left), new test apparatus (center), close view of a specimen during testing with the new apparatus (right).*

Table 2. ~ *Properties of test specimens tested in the course of the main test series.*

Glulam producer	Adhesive†	Established device		New device		Glulam class¶
		Sample size	MC (%)‡	Sample size§	MC (%)‡	
A	RF	21		17 (4)		
	UF	18		18		
B	PUR	40		26 (14)		GL 24h
C	MUF	65		54 (11)		
D	PUR	38	11.5 (0.045)	22 (16)	12.3 (0.034)	
E	PUR	21		18 (1)		unknown
F	MUF	40		37 (3)		GL 24h
G	MUF	42		42		GL 24c
H	EPI	40		36 (4)		GL 24h

†PUR = Polyurethane, MUF = Melamine-Urea-Formaldehyde, RF = Resorcinol-Formaldehyde, UF = Urea-Formaldehyde, EPI = Emulsion Polymer Isocyanate.

‡MC = moisture content: mean value and (coefficient of variation).

§( ): Number of tests where the ultimate load could not be reached due to insufficient travel of the piston.

¶According to EN 14080 (CEN 2005).

one (**Fig. 7**). Force was applied by a 100 kN universal testing machine Zwick (Ulm, Germany) with a loading rate of 3 mm/min. Maximal error of the force measurement was <1%. Shear strength was calculated and the percentages of wood failure in the bondlines were determined using a new semi-automatic method (Künniger 2008). Before testing, the bars were stored in a climatic chamber at 20°C and 65% RH. After the shear tests the moisture content of the specimens was derived according to ISO standard 3130. A mean value of 11.5% (variation between 9.8 and 12.5%) was found for the specimens tested with the established shear test device. The respective values for the specimens tested with the new device were 12.3% (mean value) and 11.3 to 13.3% (variation). The impact of the small moisture content difference (about 0.8%) on the shear strength, which may result in a maximum change of 2%, has been neglected.

Mean values, 10-percentiles and 90-percentiles of shear strengths and percentages of wood failure are shown in **Fig. 8**.

Lower and upper percentiles were taken directly from ranked test results without any interpolation or distribution fitting but rather by assigning those single test values to the 10/90-percentile, which was directly below/above the respective percentile. From **Fig. 8** it can be concluded, that independent of the type of adhesive, shear strengths derived with the new test device as well as their variability are lower than those resulting from tests with the established device. The differences exhibit the same trend on the mean level and on levels of 10 and 90 percent, which at the first glance would mean that the differences are not affected by strength of material or of adhesive bond respectively. When correlating all pairs of shear strength values derived with both test devices, the test data exhibit a linear trend but the coefficient of determination is low (**Fig. 9**). The dependency of shear strengths derived with both test devices is influenced by the level of strength: at high levels of bondline strength, testing with the new device leads to lower values compared to tests performed with the established device. The reason for this phenomenon was identified by a detailed examination of the specimens. As a result of the limited area of load transfer, specimens with high bondline strength tend to crush due to exceeding compression stresses parallel to the grain.

Regarding percentages of wood failure (**Fig. 8**, bottom) no clear difference between the established and the new test tool can be seen. Wood failure percentages for PUR-type adhesives were generally very high and exhibited a small variation. On the other hand, some very low percentages of wood failure, especially for MUF-type adhesives occurred.

Benchmarking of test results to the limits required by bondline quality control standard EN 386 (CEN 2001) revealed that the requirements for the mean values of shear strength and percentages of wood failure are met by all producers in the case of shear tests performed with the established device, whereas the respective values of specimens provided by two producers do not reach the target limit anymore when tested with the new device. A detailed analysis of data grouped according to type of adhesive showed that in the MUF group, individual values that are not sufficient occur more frequently. When the tests are performed with the established test device 9, test results are beyond the limits, compared to 15 specimens being out of limit when tested with the new device. Specimens bonded with PUR practically meet the required limits (one outlier) independently of shear test device used to carry out the tests. The respective numbers of test values not reaching the quality limits in the group of EPI, RF, and UF adhesive are: 20 (12 EPI, 4 RF, 4 UF) when tested with the established device and 24 (12 EPI, 2 RF, 10 UF) when tested with the new device.

Hence, the type of test equipment used for the block shear tests affects the test results in terms of shear strength and percentage of wood failure. That is why the limits given by quality control standards (e.g., EN 386) cannot be directly applied to the new shear test device. They need further verification and development. Additionally it has to be clearly stated that the limits given in the standard EN 386 are only valid for the type of shear testing device that they were derived with. In
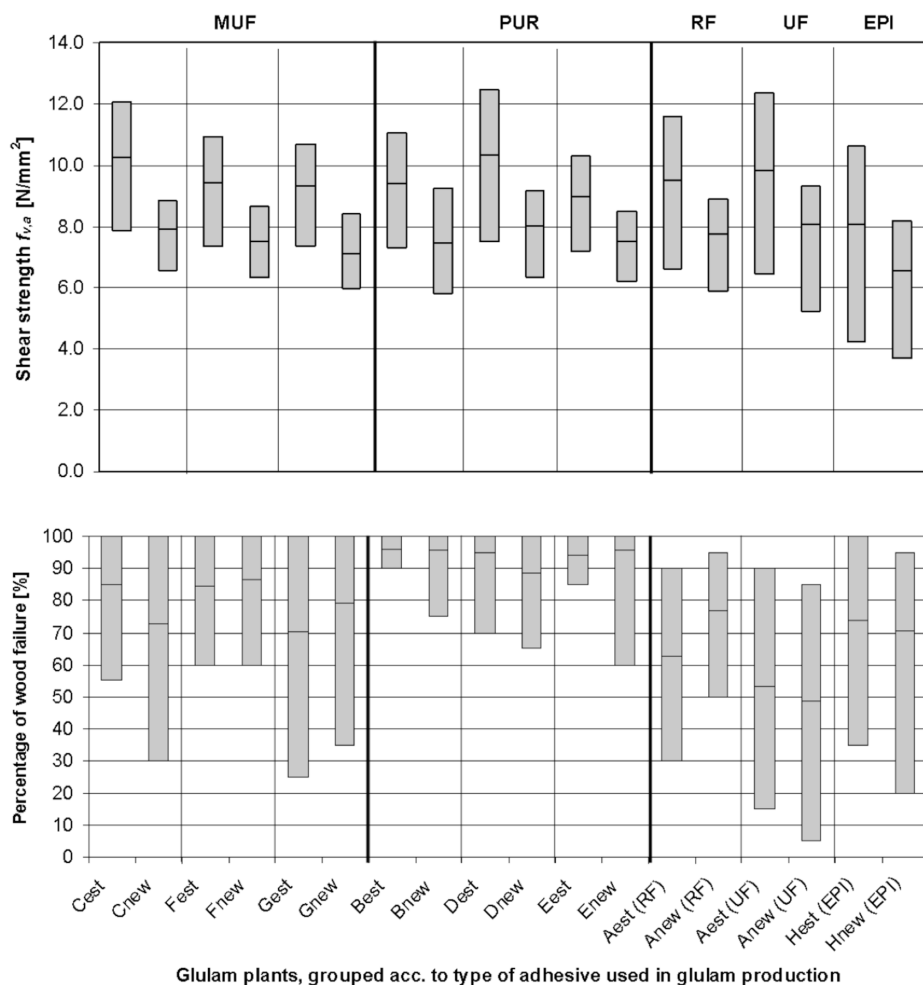
Figure 8. ~ *Mean values, 10- and 90-percentiles of percentage of shear strength (above) and wood failure (below) derived with either the established shear-testing device or the new one. Test data are grouped by producer and type of adhesive.*

that sense the standards EN 386 and EN 392 lack precision in describing the properties of this shear test device. Furthermore, to reliably assess and compare percentages of wood failure the bondlines could be analyzed using a computerized method, as suggested in Künniger (2008).
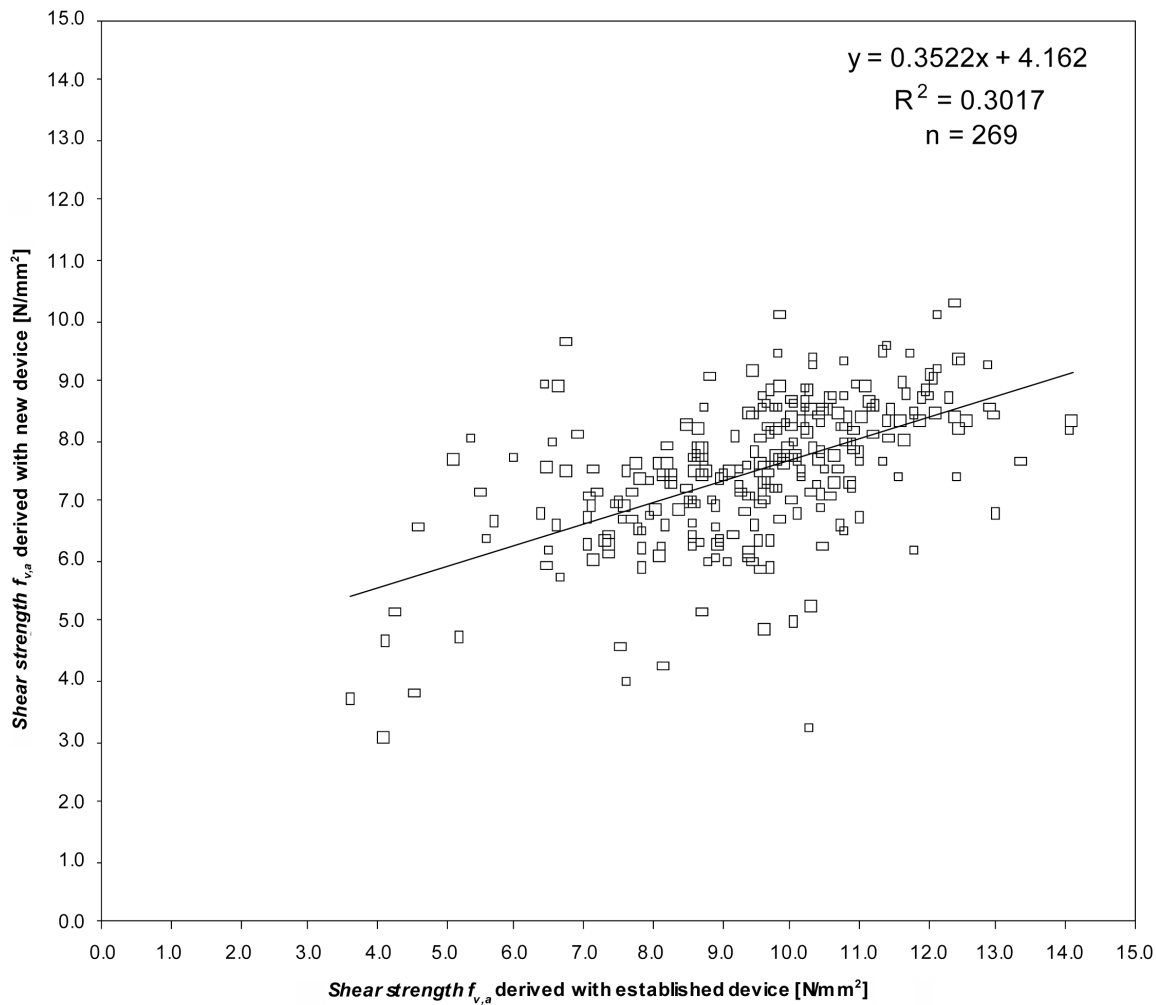
Handling of the New Test Device

The test series with the new test device could be carried out without any noticeable complication compared to the established procedure. When using templates, the cutting of single block shear specimens from test bars with the new device can easily be done. Necessity of geometrical precision in trimming the single block shear specimens however is higher, especially regarding the correct position of the bondline with respect to the sheared area within the new test device (**Fig. 7**, center and right). Due to limited travel of the piston of the new test device some specimens could not be sheared completely until failure occurred. This shortcoming has to be overcome by a further development of the test device, since manually splitting the bondlines perpendicular to the grain after the test can provoke misinterpretation of percentages of wood failure. One main advantage of the new test device lies in the fact that the test results may not be influenced by the person who carries out the test, since the test specimen is not to be taken hold of during the shear test.

Conclusions

Commonly applied shear tests suffer from a non-uniform shear-stress distribution with a stress concentration near the corner of the specimens. The test results are influenced by the actual materialization of the shearing tool as well as by the person carrying out the test. Furthermore, the hindering of shear strains developed during testing shows unknown side effects on the test results. To overcome these limitations, a prototype of a shear-test device has been developed aiming to ensure a clearly defined state of shear loading of the specimens and to make test results independent of human error. The test principle is to perform axial compression tests with an oblique angle between the grain and the loading direction of 14° (slope 1:4). Tests performed with the prototype device show that the new shearing tool has the potential of deriving reproducible shear-strength values that are not influenced by the operator. Shear strengths of bondlines exhibit lower variation when the tests are carried out with the new shearing tool, whereas with regard to percentages of wood failure no differences were found.

The validity of target limits of shear strength and percentages of wood failure in glulam quality control standards has to be questioned. Actual limits seem to be related to certain types of shearing tools. However, as already stated above, construction details of these tools have to be prescribed more precisely in the respective

$$y = 0.3522x + 4.162$$
$$R^2 = 0.3017$$
$$n = 269$$

Shear strength $f_{v,a}$ derived with new device [N/mm^2]

Shear strength $f_{v,a}$ derived with established device [N/mm^2]

Figure 9. ~ *Correlation of shear strengths derived with established and with the new test equipment.*

standards. For the new test device, respective limits for shear strength and percentage of wood failure have yet to be developed. In the course of quality control of glulam the main focus has to be given to shear strength, the latter directly influencing the mechanical properties of the glued-laminated timber; percentages of wood failure are of lower interest. However, when investigating and further developing adhesives, percentages of wood failure gain importance since they help improve adhesive products and application techniques.

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