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Cross Laminated Timber (CLT) – Reinforcements with Self-Tapping Screws

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ABSTRACT: This paper illustrates a research project about the calculation and design of Cross Laminated Timber (CLT) elements stressed by concentrated loads. Its focus lies on the shear design of CLT-elements next to punctual supports including reinforcements with self-tapping screws with continuous threads in areas of high shear stresses. Different influencing parameters on the distribution of shear forces next to a punctual support were evaluated by using comparative FEM-analyses. In the course of laboratory tests material-mechanical principles were determined to consider the interaction of rolling shear stresses and compression perpendicular to the grain. In addition to FEM-simulations several experimental tests were carried out to describe the load bearing behaviour and the strengthening effect of CLT-elements reinforced by self-tapping screws. The investigations aim at developing a design concept including the effects mentioned above.

KEYWORDS: CLT, X-Lam, slab, punctual support, concentrated load, rolling shear, design, reinforcement, screw

1 INTRODUCTION

1.1 General Information

Various research projects have examined modelling methods and design concepts of plates and shells made of CLT. The load bearing behaviour of these elements is affected by the material and the constructive anisotropy due to the orthogonal orientation of the single layers. Moreover the shear deformation including the ductile composite must be considered. One approach that considers these circumstances is the method of shear analogy by Kreuzinger which is listed in annex D of the current German design code DIN 1052 [1]. Its approach and the verification procedure of DIN 1052 [1] enables structural engineers to design basic structural systems in CLT stressed by common loads. Generally the plates are supported on two sides and a uniaxial load transfer is activated (see Figure 1a). But due to the composition of the CLT-elements, with an orthogonally alternating orientation of neighbouring board layers, the slabs are also suitable for more ambitious systems like multilateral (see Figure 1b) or punctually supported ceilings (see Figure 1c and 1d). These systems profit from the biaxial load transfer and the large-scale dimensions of the prefabricated elements.

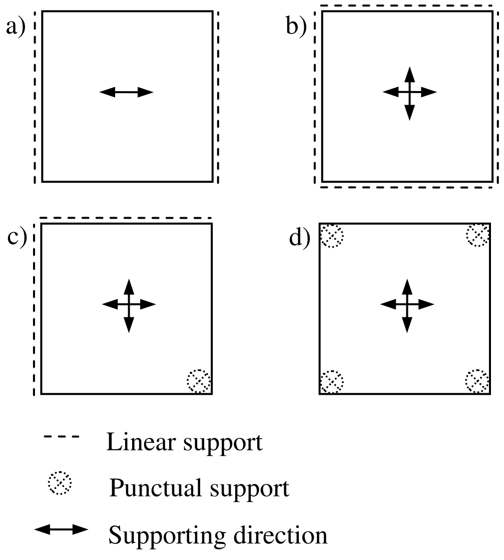

Figure 1: *Possible supports of CLT-slabs*

Analyses of punctually supported slabs reveal that generally the rolling shear capacity in the cross layers govern the design. As Figure 2 shows, the boards of the cross layers are stressed by rolling shear, that means shear stresses perpendicular to the grain. Since the rolling shear capacity is considerably lower than the shear capacity parallel to the grain shear-fracture appears in the cross layers of CLT elements (see Figure 2).

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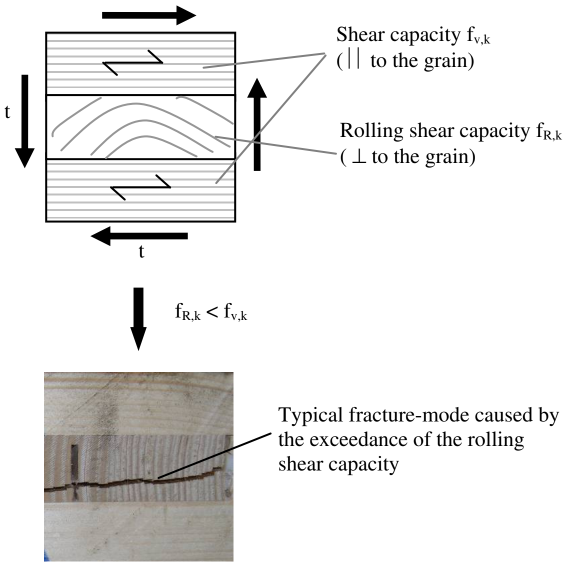


***Figure 2:** Shear-fracture*

First tests within the scope of pilot projects reveal that reinforcements with inclined self-tapping screws in areas of high load application noticeably enhance the shear capacity of the CLT-elements. An essential impact on the increase of the bearing strength is supposed to lie in the interaction of rolling shear and compression perpendicular to the grain caused by the inclined self-tapping screws and the punctual support.

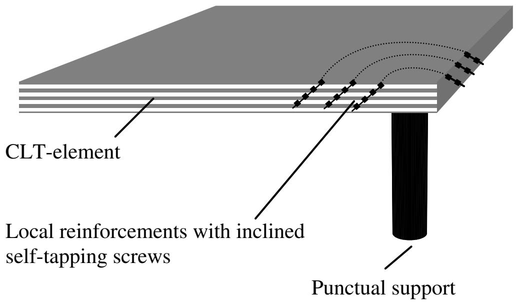


***Figure 3:** Punctual support with shear-reinforcements*

1.2 Research objectives

Following the main objectives of this research project, the required approaches and work steps for the realization can be summarised as follows:

- Reduction of the effort for calculation and design
  In the first instance it is required to reduce the effort for planning, calculation and design of basic structural systems that are punctually supported or stressed by concentrated loads. Therefore universally valid rules for the shear-design of CLT slabs that are punctually supported in the corners will be developed. Using comparative calculations the influence of different system parameters on the distribution of the shear forces in primary and secondary supporting direction will be examined. The system parameters mentioned are e.g. the dimensions of the system, the thickness and the cross section of the element as well as the number of layers. Simplified equations that are valid for standardized types of cross sections enable the calculation of rolling shear stresses that govern the shear-design.

- Interaction of rolling shear and compression perpendicular to the grain
  In areas of punctual supports high rolling shear stresses appear in combination with compression perpendicular to the grain. The same stress combination can be observed in areas of reinforcement with self-tapping screws. In the course of laboratory tests material-mechanical principals were determined to consider the mentioned stress interaction while designing the CLT-elements.

- Reinforcements with self-tapping screws
  The results of the experimental tests and accompanying FEM-analyses will form the basis of a theoretical model that enables the description of the load bearing behaviour of reinforced CLT-elements.

- Design concept
  All investigations mentioned aim at developing a designing concept for CLT-structures that are punctually supported or stressed by a concentrated load including the strengthening effect of self-tapping screws with regard to shear capacity of CLT.

2 Distribution of shear forces

In contrast to linear supported slabs with uniformly distributed loads the authors are not aware of any calculation toolkit or design chart for punctually supported constructions of cross laminated timber guaranteeing a cost-effective and safe design. In the case of shear-design it is first of all necessary to evaluate the distribution of shear forces in primary and secondary supporting direction to calculate the decisive shear stresses. Generally the primary direction runs parallel to the grain of the top layers and refers to the x-direction, while the secondary direction runs perpendicular to it and refers to the y-direction. In the following paragraphs different aspects and influencing factors concerning the distribution of shear forces are going to be examined in order to find a proposal for the simple estimation of shear stressing.

2.1 Modelling of the system

Preliminary calculations with FEM-programmes using shell or volume elements show extreme values respectively stress peaks in areas of concentrated load. The use of girder-grid-models for the calculation presents the possibility to avoid such stress peaks. Thereby an average of the resulting stresses is computed automatically depending on the chosen grid pattern. Generally the distance between the single girders should be chosen in such a way, that the dimension of the slab on the one hand and the conditions of support and load application on the other hand can be modelled with sufficient exactness. To achieve sufficient accuracy of results the distance between the girders should not exceed the benchmark of the element thickness. Within the scope of the investigations the grid pattern always amounts to 0.1 m. This represents the lower limit of element thicknesses common in praxis for plates in bending and furthermore this distance accords to typical cross sections of columns and their related supporting surface.

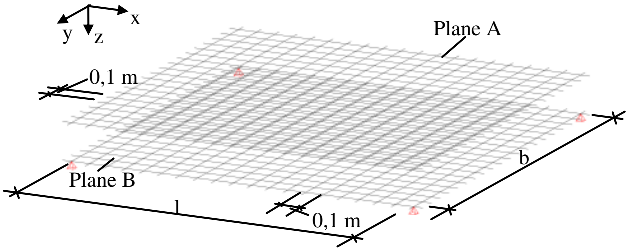


Figure 4: *Girder-grid according to shear analogy (coupling conditions are not demonstrated)*

By using the FEM-program Sofistik the simulations are based on the following input parameter and assumptions:

- The required stiffnesses are calculated according to annex D.3 of the German design code DIN 1052 [1] by applying the material constants of boards of the strength class C 24 (table F5 of [1]). Thus the rolling shear modulus amounts to 10 % of the shear modulus parallel to the grain.
- All calculation are based on the assumption that the single boards of the layers are not edge- glued. According to [1] the elastic modulus E_{90} perpendicular to the grain of the single layers was set to zero.
- The elasticity and shear modulus according to the global Cartesian coordinate system (Figure 4) of the single layers are summarized in the following table.

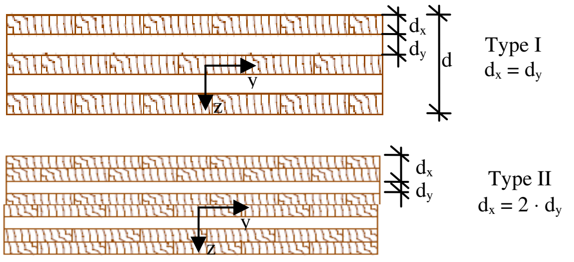
Table 1: Elasticity and shear modulus in [MN/m^2] related to the global Cartesian coordinate system

	E_x	E_y	G_{xz}	G_{yz}
Layers II to the top-layers	11000	0	690	69
Cross layers	0	11000	69	690

- Linear elastic material was used.
- All loads were applied by nodal loads in the crossing points of the girders.
- The calculations are based on the process of shear analogy. Detailed descriptions can be found among others in [2], [3] and [4].

2.2 Element Types

Due to the biaxial load transfer at punctually supported constructions element-types should be preferred that do not show significant differences concerning their stiffnesses in primary and secondary direction. Transferred to cross laminated timber elements, this applies to cross sections with orthogonally running layers and identical thicknesses of the single layers in both directions (Type I in Figure 5). The producers usually also offer element types that are optimized regarding uniaxial load transfer. These elements are characterized by higher thicknesses of the lamellas or multiple superposed lamellas running in primary direction (Type II in Figure 5). In the following the variables d_x and d_y signify the thicknesses of the single layers independent of the fact, that the layers may consist of only one lamella or of multiple superposed lamellas.



d_x thickness of the layers in x-direction
d_y thickness of the layers in y-direction

Figure 5: *Typical types of cross sections*

2.3 Evaluation of the shear forces

The distribution of the shear force respectively the support reaction in primary and secondary direction will be examined regardless of the specific distribution of shear stresses caused by the multiple layered cross sections. This means that the sum of shear forces in each direction (V_{xz} and V_{yz} in Figure 6) is crucial and not the distribution to plane A and plane B of the ideal system according to the shear analogy.

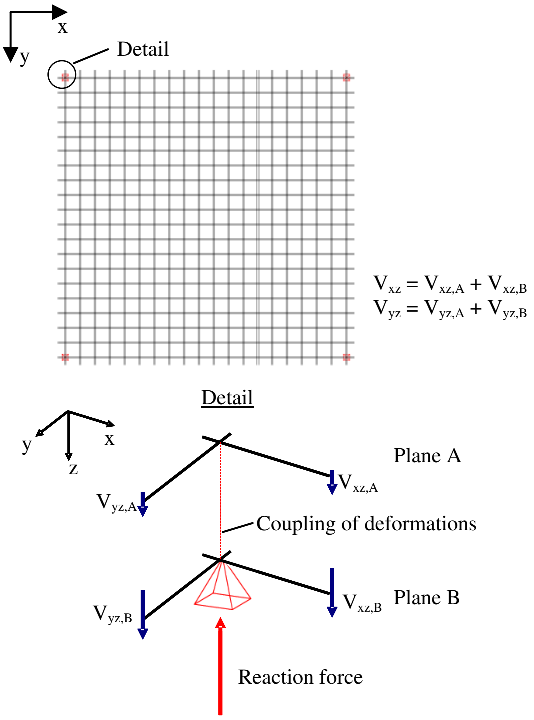


Figure 6: *Distribution of shear forces*

2.4 Results

Within the scope of the research project different influencing variables concerning the distribution of shear forces were evaluated. Detailed descriptions can be found in [8]. The significant variables and the considered limits were:

- Thickness of the elements: $0.10 \text{ m} < d < 0.22 \text{ m}$
- Ratio of l/b: $1 < l/b < 3$
- Number of Layers n: $5 < n < 11$

The results of the evaluation reveal that the distribution of shear forces next to the support of cross laminated timber elements that are punctually supported in the corner areas are predominantly influenced by the number of layers and the ratio of the thickness of the layers in primary and secondary direction (the element Types I and II in Figure 5). Other parameters, like the ratio l/b of the element dimensions or the thickness of the element can be neglected. The distribution can be described by using regression curves. These depend on the number of layers that have been evaluated separately beforehand for the element types. According to that the shear force in primary direction can be calculated by the following equations:

- Type I $(d_x / d_y = 1{,}0)$

$$V_{xz} \approx 0{,}66 \cdot n^{-0{,}095} \cdot V_z \tag{1}$$

- Type II $(d_x / d_y = 2{,}0)$

$$V_{xz} \approx 0{,}70 \cdot n^{-0{,}065} \cdot V_z \tag{2}$$

With:
n: Number of layer
V_z: Total shear force
(= support reaction force)

Figure 7 demonstrates that the proportion of the shear force in primary direction according to the structural calculation (solid line) can be well matched by the given equations of the regression curves (dotted lines).

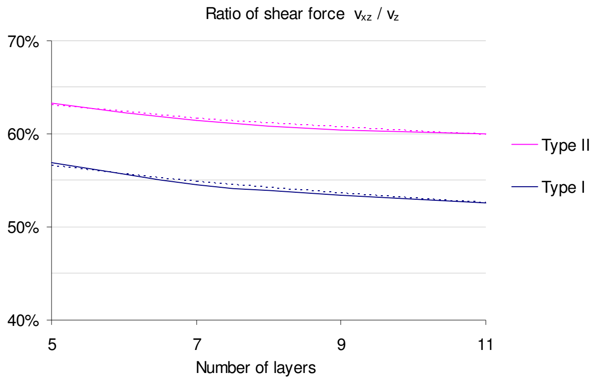


Figure 7: Proportion of shear force V_{xz}

The proportion of the shear force in secondary direction is not illustrated because it can be calculated by the equilibrium of the forces.

$$V_{yz} \approx V_z - V_{xz} \tag{3}$$

Without detailed investigations the rolling shear stresses should be verified along the outline of the load application area (Figure 8). The decisive shear forces per meter width can be calculated by the following equation.

$$v_{xz} = V_{xz} / b_y \tag{4}$$

$$v_{yz} = V_{yz} / b_x \tag{5}$$

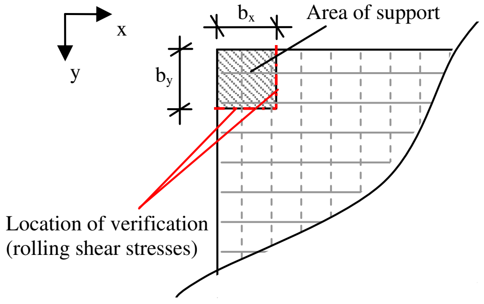


Figure 8: Location of verification

Comparative calculations confirm that the determination of rolling shear stresses according to the composite theory compared with the approach of the shear analogy provides conservative results (Annotation: The basic approach of the composite theory is described in [5] and is also listed in annex D of the DIN 1052 [1]). Since the bending stiffness of Plane B (see Figure 4) is generally more than 97 % compared to the total bending stiffness of CLT-elements it is permitted to simplify by calculating the rolling shear stresses using the total shear force in each direction and not the particular shear force of plane B. For the evaluated element Types I and II the rolling shear stress can be calculated by the following equations.

$$\tau_{R,xz} = \frac{v_{xz}}{k_{R,x} \cdot (d_x + d_y)} \tag{6}$$

$$\tau_{R,yz} = \frac{v_{yz}}{k_{R,y} \cdot (d_x + d_y)} \tag{7}$$

With:
d_x thickness of the layers in x-direction
d_y thickness of the layers in y-direction

Table 2: Coefficient $k_{R,x}$ and $k_{R,y}$

Number of layers	5	7	9	11
Coefficient $k_{R,x}$	2/1	5/2	10/3	35/9
Coefficient $k_{R,y}$	1/1	2/1	5/2	10/3

3 Interaction of rolling shear and compression perpendicular to the grain

One theoretical model that enables the description of the load bearing behaviour of reinforced CLT-elements is a strut-and-tie model as shown in Figure 9. The tension forces of the tension-ties are applied to the self-tapping screws while the timber elements form the struts in compression. In the cross layers this leads to the combination of rolling shear stresses with compression perpendicular to the grain and plane of the strip.

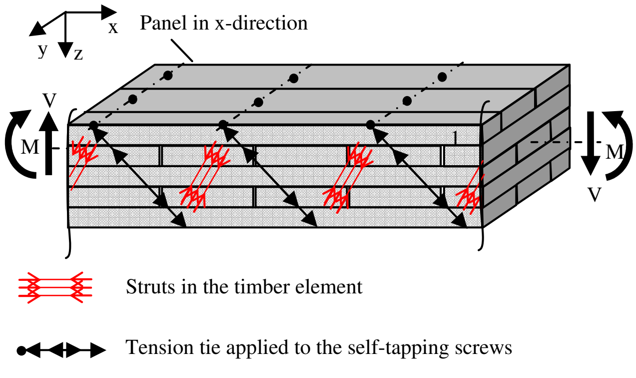


Figure 9: Strut-and-tie model of a reinforced panel

The positive effect of the lateral pressure to the shear capacity parallel to the grain is an established fact and has been object of various investigations [6], [7]. Comparable evaluations concerning the interaction of rolling shear strength and stresses (tension and pressure) perpendicular to the grain are not yet available, but an increase in the bearing rolling shear capacity in combination with compression perpendicular to the grain is to be expected.

3.1 Preliminary Investigation

Various testing methods to determine shear strength exist in the current design codes. The code DIN CEN 14966 [9] contains different “small scale indicative test methods for certain mechanical properties” while the code DIN 52187 [10] is concerned with the shear strength parallel to the grain of wood samples. The testing methods of the mentioned codes are basically similar (Figure 10), but they are related to faultless, cubic small test pieces with an edge length of about 50 mm. The same applies to the test method according to DIN EN 392 [11] that verifies the shear strength of glue lines of glue-lam by testing core or bar samples.

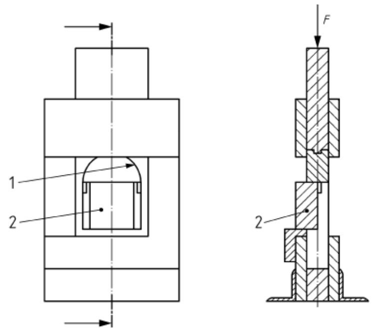


Figure 10: Shear test according to DIN CEN 14966 [9]

Another test method for the determination of the shear strength parallel to the grain is listed in DIN EN 408 [12]. The use of laterally glued steel laces for the load application causes a constant shear stress in the test specimens. The test is performed with test specimens being inclined at an angle of 14° against the vertical and the action line of the exterior shear force runs through the centre of it (Figure 11).

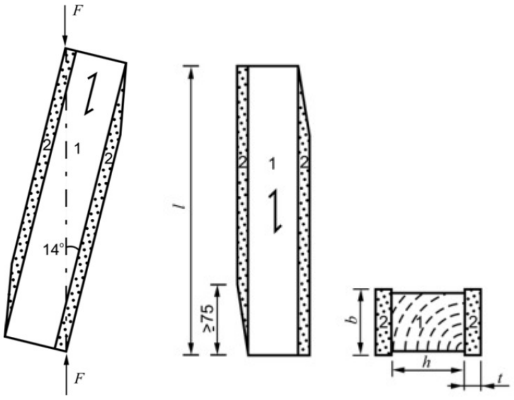


Figure 11: Shear test according to DIN EN 408 [12]

On the basis of the testing method of DIN EN 408 [12] different test configurations with regard to the determination of the rolling shear strength were examined. The configuration is meant to induce a continuous distribution of rolling shear stress τ_R and at the same time a specific lateral pressure σ_{90} perpendicular to the shear plane (axe A-A of Figure 12). The stressing and the dimensions are illustrated in Figure 12.

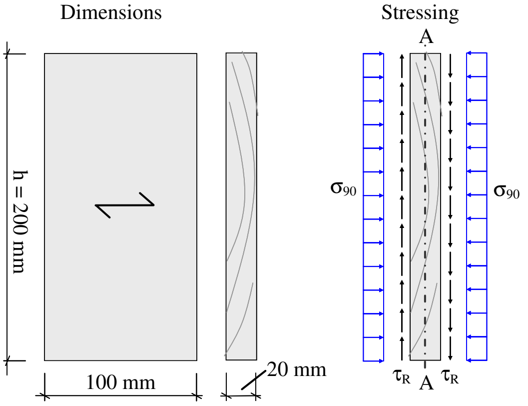


Figure 12: Dimensions and stressing of the test sample

The simulations of the various test configurations were also implemented with the FEM-programme Sofistik. This time shell elements and linear elastic material properties were used. The following influencing parameters were evaluated:

- Inclination α
- Material of the laces
- Geometry of the laces (thickness, overhang…)

The results of the simulations lead to the configuration demonstrated in Figure 13. Compared to other evaluated variants [8] it shows an almost constant distribution of the rolling shear stress along the shear plane. Stresses perpendicular to the grain can be noticed in the area of the upper and lower edges of the shear plane. But these stress peaks decrease significantly with increasing distance to the load application. In the middle area the stress perpendicular to the grain shows quite a constant distribution.

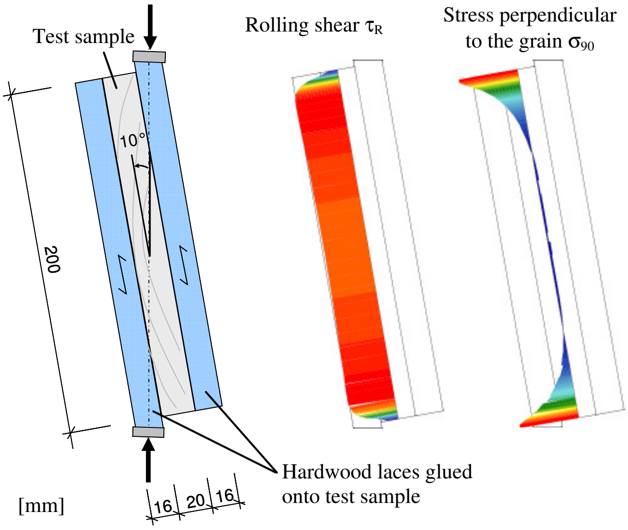


Figure 13: Test configuration and distribution of stresses

3.2 Final test configuration

As already mentioned some of the test samples will be stressed by a combination of rolling shear and a specific lateral pressure perpendicular to the shear plane. The initiation of the lateral pressure will be developed by lateral steel plates coupled with exterior rods. The rods in combination with the head plates and the impression cylinder enable the initiation of a specific lateral pressure that can be controlled by the load cell as well (Figure 14). Fraction minimizing teflon plates between the hardwood laces and the steel plates avoid any transfer of shear forces by the framework and guarantee free shear deformation of the test sample.

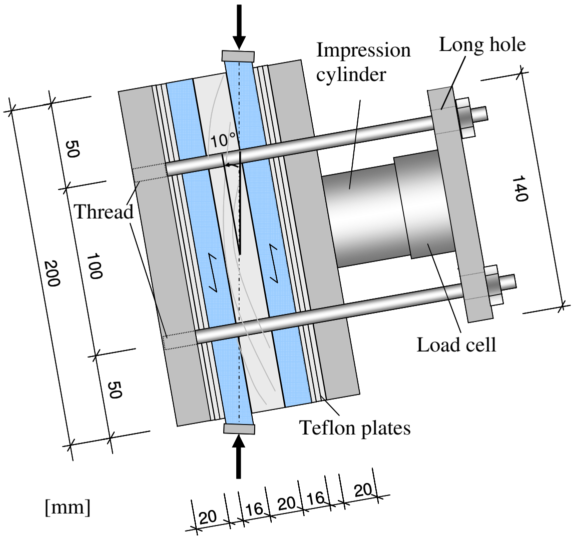


Figure 14: Test configuration for the case of specific, additional lateral pressure

Due to the process of production cross laminated timber elements may have gaps between the single boards of one layer or even relief grooves parallel to the grain in the board itself. In order to evaluate their influence on the rolling shear capacity some test samples were prepared with such relief grooves. The dimensions and the arrangement of the grooves are shown in Figure 15.

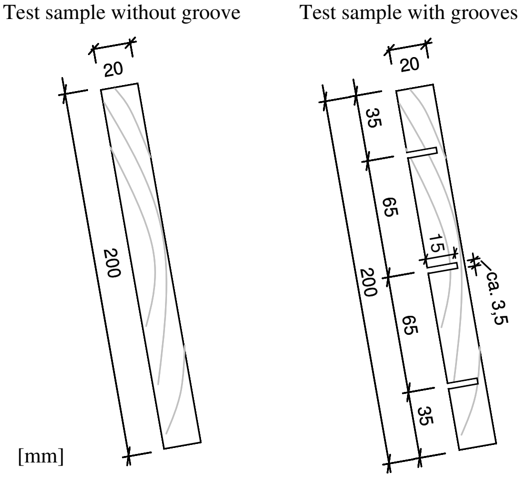


Figure 15: Test samples with and without relief grooves

Shear deformation induces tension perpendicular to the grain in the corner regions of the relief grooves. The rolling shear capacity is reduced in these areas and it may be expected that failure will also be initiated there. Analyses of the FEM-simulation reveal the mentioned stress peaks next to the relief grooves (Figure 16).

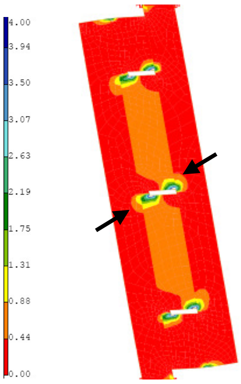


Figure 16: FEM-Analysis – tension stress perp. to the grain

3.3 Research objective

The laboratory tests described aim at the determination of material-mechanical basic principles concerning the interaction of rolling shear stresses and compression perpendicular to the grain. Comparing the test results of samples with and without additional lateral pressure first predictions can be made about the strengthening effect due to lateral pressure. Because of the small random sample used in the preliminary tests the main focus is directed on the increase of the strength and not on the value of the rolling shear strength itself.

4 Experimental test on CLT-elements with reinforcements of self-tapping screws

Within the scope of this project different types of shear tests on CLT-elements with reinforcements of self-tapping screws with continuous threads are being planned. By varying the types of cross sections, the arrangements of the screws and by comparing test samples with and without gaps and relief grooves in the cross layers information will be received about the load bearing behaviour of reinforced CLT-elements.

4.1 Preliminary Investigation

Obtaining technical approvals for cross laminated timber, both on national level in form of an abZ issued by the DIBt and on European level (ETA issued by the EOTA) shear tests are required to determine the rolling shear strength of the elements. The test were carried out on the basis of DIN EN 408 [12] respectively CUAP 03.04/06 [13] by four-point-bending tests. Generally the span is about ten times the thickness of the element and the load application is placed in each third of the span. It is assumed that the ideal shear stress distribution will appear in the area between the support and the load application. In fact compression perpendicular to the grain appears in the areas of support and load application and induces combined stress in the cross layers governing the shear-design. To illustrate this stress combination the system of a typical four-point-bending test according to CUAP 03.04/06 [13] has been simulated for a seven-layer CLT-element. Figure 17 shows the course of the resulting shear stresses and the lateral pressure in selected paths. Gaps or relief grooves in the single boards of the cross layers were not taken into consideration in the FEM-model.

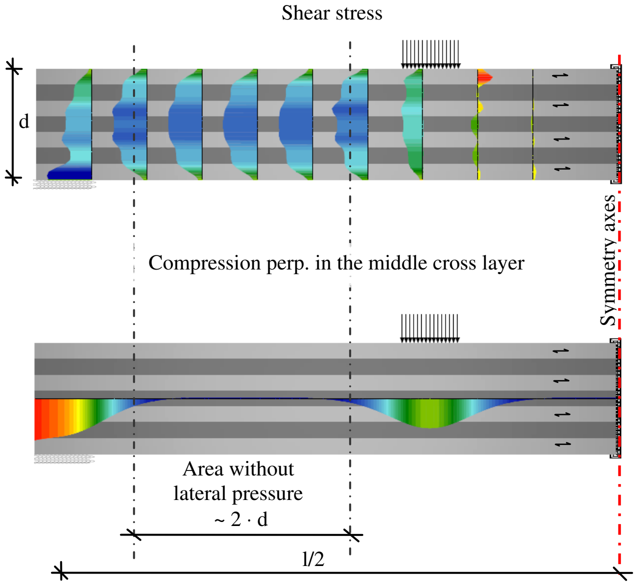


Figure 17: *Four-point bending test - stress distribution*

The results of the FEM-calculation with shell elements reveal that the area without lateral pressure is only twice the thickness of the element. In the remaining area between the support and the point of load application shear stresses as well as lateral pressure appear. As explained in chapter 3 it may be expected that the interaction will have strengthening effects on the shear capacity due to the compression perpendicular to the grain so that the shear-test results will be influenced positively. Furthermore the shear-free area in the central third of the span and the areas with the stress interaction mentioned cause dowelling effects similar to the one that appears next to the overhang of a beam and its support. It can be assumed that the rolling shear strength obtained in these four-point-bending tests is caused by system-specific shear strength.

Hence an alternative test method will be applied in the course of the project to determine the rolling shear strength minimizing the negative effects mentioned. Therefore a shear element inclined against the vertical by 10° will be stressed by a shear force. The load will be induced at the cross-grained wood of the layers parallel to the primary direction. This test configuration has been simulated by using a FEM-shell-model. Figure 18 shows the distribution of rolling shear stresses and lateral stresses in the centre cross layer.

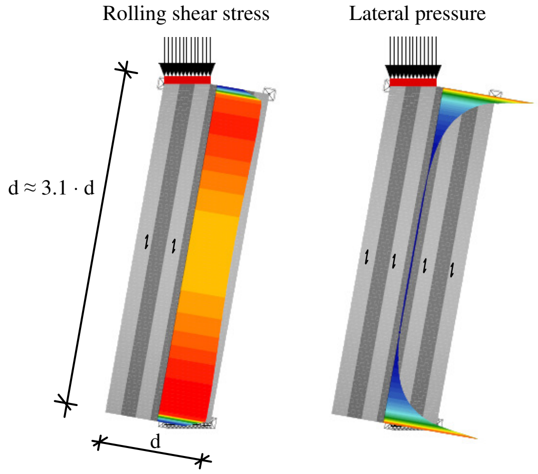


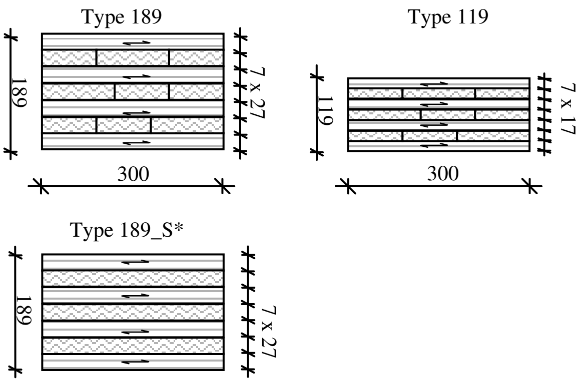
Figure 18: *Shear element - stress distribution*

In contrast to the four-point-bending test an almost constant distribution of rolling shear stresses along the whole length of the test specimen appears in the shear element, so that dowelling effects are not expected. The lateral pressure perpendicular to the shear plane due to the inclined load initiation is mainly located in the boundary region and it decreases comparatively quickly.

To evaluate the differences between the mentioned methods both configurations will be tested within the scope of the research project.

4.2 Composition of test samples

The evaluated cross sections consist of seven-layer elements with an invariable thickness of the single layers. The total thickness amounts to 119 and 189 mm. Except for the series of the element type 189_S, that is produced with edge-glued cross layers, the remaining elements contain gaps and relief grooves between or in the single boards.



* edge-glued cross layers!

Figure 19: *Element types*

Due to the different thicknesses of the element types the arrangements of the self-tapping screws with continuous threads are adapted to the different test series. Table 3 and Table 4 allow a general view of the chosen arrangements depending of the total thickness of the element. The same arrangements of the screws are used for the four-point bending tests as well as for the test method with the shear element.

Table 3: Type 119

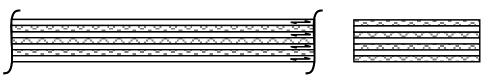
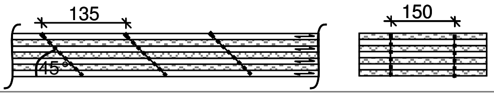
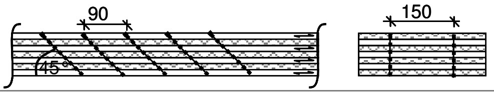
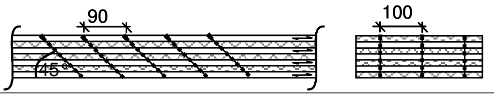
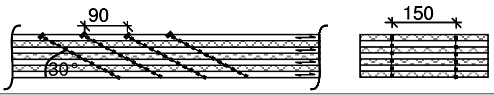
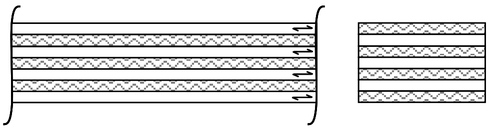
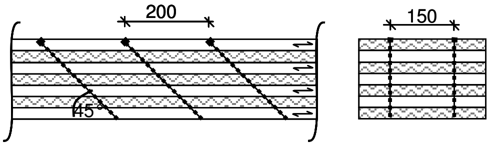
Arrangement of the screws [mm] Screws with continuous thread d = 8.0 mm	Series
	119-0
	119-1
	119-2
	119-3
	119-4

Table 4: Type 189 respectively 189_S

Arrangement of the screws [mm] Screws with continuous thread d = 8.0 mm	Series
	189-0
	189_S-0
	189-1
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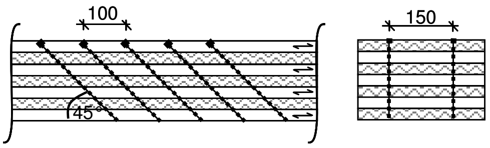
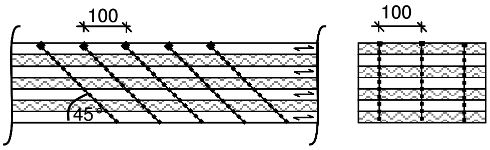
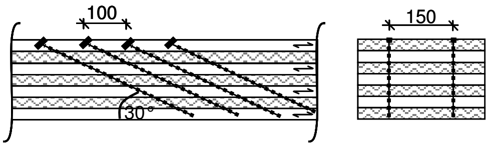
	189-2
	189_S-2
	189-3
	189_S-3
	189-4
	189_S-4

The main focus of the test is directed to the strengthening effects due to the reinforcement by self-tapping screws with continuous threads. As the tests are still being run the first results will be presented at the oral presentation of the conference.

5 CONCLUSIONS

This paper presents a view of the planned and in some cases already accomplished investigations in the course of the current research project carried out by the authors of the Chair of Timber Structures and Building Construction. Based on comparative analyses an approach was developed to estimate the distribution of shear forces in primary and secondary direction caused by the reaction force of punctual support. It will allow calculating the resulting rolling shear stresses for standard types of cross sections by simplified equations. Using FEM-simulations several test configurations were designed to investigate basic principals concerning the interaction of rolling shear and lateral pressure as well as gathering information on the strengthening effect of reinforcements by self-tapping screws with continuous threads. The results of these experimental tests and accompanying FEM-analyses will form the basis of a theoretical model that enables the description of the load bearing behaviour of reinforced CLT-elements.

The investigations aim at developing a design concept for CLT-structures that are punctually supported or stressed by a concentrated load, including the strengthening effect of self-tapping screws in regard to the shear capacity of CLT.

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