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Assessment of the glue-line quality in glued laminated timber structures

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Abstract. Timber constructions with glulam members have regularly to be proofed for their performance to avoid structural collapse. For the assessment of glued laminated timber, it is important to know reliable methods and criteria. The requirements given in standard EN 386:2001 are valid for the quality control of the glulam production. The use and application of these two different methods at existing timber structures were investigated and discussed. The experimental test series comprise different adhesives as well as specimen from new material and existing structures. Problems and issues noted during the test series and analyses of the results are discussed. The correlations found provide advice for the assessment of existing structures.

Introduction

Nowadays glued laminated timber is the most common structural material for timber constructions. Glued laminated timber was already introduced by Otto Hetzer in Europe in the year 1906. There were several evolution steps between the introduction of the glulam and today, where the adhesive, the gluing process and also the produced dimensions have changed. In general, timber constructions with glulam members are regularly proofed for their performance and to detect abnormalities to avoid structural collapse. For the assessment and monitoring of glued laminated timber constructions it is important to know reliable methods and criteria, but the practical engineer has got less guidance. Usually after the first visual inspection where openings along the glue-line will be detected, the failure reason has to be clarified.

The requirements given in standard EN 386:2001 are valid for the quality control of the glulam production. These requirements are also used and discussed from practical engineers for the assessment of existing timber structures, [1], [2]. On the other hand nondestructive test methods are developed and investigated for the detection of defects along the glue line, [3], [4]. At present these methods are proofed in first steps under laboratory conditions, a practical application or availability is not known. Thus the paper focuses on the proof of a reliable application of the EN 386:2001 on existing timber structures.

The standard EN 386:2001 refers to a delamination test according to EN 391:2001 and a shear test of the glue-line according to EN 392:1995. The methods according to the two test standards result in different stress situations within the test specimen, on the one hand transverse tension stress and on the other hand shear stress. The application of these methods and requirements at existing timber structures has been investigated and discussed in comprehensive experimental test series. The experimental test series comprise different adhesives. The test methods were extended with the shear test setup according to EN 408:2010 and a modified three point bending test series.

Material and Method

Glulam and adhesives. Wood is natural grown material which limits the available cross sections and lengths for large span constructions, bridges or even for multistory buildings. However, glulam can overcome this limit. It is a well-established engineered wood product of single lamellas of solid wood glued together. The lamellas are finger jointed in length and glued together in the depth of the cross sections. Glulam is commonly produced of European spruce, fir or larch and nowadays also of hard wood like ash, beech or oak, [9], [10], [11]. The adhesive used for the lamination of the lamellas ranges from casein (historical) to a wide range of modern glues like polyurethane (PUR), resorcinol-formaldehyde (RF) and melamine-urea-formaldehyde (MUF).

Test methods and requirements. For the quality control of the glulam production, the requirements for a delamination test according to EN 391:2001 and shear strength test according to EN 392:1995 are given in EN 386:2001. The delamination test setup has been used to proof the resistance against the climate exposure during the life time of the glulam member. The test begins with a fully adsorption of water of the specimen by applying controlled vacuum and compression cycles while the specimen is under water. Finally the specimen has to be dried climate controlled using an oven with air circulation. The wet and dry cycle results in tension stress in radial direction respectively transvers to the glue line in the specimen. For the assessment, the sum of the openings along the glue line and at the end grain developed during the tests has to be taken in relation to the total glue line length at the end grain of the specimen. To respect different service classes according to EN 1995-1-1:2004 the delamination test standard differs between three methods for the wet/dry cycles. The block specimen, shown in Fig. 1, needed for the quality control of the production can easily be extracted. But for the assessment of existing structures, the block specimen defined in EN 391:2001 cannot be extracted from the structure. Therefore in addition to the standard test specimen, the test setup was also validated on core specimens as shown in Fig. 2, because this specimen can easily be extracted from existing structure.

The second required test for the quality control of glulam is a shear test of the glue line loaded in longitudinal direction. The test standard provides two specimen shapes, on the one hand the block or bar with a cross section of 50 mm by 50 mm including all glue lines of the member depth and on the other hand a drill core including only one glue line as shown in Fig. 3. The core specimen is here commonly used for the assessment of existing glulam structures. Parallel to the shear strength, the percentage of wood failure (PWF) at the failure plane after testing is visually examined. In addition to this test standard, the shear strength of the glue line was tested with a single shear test on a cube and according to EN 408:2010. The test specimens for both additional test setups were reduced at midsection to a cross section of 80 % to induce the shear stress close to the glue line, which was located at the center of the test specimen, Fig. 5.

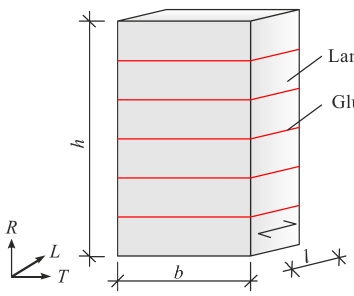

Fig. 1 Test specimen for delamination at a block

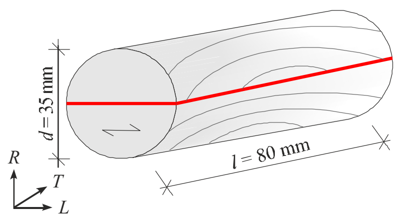

Fig. 2 Test specimen for delamination at a drill core

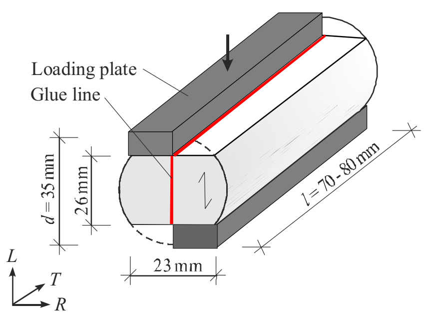

Fig. 3 Test setup for core, EN 392:1995

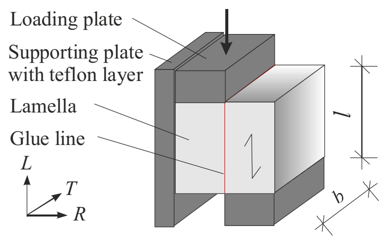

Fig. 4 Test setup for single shear test

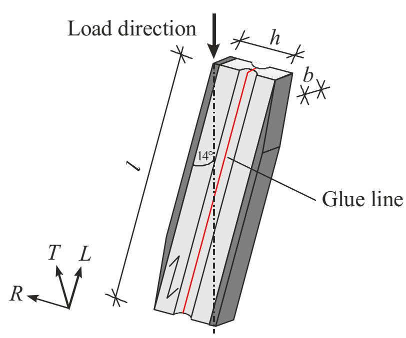

Fig. 5 Test setup for shear, EN 408:2010

Experimental test program. The experimental test program comprises delamination test series and shear strength test series. For each test series different specimens from glulam members and adhesives were considered. Table 1 summarizes the different specifications classified after the test methods used. The test method for the delamination used according to EN 391:2001 is marked with the capital letters A or B behind the standard. The shear test in test series no. 13 and 14 refer to a single plane shear test with the reduced cross section and test series no. 15 to 17 to a short three point bending test (reduced ratio of depth to span) to induced a shear failure. All specimens with the same adhesive are taken from one production series of glulam members in European spruce. The specimens are conditioned in normal climate, 20 °C and 65 % relative humidity until testing.

Table 1: Test program for delamination and shear tests

Series	Test method	Standard	Shape	Sizes [mm]	Number	Material	Adhesive
01	Delamination	EN 391-A	Block	$b/h/l$ = 160/320/75	51	GL28k-spruce	PUR
02	Delamination	EN 391-A	Block	$b/h/l$ = 160/160/75	42	GL24k-spruce	MUF
03	Delamination	EN 391-A	Core	Ø 35, l = 80	17	GL28k-spruce	PUR
04	Delamination	EN 391-A	Core	Ø 35, l = 80	14	GL24k-spruce	MUF
05	Shear test	EN 392	Core	Ø 35, l = 80	51	GL28k-spruce	PUR
06	Shear test	EN 392	Core	Ø 35, l = 80	42	GL24k-spruce	MUF
07	Shear test	EN 392	Core	Ø 35, l = 80	9	GL24h-spruce	RF
08	Shear test	EN 408	Block	$b/h/l$ = 32/55/300	9	GL24h-spruce	RF
09	Shear test	-	Block	$b/h/l$ = 160/200/200	17	GL28k-spruce	PUR
10	Shear test	-	Block	$b/h/l$ = 160/200/200	14	GL24k-spruce	MUF
11	Shear test	-	Beam	$b/h/l$ = 160/320/1350	17	GL28k-spruce	PUR
12	Shear test	-	Beam	$b/h/l$ = 160/160/800	14	GL24k-spruce	MUF
13	Shear test	-	Beam	$b/h/l$ = 80/120/650	9	GL24h-spruce	RF

Experimental results

Delamination tests according to EN 391:2001. Fig. 6 shows the standard test specimen after the test with the delaminations observed. On the other hand, a core specimen with delaminations is shown in Fig. 7. The comparison of the test series no. 01 and 05 as well as no. 02 and 06 are shown in Fig. 8 and Fig. 9 respectively. The total percentage of delamination should be less than 5 % for standard specimen of the test method A after EN 386:2001. For the assessment of the delamination of the core specimen, the same criterion was used as for the standard test specimens. However in some cases, a delamination occurred and lead to a significantly larger total percentage of delamination compared to the standard test specimens. For both adhesives PUR and MUF no correlation could be observed between the standard test specimen and the core specimen. The two test specimens result in opposite way for failed or passed.

The reason for the disagreements is due to the different transverse stress situation as result of the moisture gradient reached in the wet/dry cycle. The moisture gradient generated in the dry cycle is more homogenous and with less amplitudes for the core specimen than for the standard test specimen. Especially, the cross section ratio between the standard specimen and the core specimen results in a smaller moisture gradient for the core specimen. Furthermore the round surface leads to other stress situations than the flat sides of the standard test specimen, as shown in the numerical solutions in Fig. 10 and Fig. 11. The numerical simulation of the standard and core test specimen is based on an orthotropic material law with properties for European spruce and shows as result the stresses perpendicular to the glue line for a uniform moisture gradient during the drying process.

Shear test according EN 392:1995. In addition to the delamination test series also shear tests were carried out from the same glulam members. Furthermore test series with the adhesive RF were investigated. The core samples are used in all test series to determine the shear strength and the percentage of wood failure (PWF). The failure criterion for the shear tests depends on the shear strength reached and the corresponding PWF, as given in EN 386:2001 and shown in Fig. 13 for soft wood. With an increase of the shear strength, the allowing PWF is smaller but must be at least 20 %. Fig. 12 shows the shear failure surface for a core with RF adhesive. Fig. 13 shows the results observed for the test series no. 5 and 6 (PUR and MUF).

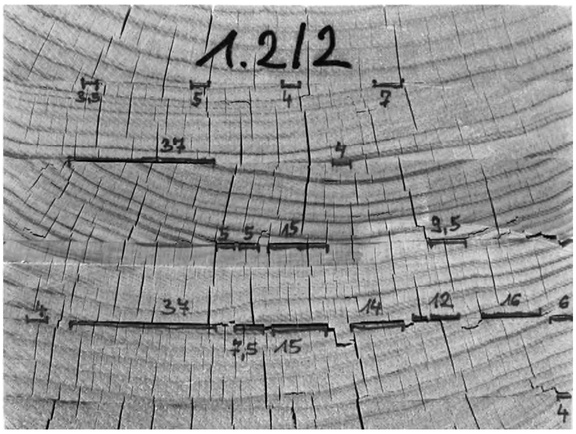

Fig. 6: Standard test specimen after the test with marked delamination

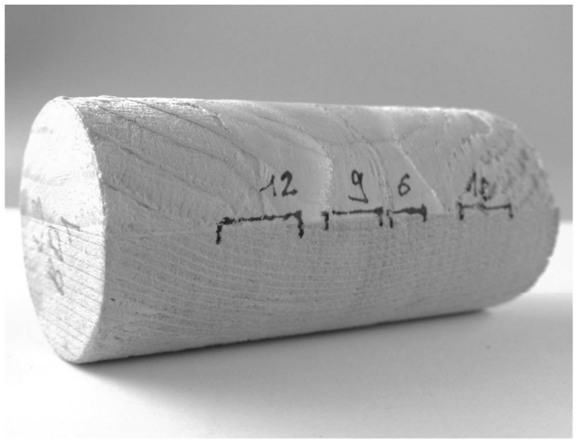

Fig. 7: Core specimen after the test with marked delamination

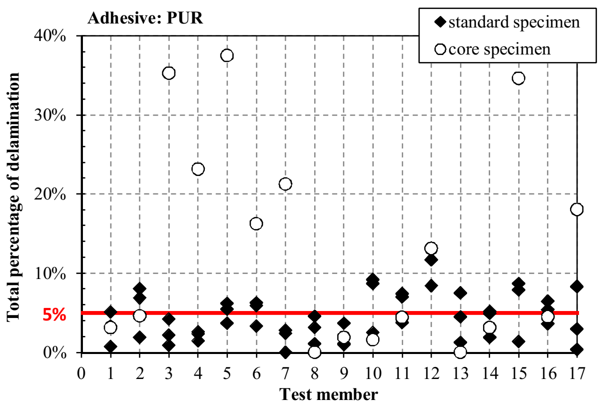

Fig. 8: Delamination test results for adhesive PUR

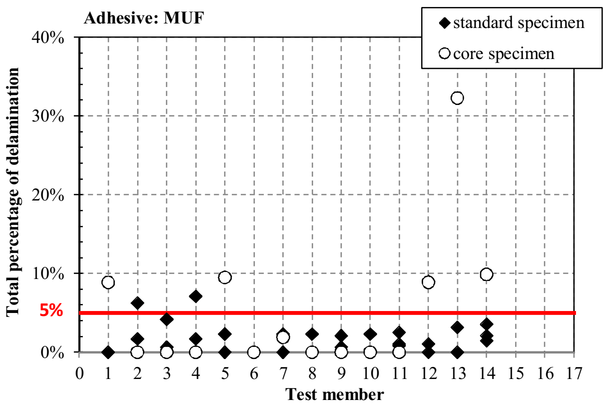

Fig. 9: Delamination test results for adhesive MUF

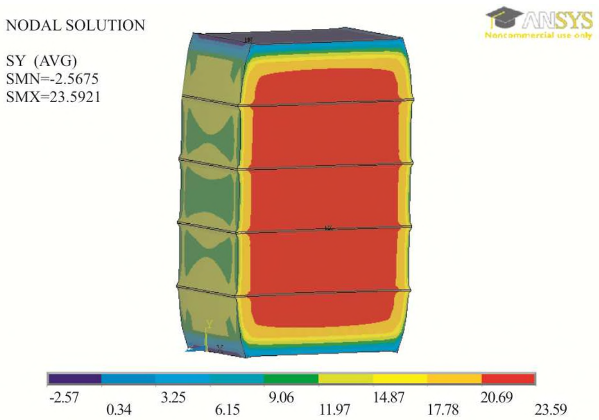

Fig. 10: Stress perp. to the glue line due to moisture gradient for the standard specimen

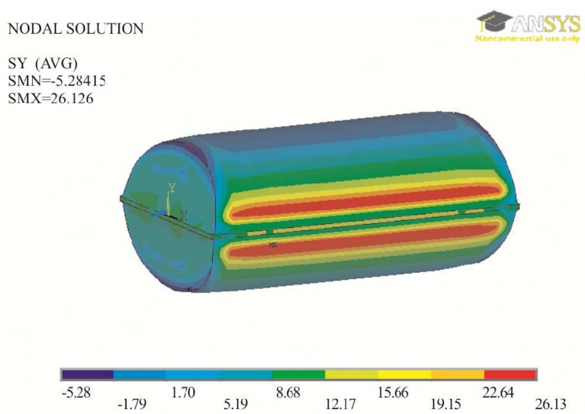

Fig. 11: Stress perp. to the glue line due to moisture gradient for the core specimen

Further shear tests. For the evaluation of the shear strength of the glue line, further shear tests with different test setup were carried out and compared as shown in Fig. 14 to Fig. 16. Parallel to the shear tests according to EN 392:1995, short three point bending tests with a reduced depth to span ratio and a reduced cross section at the glue line as well as single shear tests were carried out. The coefficient of variation is small in each test configuration. The comparison between the test setups shows differences in the mean shear strength levels because of the size effect of the specimen and the resulting interaction of different stress situations (compression, tension and shear). Furthermore the shear strengths determined are not directly comparable with the shear strength classes at the design standards.

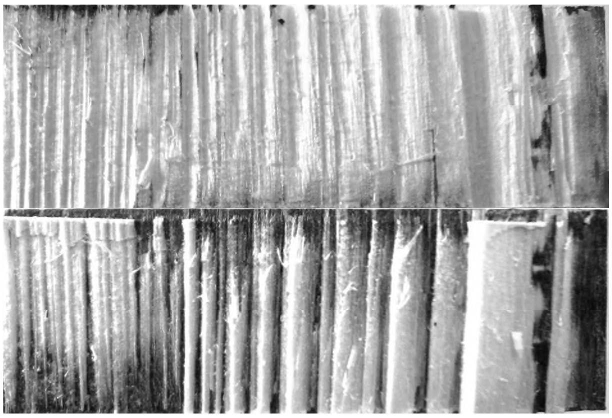

Fig. 12: Fracture surface with wood failure of a tested drill core

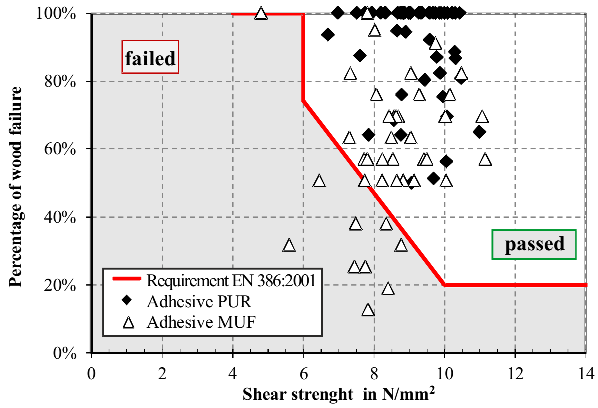

Fig. 13: Shear test results for the test series with PUR and MUF

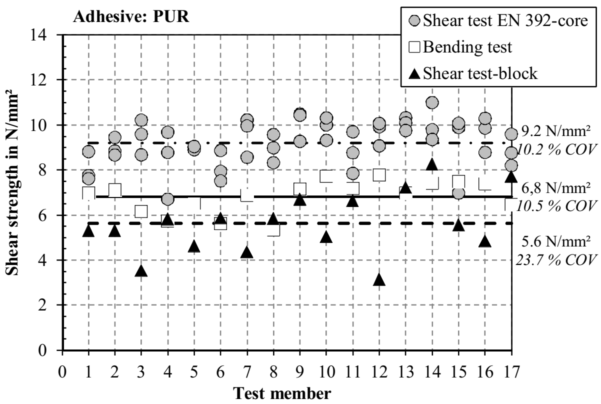

Fig. 14: Shear strength for glulam (PUR)

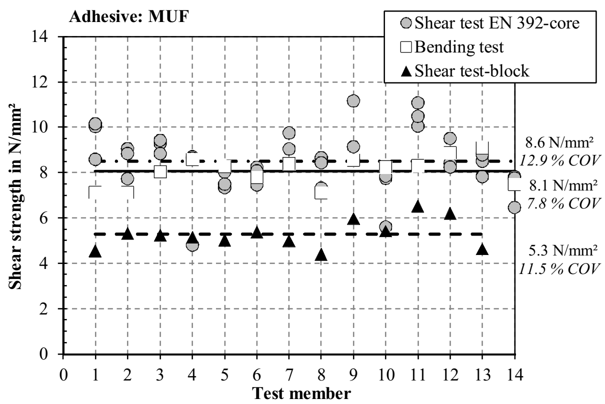

Fig. 15: Shear strength for glulam (MUF)

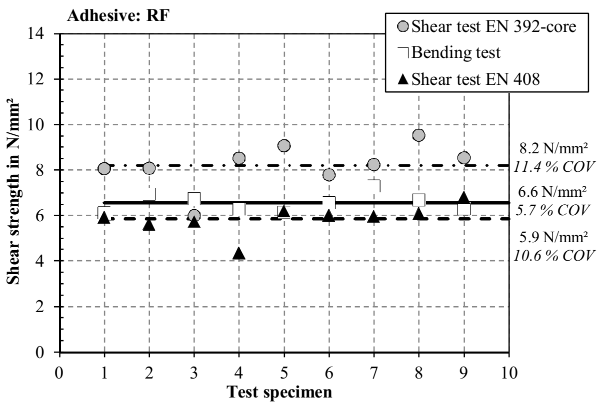

Fig. 16: Shear strength for glulam (RF)

Discussion and comparison

The EN 386:2001 requires only one of the two quality tests, the delamination or shear test, for service class 1 or 2 according to the correlation between the delamination and shear test found by Zeppenfeld & Grunwald [13]. This means theoretically that only one of the tests has to be carried out for the quality control of the production line but may also be in the assessment of existing timber structures in service class 1 or 2, EN 1995-1-1:2004. However in existing timber structures, the real moisture content can vary in a wide range and easily reach service class 3 where this agreement is not valid. Furthermore defects in the construction or temporary changes can increase the local moisture content of timber members easily. Also the correlation reachable can depend on the adhesive and wood species used, [14], [15].

Fig. 18 and Fig. 17 show the comparison of the delamination and shear tests for the test series carried out with PUR and MUF. For the direct comparison of the delamination and shear test series, the minimum required percentage of wood failure (PWF_{min}) are calculated reversely using the shear strength determined. If the ratio between the effectively (PFW) and the calculated required percentage (PWF_{min}) is less or equal to one, the specimen passed the requirements. For the delamination test series the same criteria of 5 % is used as presented before.

For the test series with the adhesive MUF, a correlation of 76 % is reached and for the test series with adhesive PUR only of 59 %. The results reached show no satisfied correlation between the shear and delamination tests. The disagreements observed confirm the dependency on the adhesive used for the production of glulam. Furthermore the delamination test is obviously the more demanding test setup, because in the cases where specimens passed the shear test, they failed in the delamination test which discloses the defects.

The delamination test replicates the different climate situation during the life time of the timber member. On the other hand shear stresses are always existent in the structure. Therefore it is important to proof the quality of new glulam member or to assess existing timber structures using both test setups, delamination and shear. However, both methods only allow a local assessment and cannot be assumed to be valid for the complete timber structure, [2].

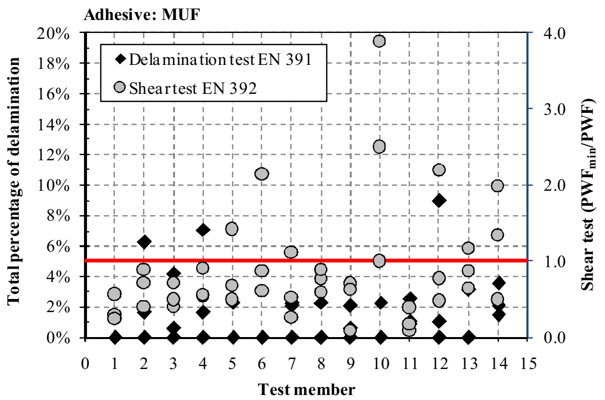

Fig. 17: Comparison of delamination test and shear test for MUF

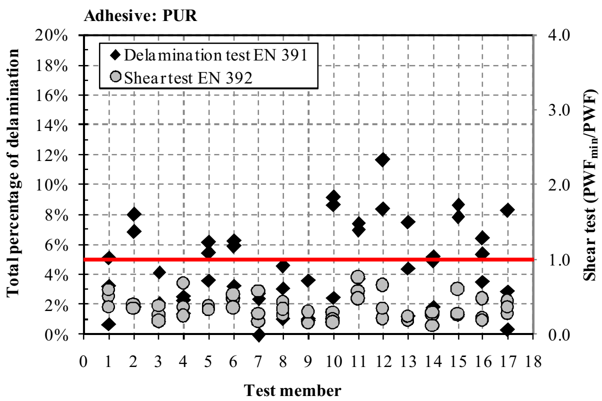

Fig. 18: Comparison of delamination test and shear test for PUR

Conclusion and view

For the objective to find reliable methods for the assessment of existing timber structures, both test setups, delamination and shear, according to EN 386:2001 were used and compared between each other and further shear test setups were carried out. For the delamination test, generally the test specimen required cannot be extracted from existing timber structures. Therefore core samples are prepared and tested with the current specified wet/dry cycles in EN 391:2001 in addition to the standard test specimen. The test results reached and the numerical simulation show that the stress situation between these two test specimens is not equal and therefore not useful for the assessment when applying the current method. The test procedure for the delamination test has to be adjusted for the core sample.

Secondly the shear strength in combination with the percentage of wood failure are determined on core samples and compared with further shear test. The comparison of the shear strength points out a size effect on the strength class. Furthermore the results observed on core samples represent only the local condition of the timber structures and is not valid for the complete structure.

Finally the correlation between the delamination and shear test according EN 386:2001 show that both test setups are necessary for a comprehensive assessment of timber structures. The two test setups are totally different in the stress situation resulting in the specimen; on the one hand transverse tension stress on the glue lines due to the wet/dry cycle and on the other hand the shear stress parallel to the glue line. The delamination test represents the loads/stresses according to the climate condition during the life cycle of the timber structure, whereas the shear test reflects more the structural loading situation. A comprehensive assessment of existing timber structures is not possible with only one test setup. To include the delamination test setup in the assessment of timber structures, a new test procedure has to be developed for small samples like the core sample used in first steps.

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