Quality control of glulam: Improved method for shear testing of glue lines

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Abstract

Among other tests, shear tests of glue lines are required in the course of quality control measures to be carried out in glulam plants. The procedures to be followed are given in different standards like for example EN 392:1995 and ISO 12579:2006. In most of the standards the method of applying shear stress to the glue line is only given by a principle scheme. Based on this scheme a variety of test equipment has been produced and is in use by materials testing laboratories, glulam manufacturers and producers of adhesives. Depending on the actual construction of the test equipment as well as on the procedure of testing, the resulting stress in the glue line is not pure shear but rather a combination of shear and normal stresses. In case of simultaneously acting shear stress and tensile stress perpendicular to the grain, the shear strength values can drop dramatically, whereas compression stresses perpendicular to the grain lead to an overestimation of the shear strength of the bond line. 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 aiming to ensure 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.

1 Introduction

Shear tests of the glue lines are required in the course of quality control measures to be carried out in glulam plants. The procedures to be followed are given in various standards like for example EN 392 (CEN 1995), ASTM D 905-03 (ASTM 2003) and ISO 12579 (ISO 2006). However, the method of applying shear stress to the glue line is only given by a principle scheme (Figure 1). Based on this scheme a variety of test equipment has been produced and is used by test laboratories and by producers of glulam and adhesives.

Depending on the actual construction of the test equipment as well as the procedure of testing, the resulting stress in the glue line is neither uniformly distributed nor pure shear but rather a combination of shear and normal stresses. In case of simultaneously acting shear stress and tensile stress

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perpendicular to the grain, the shear strength values drop dramatically, whereas compression stresses perpendicular to the grain lead to an overestimation of the shear strength of the bond line. The problem of the test method not being suitable to test the capacity of the glue line correctly has been addressed in several stages of the development of EN 392 but has not been solved yet. To overcome this problem, a prototype of a shear test device which ensures a clearly defined state of shear loading of the specimens should be developed.

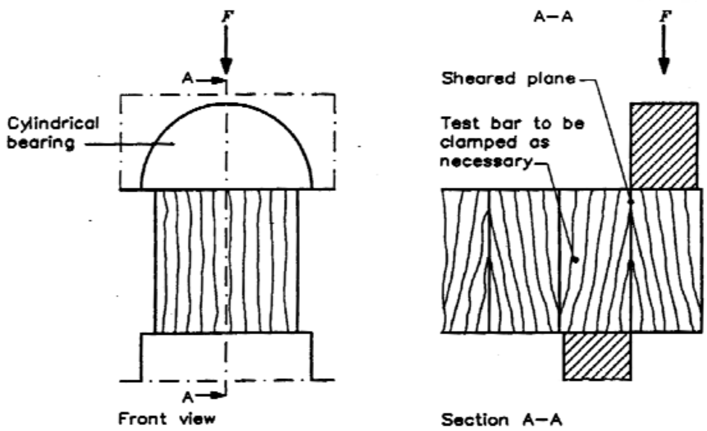


Figure 1: EN 392 method of applying shear stress to a glue line

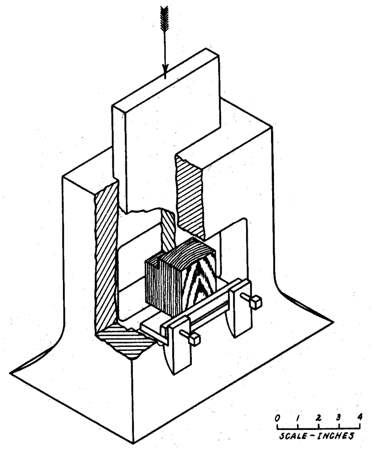


Figure 2: ASTM D 905-03 shearing test equipment

2 Normatives for block shear tests of glue lines

2.1 European standards

In Europe the bonding strength of glue lines is assessed as a glue line integrity test according to one of the test procedures defined in EN 386 (CEN 2001), being either delamination tests according to EN 391 or block shear tests according to EN 392. The shear strength $f_{v,a}$ of each glue line shall be at least 6 N/mm^2. For coniferous wood and poplar lower individual values of shear strength (down to 4 N/mm^2) shall be regarded as acceptable if the wood failure reaches a certain percentage. The EN 392 block shear test is intended to be used in the course of continuous quality control of glue lines. A principle scheme for the shearing tool is given in the standard (Figure 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 glue line and the sheared plane nowhere exceeds 1 mm. The width and the thickness (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.

2.2 American standards

In the United States shear testing of glue lines is addressed by the standard ASTM D 905-03 (ASTM 2003). The standard makes 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". It is also 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. Figure 2 shows a respective tool.

2.3 ISO standards

The formulations in the ISO standards are similar to the European pendants. For block shear tests the standards ISO 12579 (ISO 2006) and ISO 6238 (ISO 2001) are ruling. ISO 12579 provides a combination of rules taken from EN 392 and ASTM D 905. Concerning the apparatus to be used for the shear tests, the ISO standard as well gives only a schematic sketch similar to EN 392. In ISO 6238 (ISO 2001) a shearing tool for compressive shear block tests being identical to the one shown in ASTM D 905-03 (Figure 2) is mentioned.

3 Advantages and 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 on the other hand 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 it was shown by experimental and theoretical stress analysis (Coker & Coleman 1935, Radcliffe & Suddarth 1955).
- The test results are influenced by the actual materialisation of the principal sketch in EN 392 (Figure 1) as well as by the person carrying out the test (see 4).
- 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.

4 Analysis of static equilibrium

The state of static equilibrium in specimens tested according to EN 392 is shown in Figure 3. Being not aligned but rather eccentric (with a gap e depending on the dimensions of the stamps ℓ_A of the actual test equipment) the acting shearing forces A_v cause a moment $A_v \cdot e$, which has to be compensated by a counteracting moment $h \cdot A_h$. Both the eccentricity e and the counteracting moment are indeterminate, depending on the shearing device. Actually there is a state of compression at an angle to the grain ($\alpha \approx \arctan(A_h/A_v)$) 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 shear stresses and the specimen tends to fail early at low level of shear stress.

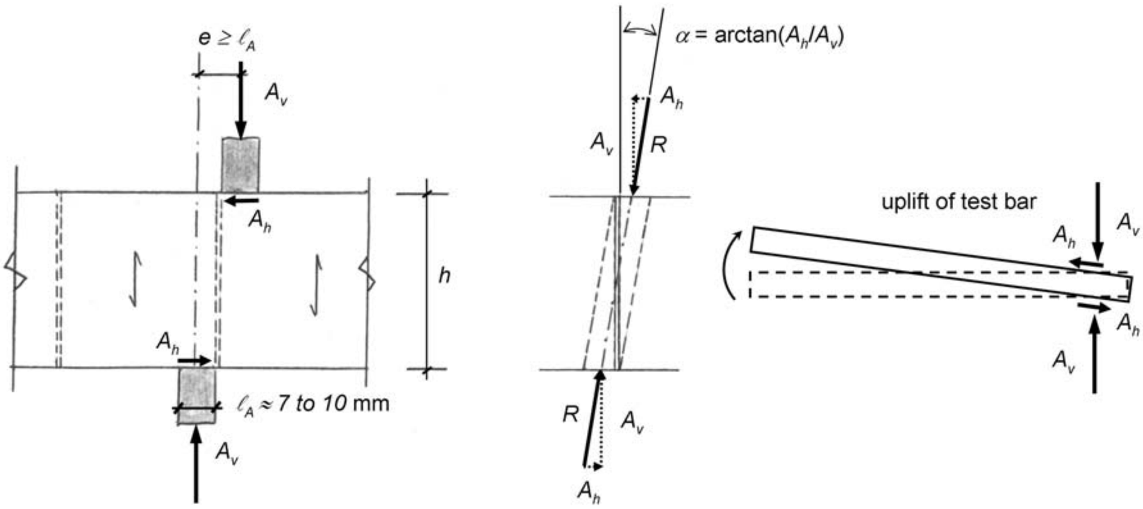


Figure 3: Static equilibrium in specimens tested according to EN 392

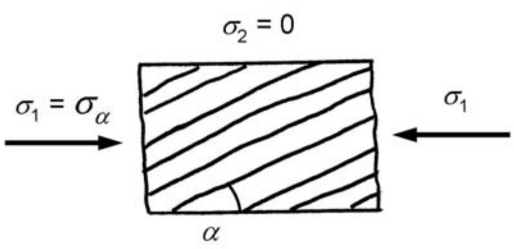
5 Optimized block shear test

5.1 Approach

Shear strength can also be derived by carrying out compression tests with a certain inclination between load and grain direction. Panel shear tests to derive shear strength according to EN 408 (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.

5.2 Compression and tension stresses at an angle to the grain

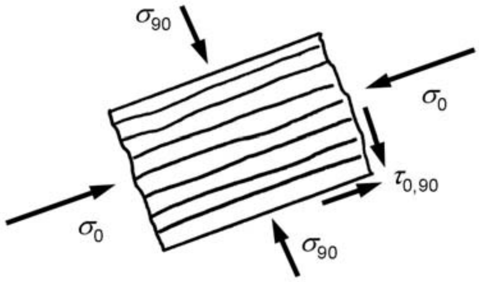
Different angles α between loading directions and grain can e. g. be modelled by the Hankinson-formula (Hankinson 1921), which independently was also found by Kollmann (1934) based on scientific findings in crystal physics by Hörig (1931). However, the Hankinson formula does not provide any information on failure modes to be expected with varying angles α. Analysing stress equilibrium of an isotropic plane strain element subjected to a stress σ_α inclined by an angle α with reference to the grain direction Stüssi (1946, 1949) showed a relation between normal stresses σ and shear stresses τ. The principle stresses σ_1 and σ_2 are:



$$\sigma_1 = \sigma_\alpha$$ Equation 1

$$\sigma_2 = 0$$ Equation 2

Respective stresses parallel and perpendicular to the grain σ_0, σ_{90} and shear stresses $\tau_{0,90}$ can be calculated according to the theory of the strength of materials:



$$\sigma_0 = \sigma_\alpha \cdot \cos^2 \alpha$$ Equation 3

$$\sigma_{90} = \sigma_\alpha \cdot \sin^2 \alpha$$ Equation 4

$$\tau_{0,90} = \sigma_\alpha \cdot \cos\alpha \cdot \sin\alpha$$ Equation 5

Depending on the actual angle α between the loading and the grain direction three different failure modes can occur:

- compression failure parallel to the grain: $$\sigma_\alpha = \frac{\sigma_0}{\cos^2 \alpha}$$ Equation 6
- shear failure: $$\sigma_\alpha = \frac{\tau_{0,90}}{\sin\alpha \cdot \cos\alpha}$$ Equation 7
- compression failure perp. to the grain: $$\sigma_\alpha = \frac{\sigma_{90}}{\sin^2 \alpha}$$ Equation 8

Solving Airy's stress function, Ylinen (1963) showed 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 Figure 4. 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 Equation 7:

$$f_{v,0,90} = f_{c,\alpha} \cdot \cos\alpha \cdot \sin\alpha$$ Equation 9

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

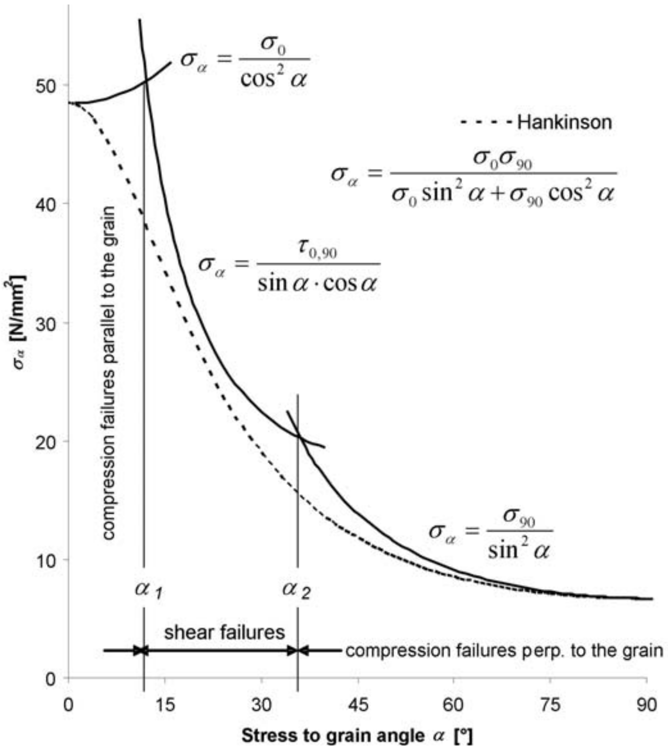
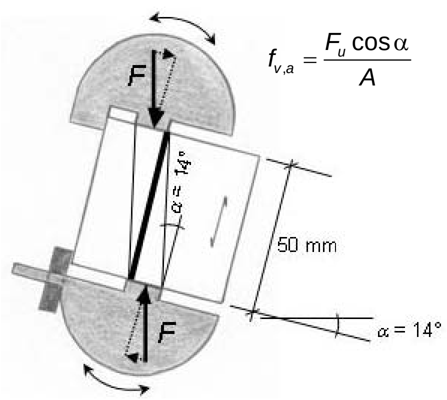


Figure 4: Influence of the stress to grain angle on compression strength (Stüssi 1946, 1949)

5.3 Prototype of a new shearing tool

Owing to the fact that high compression stresses perpendicular to the grain result in higher shear stresses, a small angle α is to be preferred. In analogy to the EN 408 rules for panel shear tests an angle α of 14° is chosen (Figure 5, left). Prototype tests and calculations showed that with smaller slopes the specimens might crush due to exceeding compression stresses parallel to the grain in the loading zone. With α = 14° for coniferous specimens shear strengths up to 10 – 12.5 N/mm^2 were recorded resulting in compression stresses parallel to the grain of 40 to 50 N/mm^2. As it is shown in Figure 5, right and experimentally proven (Keylwerth 1951), a shear strain occurs during the shearing test, which may not be hindered or blocked but rather be made possible. Therefore the upper and the lower plungers are coupled to the loading parts by pivot bearings and to account for the specifications given by EN 392 (cylindrical bearing, Figure 1) one of the plungers has a two-way pivot bearing.



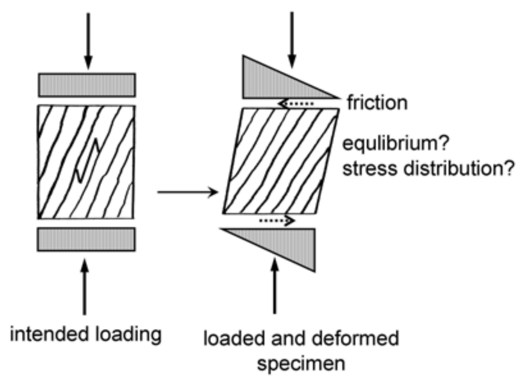


Figure 5: Loading scheme (left) and stress distribution in the specimen (right)

6 Application of the new shearing tool

A test series was conducted aiming at comparing shear strengths and percentages of wood failure derived from tests with either the established EN 392 type device or the new one (Figure 6).

Figure 6: EN 392 type shearing tool (left), new test apparatus (center), close view of a specimen during testing with the new apparatus (right)

Comparability of test results was made possible by testing pairs of edge and centre bars taken from two slices cut from front ends of glulam beams directly after finishing the production in the glulam plant. Eight glulam producers of the Swiss Glulam Association SFH (www.glulam.ch) supplied the test bars cut from 3 to 4 different glulam beams each. The bars contained 8 to 10 bond lines of different types of adhesives (RF, UF, PUR, MUF, EPI) and had a cross-section of 50 x 50 mm^2. Approximately 600 block shear tests were carried along the test series. In the far most cases the glulam strength classes were GL24h or GL24c. The glulam beams were made from Norway spruce (*Picea abies Karst.*).

The block shear specimens were tested to shear failure using either the established shear test device or the new one (Figure 6). Force was applied by a 100 kN universal testing machine Zwick with a loading rate of 3mm/min. Maximal error of the force measurement was <1%. Shear strength was calculated and the percentages of wood failure in the bond lines 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% r. H. 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 Figure 7. 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. Regarding percentages of wood failure (Figure 7, bottom) no clear difference between established and 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.

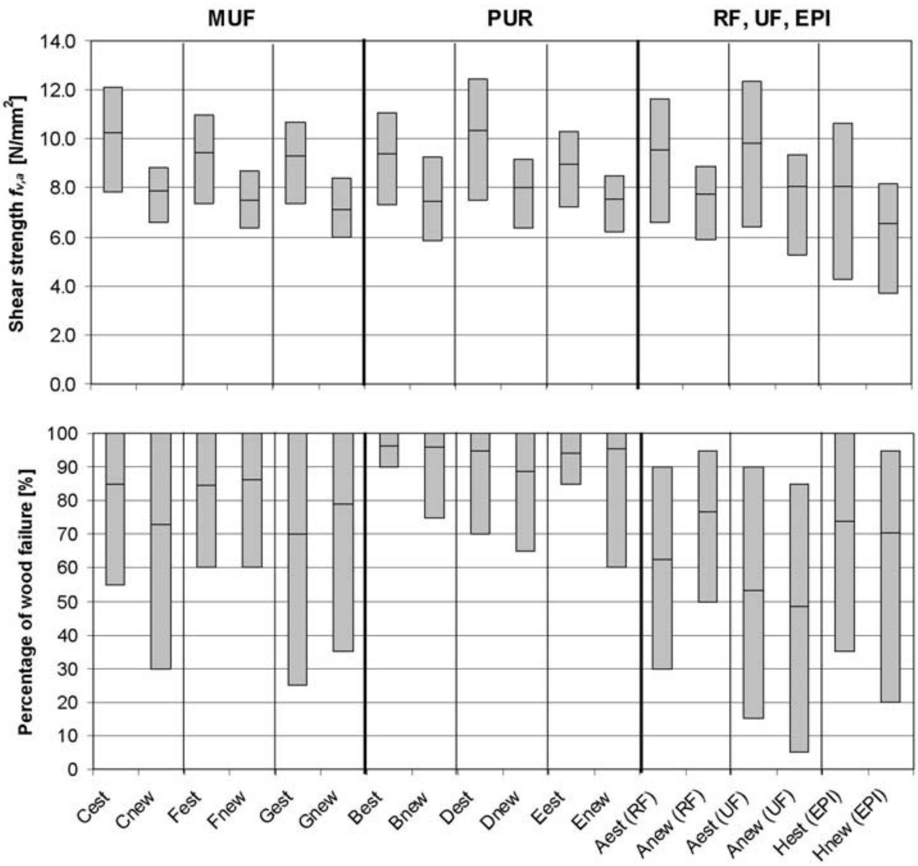


Figure 7: Mean values, 10- and 90-percentiles of shear strength (above) and percentage wood failure (below) derived with the EN 392 type shear testing device or the new one. Data grouped by producer (A – H) and type of adhesive

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 (Figure 8). The dependency of shear strengths derived with both test devices is influenced by the level of strength: At high levels of bond line 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 limited area of load transfer, specimens with high bond line strength tend to crush due to exceeding compression stresses parallel to the grain.

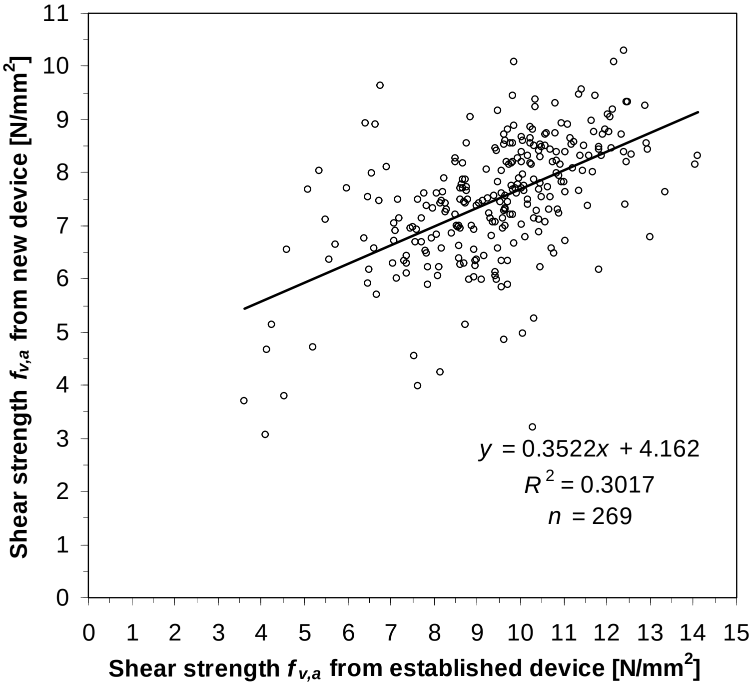


Figure 8: Correlation of shear strengths derived with the two test tools

Benchmarking of test results to the limits required by bond line quality control standard EN 386 revealed that the requirements for the mean values of shear strength and percentages of wood failure were met by all producers in case of shear tests performed with the established device, whereas the respective values of specimens provided by two producers did 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 which are not sufficient occur more frequently. Along the tests performed with the established test device 9 test results were beyond the limits, compared to 15 specimens being out of limit when tested with the new device. Specimens bonded with PUR practically met the required limits (1 outliner) 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 were: 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 they were derived with. In that sense the standards EN 386 and EN 392 are lacking of precision in describing the properties of this shear 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 models, the cutting of single block shear specimens from test bars to be tested with the new device can easily be done. Request on geometrical precision of trimming the single block shear specimens however is higher, especially regarding the correct position of the bond line with respect to the sheared area within the new test device (Figure 6, centre and right). Due to limited travel of 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 bond lines 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 touched during the shear test.

7 Summary and conclusions

Common 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 materialisation of the shearing tool as well as by the person carrying out the test. Furthermore, the hindering of shear strains developed during testing shows 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 from manipulations. 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). Test performed with the prototype device show that the new shearing tool has the potential of deriving reproducible shear strength values not being influenced by the operator. Shear strengths of bond lines exhibited lower variation when the tests were 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. Hence, construction details of these tools have to be prescribed more precisely in the respective standards. For the new test device respective limits for shear strength and percentage of wood failure have to be developed yet. 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. Here percentages of wood failure are of lower interest. When investigating and further developing adhesives, percentages of wood failure gain of importance since they help improving adhesive products and application technique.

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