5th International Conference on Structural Health Assessment of Timber Structures

25-27 September 2019, Guimarães, Portugal

EXPERIMENTAL INVESTIGATIONS ON THE SHEAR RESISTANCE OF EXISTING GLULAM STRUCTURES

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Keywords: Glued-laminated timber, Shear resistance, Aging processes, Bending tests, Drill cores

Abstract

Numerous large-span, load-bearing structures, e.g. for public venues, sports halls or industrial facilities, utilize glued-laminated timber (glulam) due to its versatility and aesthetic appearance. Since glulam is an organic and composite material consisting of wooden lamellas joined with glue, mistakes during planning, fabrication and use of the structure can lead to deficiencies or even damages. Following a visual inspection suitable to detect surface deterioration, further holistic investigation of the glulam material is necessary to appraise structural safety or estimate the need for restoration. Besides the integrity of the wooden lamellas, the glue bond of the lamellas is vital for the operational reliability of glulam. A currently practiced, semi-destructive assessment method to revalue the condition of the glue lines consults a shear test on drill core samples with included glue line. The presented paper links this method to medium-scale shear tests and large-scale 3-Point bending-shear tests representing a practical loading situation. To provoke shear failure during bending, reinforcements of the specimens at critical tension and compression zones included glued-on beech veneer lamellas and self-tapping screws, respectively. Executed on the same sample material, shear resistance was determined for all three testing formats. The sampling included aged and new glulam. Published values derived from comparable test programs augmented the database. Based on the evaluated test results of the drill cores under shear loading, suggestions regarding the drill core extraction and the implementation of the valuation method of EN 14080 are outlined. After incorporating a size effect to account for varying dimensions of the bending-shear specimen, their shear resistance values correlated well with the obtained values from the drill core tests. This adumbrates the possibility to derive the shear resistance of structural members from shear values of drill core samples taken from an existing glulam structure.

1 INTRODUCTION

Some people entering an airplane have an uneasy feeling that their life is in danger while flying. Only very few people are concerned and aware of potential threats when entering an engineered building. In both cases, engineers do their best during planning, production/erection and use of the load-bearing structures to avoid fatal accidents. Usually, people are very confident about the functionality of buildings. However, a single, destructive incident can easily harm this trust, as a collapse of a building often results in loss of lives. It is the job of engineers to make sure that structures maintain their sound and safe condition during their whole life span.

Engineered structures alter more or less during the time of use, depending on the material, initial design and the surrounding environmental circumstances. As no design is perfect, and surrounding conditions may change, inspection and maintenance plays a big role in keeping the structures sound and safe. In case of an airplane, inspection and maintenance have high priority. Buildings on the other hand are often neglected in this regard. In case of existing timber structures employing glued-laminated timber (glulam), systematic assessment of functionality gained momentum during the last decades only after some obvious damages occurred, occasionally even being fatal [1].

To assess the condition of an engineered timber structure, sound knowledge about material and material-specific load-carrying mechanism is needed. Expert engineers utilize numerous methods for inspection, from historical documentation, visual inspection, measurements of material moisture and crack development up to drill resistance or ultrasound transmission, just to name a few [2,3]. However, little guidance exists about a specific course of action, only fundamental guidelines are available [4,5]. Therefore, expert engineers rely on their experience to choose an approach.

Common investigation practice for glulam structures utilizes semi-destructive drill core sampling with consecutive shear testing. The method is adapted from a European standard mainly relating to the production control of new glulam. The drill cores are extracted with a diameter of 35 mm and usual lengths between 50 mm and 120 mm, including a glue line in its centre. After side-cutting to create loading planes, the test specimens are shear loaded parallel to the grain and glue line. For derived single values and sample mean values of shear resistance in combination with the percentage wood failure, the glue bond is rated “passed” or “failed” according to threshold values provided in the standard [6].

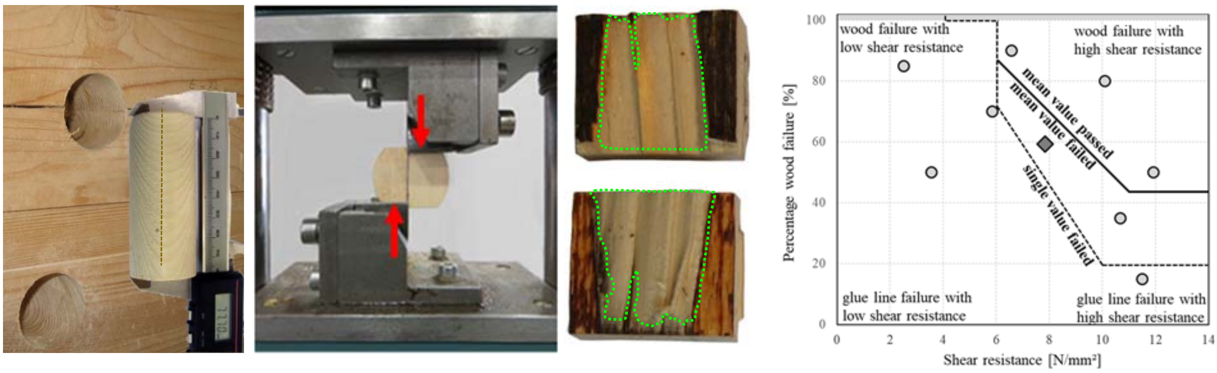

Figure 1: Extraction and testing procedure (from left to right) for drill core sample shear tests according to EN 14080 (right: rating of random series values; circles: single values; rhomb: sample mean value)

Figure 1 depicts the testing procedure, from drill core extraction, shear loading, and percentage wood failure estimation, to result rating. Uncertainties in the method arise regarding the number of samples and location of extraction from structural glulam members. The visual estimation of percentage wood failure proved to be difficult for glues with little colour difference to the wood material and unclear distinction of wood/glue fracture interface [7]. Also criticized is the transfer of threshold values for newly produced glulam to the investigation of aged glulam material [8]. Translating the shear values of the drill cores into a remaining shear resistance of the sampled structural glulam members has not yet been attempted, as correlation has not been assumed [9].

2 TESTING PROGRAM

2.1 Material sampling and documentation

The project presented in this paper aimed at a comparison of shear resistance values derived from bending tests, representing a realistic loading situation of beams in glulam structures, and small-scale shear tests specified in European standards. Two utilized softwood glulam samples, gathered from decommissioned structures, had been stored under laboratory conditions for more than eight years, equalizing the moisture content to about 11 %. One of the samples (named "K", l x w x h = 7,6 m x 0,22 m x 2,2 m, lamella thickness 30 mm) showed severe delamination of glue lines already during dismounting, and a lack of structural safety. The other sample (named "O", l x w x h = 7 m x 0,20 m x 0,6 m, lamella thickness 40 mm) originated from a temporary tent structure with little glue line delamination on only one side. An additional sample of nine softwood beams (named "R", l x w x h = 3,5 m x 0,20 m x 0,4 m, lamella thickness 40 mm, series "R") taken from running glulam production was included for comparison.

Prior to specimen preparation, all cracks in lamellas and delamination of glue lines in the aged samples were documented regarding their location and depth, to be able to consider pre-existing damage during data evaluation.

2.2 Large-scale 3-Point bending-shear tests

The original beam sample "K" was redevived by vertical and horizontal cuts into eight specimens. Sample "O" segmentation yielded two specimens. Nine specimens from sample "R" were ordered in matchable specimens' dimensions. The bending-shear specimens' geometry followed a preliminary design calculation, aiming for a span of approximately 3 m and a ratio of l/h = 6.

To provoke shear failure, glued-on lamellas out of beech veneer (h = 40 mm) reinforced the tension and compression zones of the bending-shear specimens. In addition, self-tapping screws (STS) in areas of load application and vertical supports absorbed high compression stresses perpendicular to the grain, and distributed the induced load along the total specimens' height. The screws did not influence initial shear failure due to their low embedment stiffness and the small shear deformations before failure. In combination with a loading point shifting towards one end of the specimen, and therefore concentrating the shear force, shear failure occurred in all specimens. Figure 2 shows the general test setup.

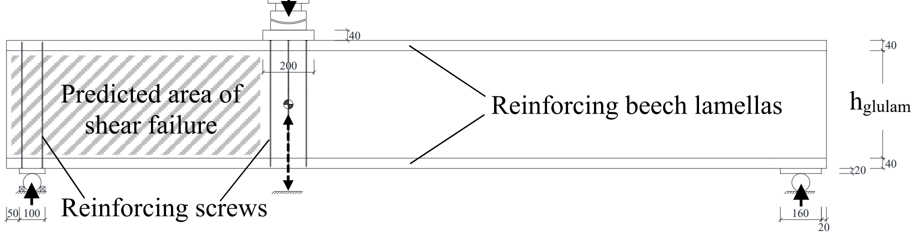

Figure 2: Test setup for 3-Point bending-shear tests

The bending-shear tests were performed in a hydraulic press at a loading speed of 0,05 mm/s. Steel plates distributed the induced forces directly into the reinforcement screws. In case of existing delamination of glue lines, shear failure often initiated therein, however cracks mainly propagated into adjacent lamellas. Loading continued until numerous shear failures had occurred, yet the shear resistance of each specimen was determined based on the first load peak F_{max} with visual shear crack formation at the same time, also defining crack height (Figure 3).

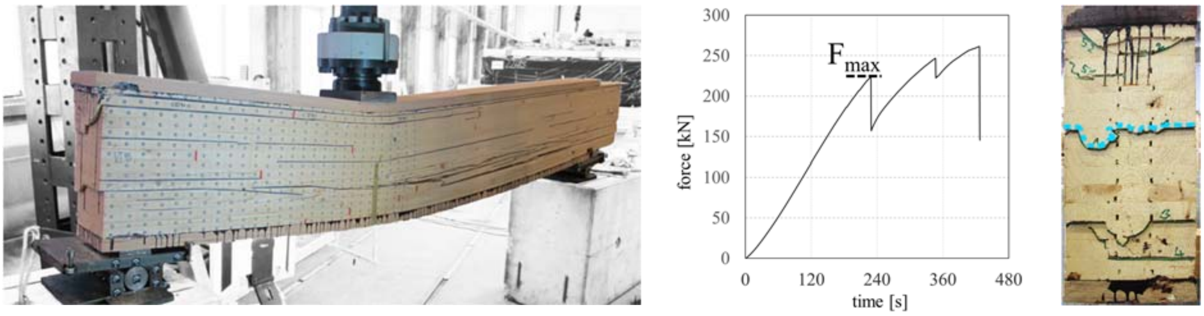

Figure 3: Left: bending specimen after loading; middle: loading history; right: shear cracks at end grain

The shear resistance was calculated according to the classical beam theory, assuming a rigid laminate between glulam and reinforcement lamellas. Standardized values of stiffness for the varying material in the composite beam specimens were incorporated in the determination of moments of inertia. Prior documented crack depths corresponded well with observations on fractured surfaces after specimens' separation, where previous openings could be distinguished by darker colouring. Therefore, subtraction of measured crack depths from cross section width resulted in an effective width b_{red} of the strained shear plane. The observed height of the shear crack in the cross section (Figure 2, right, dashed blue line) was visually averaged, and taken into account in the static moment calculation. Hence, the shear stress at the time of failure, i.e. the assumed shear resistance of the beam, was calculated according to

$$\tau = \frac{V \cdot S_{y,\,crack\,height}}{I_{eff} \cdot b_{red}} \tag{1}$$

where: V = shear force, $S_{y,\,crack\,height}$ = static moment at crack height, I_{eff} = effective moment of inertia, b_{red} = width of cross section minus previously existing, average crack depths.

Specimen dimensions varied slightly between the three series. Literature reports a size effect regarding varying specimen dimensions [10]. More recent publications based on comparable test setups suggest consideration of a size effect regarding the strained area of pure shear A_s (with A_s = specimen width times the length of pure shear without compression stresses perpendicular to the grain), which had been often confirmed and proposed to be the main geometric parameter to predict size effects on shear resistance [11,12]. The power parameter of 0,2 was chosen accordingly. To be able to compare different series in this project, normalizing of shear resistance values to a homogeneous shear area (series "R" randomly taken as a reference) succeeded with

$$\tau_{norm} = \tau \cdot \frac{1}{\left(\frac{A_{s,spec\,i}}{A_{s,spec\,ref}}\right)^{0,2}} \tag{2}$$

where: τ_{norm} = normalized shear force, $A_{s,spec\,i}$ = shear strained plane of individual specimen, $A_{s,spec\,ref}$ = shear strained plane of reference specimen.

In Table 1, the main parameters and statistic values of the results are presented. Poor glue bond condition and severe prior glue line delamination explain the lower shear resistance values of series “K”. Lower wood density of samples “R” might attribute to the lower shear resistance values compared to the aged material of series “O”, at the same time indicating an intact glue bond in sample “O” at the time of decommissioning of the original structure.

Table 1: Main parameters and statistical results of the 3-Point bending-shear tests

series	n	l_{span}	h_{glulam}	l_{span} / l_1	$\bar{x}$ (τ_{norm}) [1)]	σ (τ_{norm}) [2)]	COV (τ_{norm}) [3)]
	[-]	[mm]	[mm]	[mm]	[N/mm²]	[N/mm²]	[%]
K	8	3000	424	0,33	2,00	0,53	26,8
O	2	2615	345	0,31	4,04	0,75	18,4
R	9	3000	400	0,33	3,87	1,06	27,4

1) $\bar{x}$ (τ_{norm}) : Arithmetic mean of normalized shear stress at the time of failure

2) σ (τ_{norm}) : Standard deviation of normalized shear stress at the time of failure

3) COV (τ_{norm}) : Coefficient of variation of normalized shear stress at the time of failure

2.3 Shear tests on small sample specimens

2.2.1 Shear tests according to EN 408

Conventionally, shear resistance of solid timber and glulam is determined by loading samples under an angle of 14° to the grain through glued-on steel plates [13]. The test setup aims at minimizing internal momentum and high compression stresses perpendicular to the grain. In the presented experimental program, this test was meant to represent the link between the large-scale bending-shear tests, and the small-scale drill core shear tests. A total number of 201 shear samples were extracted from the previously tested bending-shear specimens, considering annual ring orientation and glue lines. Samples were generally extracted from the undamaged side of the bending-shear specimens to avoid premature damage. No influence of failure mode and shear resistance was observed for individual samples extracted from intact glue lines adjacent to bending-shear cracks. Derived shear resistance values f_v are depicted in Figure 4.

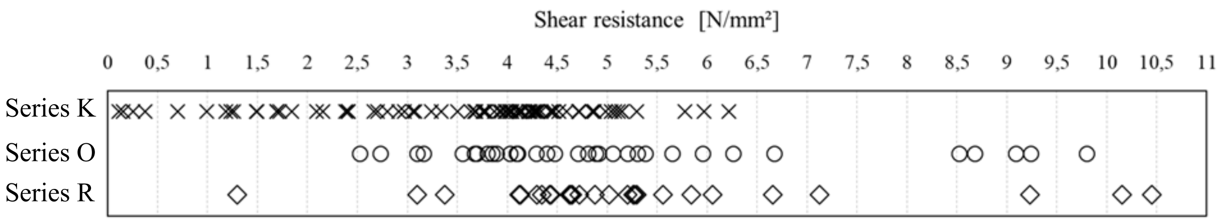

Figure 4: Shear resistance values of the sample material K, O and R according to EN 408 shear tests

For the statistical evaluation in Table 2, specimens with a failure area of more than 20 % in the glue bond to an applied steel plate were excluded according to standard EN 408. In addition, only specimens with dimensions in the standard range were considered to exclude size effects.

Table 2: Statistical value of the EN 408 shear tests

series	n	$\bar{x}$ (ρ_u)	$\bar{x}$ (f_v)	σ (f_v)	COV (f_v)
	[-]	[kg/m³]	[N/mm²]	[N/mm²]	[%]
K	56	455	3,26	1,53	46,8
O	20	471	4,32	0,96	22,2
R	17	426	4,75	0,60	12,7

Testing of an included glue line in a shear specimen disclosed to be difficult, as specimens were prone to fail with shear planes along early wood and also perpendicular to grain, especially in series “O” and “R”. Deviating from standard geometry by intentionally reducing the specimens’ width at glue lines via slot cuts helped, however the following statistical evaluation revealed inconsistencies in results due to size effects. Evaluation of series “K” specimens showed lower shear values in case of glue line failure, indicating a poor glue bond. Evaluating the results with pure wood failure across the three series presumed a potential interrelation of declining wood shear resistance with increasing age, however the relatively small sample size yielded insufficient stability in statistical values.

In general, the effort of specimen extraction and preparation proved to be rather unreasonable with respect to the emerging difficulties during testing and data evaluation.

2.2.2 Drill core shear tests according to EN 14080

Drill core samples with a diameter of 35 mm and lengths up to 95 mm (mean: 78 mm) were extracted from the sample material “K”, “O” and “R” on different locations, with and without prior existing glue line delamination. Employing the previously described shear test method resulted in a total number of 346 shear resistance values. **Figure 5** depicts the single and mean values of the three series, and the threshold value lines of EN 14080; Table 3 lists the statistical values.

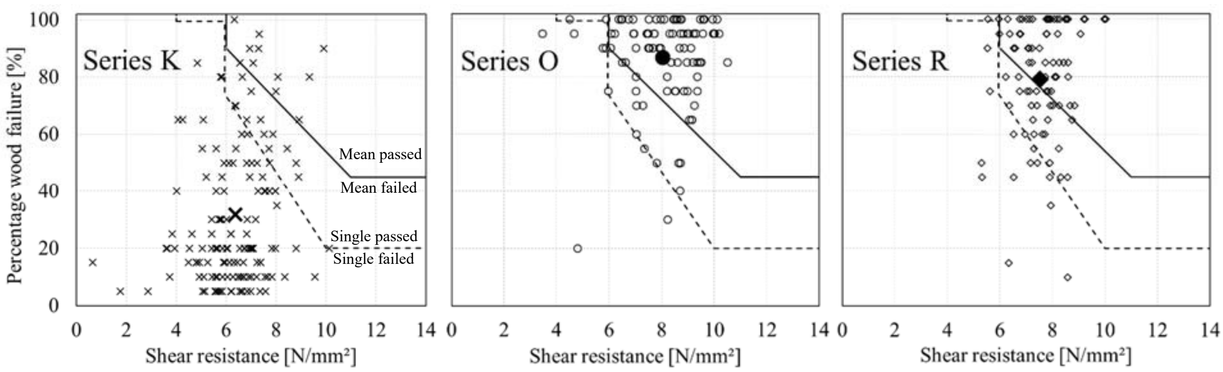

Figure 5: Drill core shear resistance values (single and mean (bold)) according to EN 14080

Table 3: Statistical value of the EN 408 shear tests

series	n [-]	$\bar{x}$ (ρ_u) [kg/m³]	$\bar{x}$ (f_v) [N/mm²]	σ (f_v) [N/mm²]	COV (f_v) [%]
K	155	464	6,37	1,40	22,1
O	98	483	8,05	1,39	17,2
R	91	441	7,53	0,98	13,0

As seen in **Figure 5**, all three sample materials yielded single test results that did not fulfil the requirements of EN 14080, even though sample R consisted of newly produced glulam material. The mean values better illustrate the condition of the glulam, with series “K” failing, concurring with the critical condition of the structure upon decommissioning. For the other two samples, the determination of percentage wood failure becomes decisive when rating the single values, underlining the need to improve methods, consistency and precision of determination. The results indicate that single outliers should be neglected or systematically excluded, instead of strictly adhering to the 100% - rule of EN 14080.

Further statistical evaluation regarding several sampling conditions revealed, that there was no difference in glue line shear resistance depending on whether the drill cores were extracted from glue lines with or without prior partial delamination. This concurs with the observation during bending-shear tests, where cracks often deviated into the wood of the lamellas at delamination crack base, indicating that there was no negative effect of the delaminated parts on the adjacent, intact glue line.

No significant difference was found between results of drill core subsamples taken along the length of the sample beams, i.e. several meters apart. Samples taken from different sides of the sample beams yielded no deviating results, even for sample “O” where prior one-sided delamination suggested a potential negative influence. Only along the original height of 2,2 m of sample beam “K”, shear resistance values seemed to increase towards the bottom of the cross section, which might relate to the stress situation of the original beam under bending load, with bending compression on top and bending tension at the bottom.

3 CONSOLIDATION OF TEST RESULTS

Data provided in previous publications [8,14] extended the available database for the following comparison of shear resistance values. The utilized softwood glulam of the additional series was sampled solely out of current production, so the material was expected to be of good quality, and standard stiffness values were assumed. The bending-shear test setup of added series “L1”, “L2” and “L3” principally matched the previously described testing procedure. Deviations in geometric dimensions were considered employing Formula (1) and (2) accordingly. Tapering out the cross section by slot cuts to accomplish shear failure during the bending tests was included in the calculation similar to the approach taken for a partial delamination of glue lines. Also the height of the shear crack in the cross sectional height was taken into account.

On the left side of Figure 6, the mean values of bending-shear resistance, shear resistance according to EN 408 (if available), and drill core shear resistance according to EN 14080, derived for six different test series on glulam samples with three test methods, are illustrated. On the right side, the correlation between values of the large-scale bending-shear tests and the drill core shear tests is illustrated.

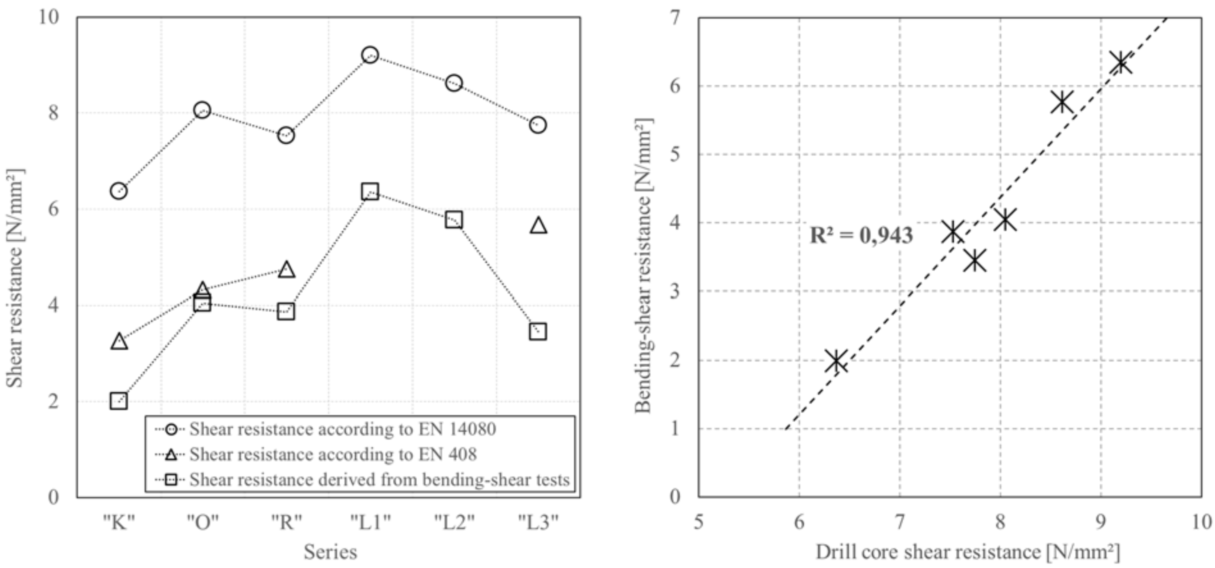

Figure 6: Left: mean values of shear resistance derived from different test setups; right: correlation between shear resistances derived from large-scale bending-shear tests and drill core shear tests

4 CONCLUSIONS

In principle, the method of drill core sampling and shear testing is suitable to assess local shear resistance values of glue lines in existing glulam structures. Together with the determined percentage wood failure, the general quality of the glue bond can be appraised. However, the standardized method of rating each single value might lead to misjudgement, as even results from freshly produced glulam material yielded solitary, failed outliers not representing the overall condition of the sample. Statistical evaluation of the derived data from tests with aged sample material indicates a negligible influence of existing delamination of parts of the glue line on the drill core shear resistance of the remaining, intact glue lines within one sample. Deviation of subsample results gathered from different locations of the samples “K” and “O” was low, respecting that each sample was taken from single beams of the original structures. If the focus of an investigation of a glulam structure lies on the general condition of the glue bond of the glulam, rather than on specific locations in certain members due to local degradation, the drill core sampling location can be chosen randomly.

To facilitate the future application of the standardized method, the project-dependent, appropriate number of drill core samples should be specified with statistical methods. Also the determination of percentage wood failure, especially for glues with little colouring, has to be further standardized. The application of lignin indicators would represent a meaningful, intermediate step towards the utilization of recently developed picture processing systems and chemical colour imaging.

Test results of EN 408 shear testing turned out somehow contradictory to prevalent presumptions, as shear resistance of the feature-clear wood material was higher for series “R” compared to series “O”, with density values being antipodal. Shear failure in glue lines could only be accomplished in specimens with very poor glue bond, otherwise failure occurred mainly in the wood, depending on the orientation of annual rings. Therefore, the EN 408 test setup is not deemed suitable for a holistic shear strength assessment of glulam.

In contrast, the EN 14080 test setup is designed to purposively test the glue line. The testing of the adjacent wood material is passively included, as it fails in shear in case of a strong glue bond. Due to the size effect, shear resistance values determined from drill core samples certainly do not concur with bending-shear resistance of the structural member. However, good correlation could be identified between the test results of large-scale bending-shear and drill core shear tests, after assuming an exponent of 0,2 for the calculative incorporation of a size effect for deviating bending-shear specimens’ shear-strained plane dimensions. This might open up the possibility to estimate the residual shear strength of existing structural glulam members on the base of drill core shear values.

5 ACKNOLEDGEMENT

This research project was funded by Forschungsinitiative Zukunft Bau, Bundesinstitut für Bau-, Stadt- und Raumforschung im Bundesamt für Bauwesen und Raumordnung, Deichmanns Aue 31-37, 53179 Bonn, Germany. The advice given by Dipl.-Ing. (FH), M.Sc. Florian Scharmacher is thankfully acknowledged.

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