WCTE WORLD CONFERENCE ON TIMBER ENGINEERING 2010

Verification of CLT-plates under loads in plane

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ABSTRACT: Cross laminated Timber (CLT) – sometimes also denoted as X-lam – can be used as a plate element for loads in and/or out of plane. Wall-elements primarily carry loads in plane. These loads develop two internal normal forces and one shear force in the CLT-element. Especially shear strength and shear stiffness of CLT-elements should be treated in this paper.

Shear stresses and shear stiffness are analysed on basis of a representative volume element (RVE) of a CLT-element. This RVE can be simplified further to a representative volume sub-element (RVSE). A theoretical infinitely thick CLT-element with layers of equal thickness has to be assumed for this simplification, because in this special case all middle planes of each layer act as planes of symmetry. Shear stiffness on basis of this RVSE was already presented at WCTE 2006 in Portland. The same RVSE can be used for shear strength verifications with its two main mechanisms shear in a single board and a local torsional moment in the gluing interface between two boards. An adjustment to real CLT-elements with an odd number of layers and different layer thicknesses has to be made subsequently especially for shear strength verifications. Shear stiffness calculations and shear strength verifications on basis of this model for CLT-elements will be shown in a concluding example.

Shear strength for loads in plane of CLT-elements is considerably higher than the corresponding value for glulam. On the basis of a test series with a new test configuration, developed at the Institute for Timber Engineering and Wood Technology in Graz in 2008, a shear strength value of approximately 8-10 N/mm² can be proposed for loads in plane. A value of 2.5 N/mm² was determined for the torsional strength in the gluing interface, which has already been presented at WCTE 2004 in Lahti.

KEYWORDS: CLT, CLT wall, loads in plane, shear stiffness, shear strength, multilayer, WCTE 2010

1 INTRODUCTION

Cross laminated Timber (CLT) – sometimes also denoted as X-lam – is a relatively young timber product, which allows the development of a solid timber construction system, similar to the traditional European solid construction system made of bricks. For a long time the utilisation of CLT was limited to the German-speaking countries, where the product is well known as Brettsperrholz (BSP).

If CLT acts as a wall-element (Figure 1), loads in plane have to be transmitted, which develop two internal normal forces and one shear force. In the following paper considerations due to stiffness and strength verification of loads in plane are considered. Especially shear strength and shear stiffness of CLT-elements, which are the more complex topics, should be discussed here.

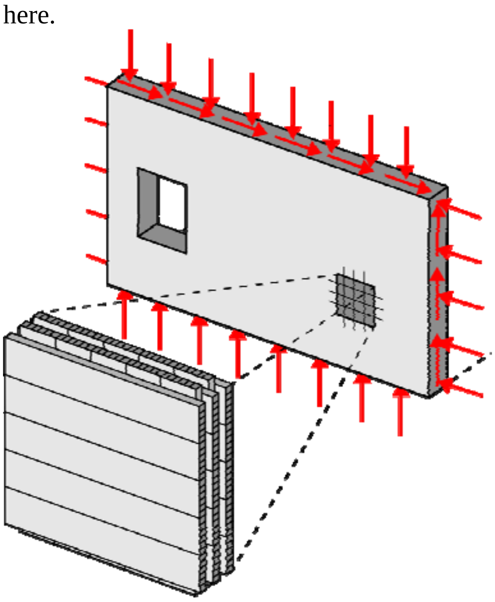

Figure 1: 5-layered CLT wall under loads in plane

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CLT is an orthogonal layered planar structure with two main orthogonal orientations, which are a result of the two possible arrangements of the timber boards in the individual layers. The smallest unit for static verifications and mechanical treatment is the Representative Volume Element (RVE). The size of one particular RVE is a result of the width of one board and possible additional gap between the boards in both main directions. The thickness of each RVE is equal to the overall CLT thickness. Regarding only loads in plane, which leads to constant stresses and strains in thickness, further simplifications can be made, if the thickness is constant for all layers and an infinite number of layers in thickness direction is considered. All middle areas of the individual boards become planes of symmetry with a normal vector in thickness direction. The remaining part between two adjacent planes of symmetry (symmetry, see Figure 2) is the smallest possible element for stiffness calculation and bearing verification and is called the representative sub-volume element (RVSE, Figure 2). This RVSE element neglects boundary effects due to the finite number of layers (i.e. 3-, 5- or 7-layered CLT-elements are commonly used in practice). These effects have to be considered in a separate subsequent step.

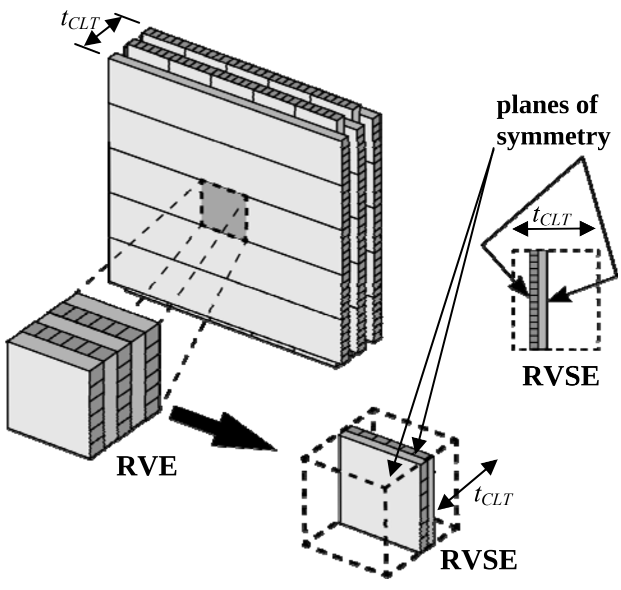


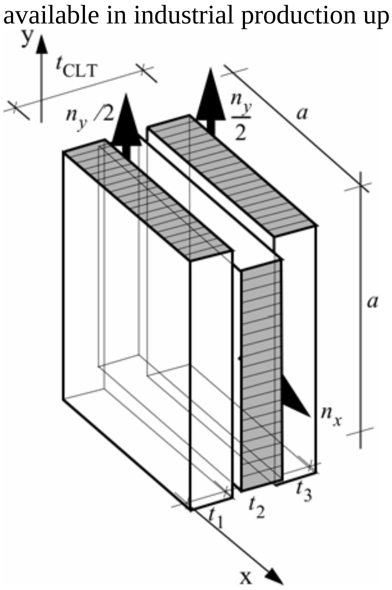
Figure 2: RVE and RVSE element of a CLT

2 CLT stiffness for loads in plane

2.1 Stiffness for normal forces D_x and D_y

Determination of stiffness values D_x and D_y is relatively simple on basis of an effective section. Only the longitudinal stiffness in fibre direction of each single board is taken into account. The stiffness perpendicular to grain is neglected completely. This negligence can be justified with e.g. easy developing cracks. Another argument is the existence of gaps between the boards, if the boards are not glued together laterally (see Figure 5).

When only cross section areas are taken into account, CLT stiffness for normal forces can be established by a simple geometric procedure (Figure 3). If the modulus of elasticity (MOE) is not equal for all boards, thicknesses have to be adequately weighted. CLT-elements with different characteristic moduli of elasticity are not available in industrial production up to now.



$$n_x = D_x \cdot \varepsilon_x + C_{xy} \cdot \varepsilon_y$$
$$n_y = C_{xy} \cdot \varepsilon_x + D_y \cdot \varepsilon_y$$

$$D_x = E_{0,mean} \cdot t_2$$
$$D_y = E_{0,mean} \cdot (t_1 + t_3)$$
$$C_{xy} \approx 0$$

$E_{0,mean}$ … mean modulus of elasticity of single board (MOE)

Figure 3: RVE element stiffness for normal forces

2.2 Stiffness for shear forces

2.2.1 General types of CLT-elements

A distinction between CLT-elements with and without lateral gluing interfaces at the narrow faces of the boards shall be made, because the mechanical treatment for shear differs in principal. These two different types of CLT-elements are illustrated in Figure 4 and Figure 5.

Figure 4: Single layer of a RVE element with lateral gluing interfaces at the narrow faces

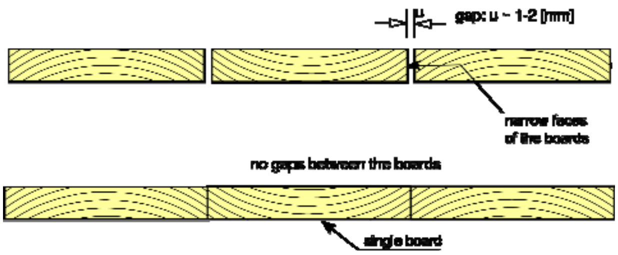


Figure 5: Single layer of a RVE element without lateral gluing interfaces at the narrow faces

Additionally a large lateral gap between the boards – denoted as *u* – can be taken into account, as it was shown in [1]. As CLT-elements should not act only mechanically, but perform also other aspects considering e.g. building physics, the lateral gap between the boards should be as small as possible in order to achieve enough air tightness. The air tightness can be proven in laboratory or in situ with the 'Blower-Door-Test'. Hence *u* is assumed to be negligible small for all following considerations.

2.2.2 Shear stiffness for CLT-elements with lateral gluing interfaces at the narrow faces

If the narrow faces of the boards are glued together, the effective shear stiffness is concordant with the corresponding shear stiffness of the timber boards.
Due to climate change cracks will develop in CLT structures. This implies, that the structural differences between CLT-elements with and without lateral gluing interfaces at the narrow faces will decrease. Therefore it is recommended to use formulas of the following subchapter in order to be on the safe side. In this case the parameter *a* (see 2.2.3) denotes a mean distance of the developed cracks, which can be estimated in most cases only on basis of experience.

2.2.3 Shear stiffness for CLT-elements without lateral gluing interfaces at the narrow faces

The determination of the shear stiffness without lateral gluing interfaces at the narrow faces was already discussed in a WCTE paper [1]. Here some remarks and extensions due to boundary effects of a real CLT-element (see 2.2.4) are appended. The theoretical investigations were carried out on the **RVSE** as described in the introduction (see Figure 2). *a* denotes the width of an individual board. If *a* is not constant for all boards, a mean value should be used for approximation. *t* indicates the thickness of the boards. In case of varying thicknesses a mean value for *t* shall be introduced. The quotient *t/a* describes the geometry of the internal structure of the CLT-element. These values together with the moduli of shear are the main parameters for the determination of the in plane shear stiffness of a CLT-element.
The total shear stiffness can be assembled by two separate mechanisms, which can be superposed regarding the flexibility. Mechanism I is a pure shear mechanism with full shear force transmission at the narrow faces of all boards, as described in chapter 2.2.2, The shear deformation γ_I is shown in Figure 6.
Mechanism II contains all changes, which have to be made at the RVSE, in order to vanish all shear stresses at the narrow faces of the boards. This local stress redistribution of Mechanism II is caused by a local torsional moment acting on both sides of the gluing interface. The shear deformation of Mechanism II is shown in Figure 7. The torsional twist φ of Mechanism II can be interpreted as an additional shear deformation γ_{II}.
Adding the flexibility of the two mechanisms leads to the effective shear deformation γ of a CLT-element

$$\gamma = \gamma_I + \gamma_{II} \tag{1}$$

with shear deformation for Mechanism I

$$\gamma_I = \frac{\tau_0}{G_{0,mean}} \tag{2}$$

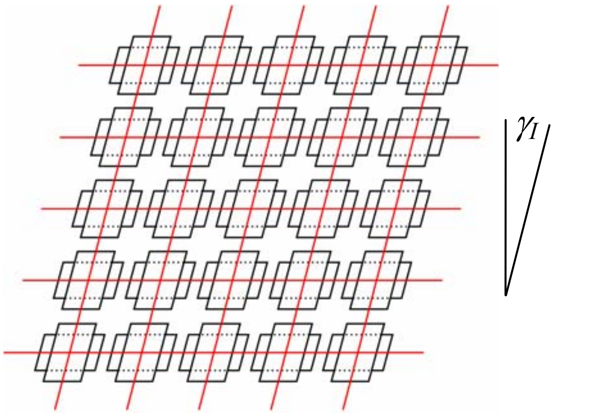


Figure 6: Mechanism I "shear" + shear deformation γ_I

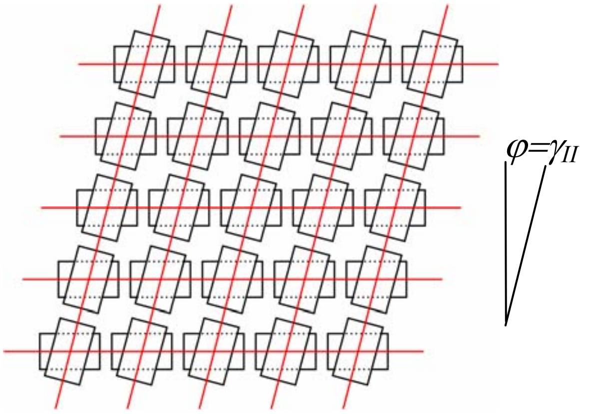


Figure 7: Mech. II "torsion" + shear deformation γ_{II}

and shear deformation for Mechanism II

$$\gamma_{II} \cong \frac{t}{2} \cdot \frac{\tau_0 \cdot t \cdot a^2}{\frac{G_{0,mean}}{2} \cdot \frac{a^4}{6}} = \frac{6 \cdot \tau_0}{G_{0,mean}} \cdot (\frac{t}{a})^2 \tag{3}$$

$G_{0,mean}$ mean shear modulus of the boards
a board width or mean distance of cracks
t mean thickness of boards
γ overall shear deformation
γ_I shear deformation of Mechanism I
γ_{II} shear deformation of Mechanism II
The torsional shear stiffness for Mechanism II is unknown, $G_{0,mean}/2$ is used as an approximation (for more details see [1]).

γ_I/γ delivers the relation $G^*/G_{0,mean}$ of the effective modulus of shear of the CLT-element (G^*) to the mean modulus of shear of all boards ($G_{0,mean}$):

$$\frac{\gamma_I}{\gamma} = \frac{\gamma_I}{\gamma_I + \gamma_{II}} = \frac{G^*}{G_{0,mean}} = \frac{1}{1 + 6 \cdot (\frac{t}{a})^2} \tag{4}$$

G^* shear modulus of CLT-element
As the shear deformation of Mechanism II can only be approximated with equation 3 and 4, a FE study was carried out for achieving better mechanical results. The

final governing equation was established by fitting the results of several FE models with increasing *t/a* parameter and is given in the following equation [1]:

$$\frac{G^*}{G_{0,mean}} = \frac{1}{1+6\cdot\alpha_{FE-FIT,ortho}\cdot(\frac{t}{a})^2} \quad (5)$$

where the correction function $\alpha_{FE\text{-}FIT,ortho}$ is

$$\alpha_{FE-FIT,ortho} = 0.32\cdot(\frac{t}{a})^{-0.77} \quad (6)$$

A graphical illustration of the effective shear stiffness as a function of the parameter *t/a* (equation 4, 5 and 6) is given in the following Figure 8.

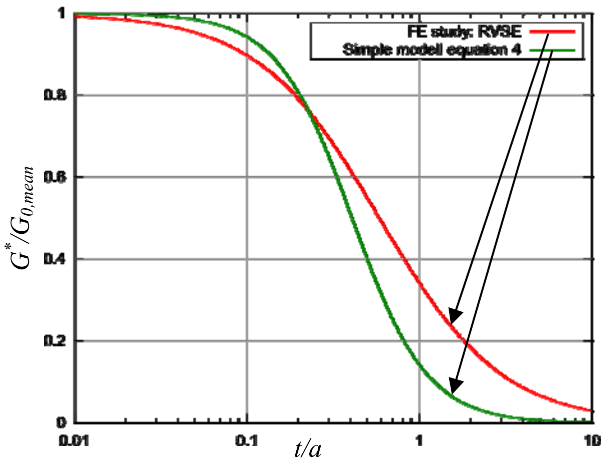


Figure 8: Effective shear function of a RVSE of CLT

2.2.4 Boundary effect on shear stiffness for CLT-elements

No effect due to the finite number of layers was considered in the above equation [1] until yet. The influence of boundary effect on shear stiffness is investigated in an actual diploma thesis at Graz University of Technology [2]. A new series of FE models was generated and investigated due to shear in plane and – as a new consideration – due to twisting.
As FE models in [1] and [2] differ in discretisation, slight differences also occur in the correction function $\alpha_{FE\text{-}FIT,ortho}$. The basic function for $G^*/G_{0,mean}$ still matches equation 5. The correction function $\alpha_{FE\text{-}FIT,ortho}$ for a RVSE is given in [2] by

$$\alpha_{FE-FIT,ortho} = 0.3117\cdot(\frac{t}{a})^{-0.7474} \quad (7)$$

Differences of shear stiffness on basis of correction function $\alpha_{FE\text{-}FIT,ortho}$ equation 6 and 7 remain very small and are neglectable. The correction function $\alpha_{FE\text{-}FIT,ortho,3}$ for a 3-layered CLT-element is given in [2] by

$$\alpha_{FE-FIT,ortho,3} = 0.5345\cdot(\frac{t}{a})^{-0.7947} \quad (8)$$

The correction function $\alpha_{FE\text{-}FIT,ortho,5}$ for a 5-layered CLT-element is given in [2] by

$$\alpha_{FE-FIT,ortho,5} = 0.4253\cdot(\frac{t}{a})^{-0.7941} \quad (9)$$

A graphical illustration of the effective shear stiffness of real CLT-elements in comparison to the RVSE on basis of different correction functions $\alpha_{FE\text{-}FIT,ortho}$ (equation 7, 8 and 9) is given in the following Figure 9.

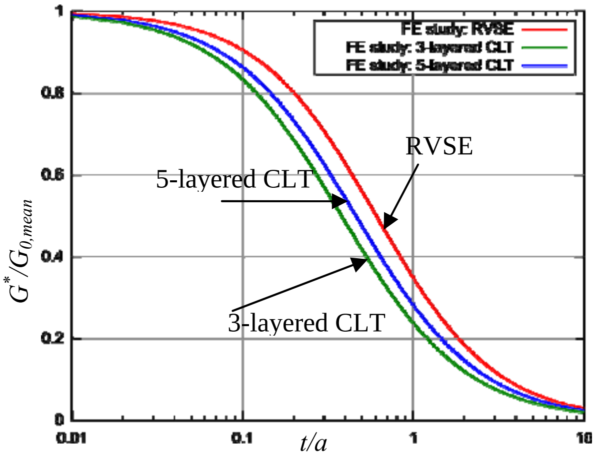


Figure 9: Effective shear function of a CLT-element

3 ULS verifications for CLT-elements

3.1 ULS verifications for normal forces n_x and n_y

ULS verifications for the design values of the normal forces $n_{x,d}$ and $n_{y,d}$ can be carried out similar to considerations given in chapter 2.1. The according design stresses are determined taking into account the effective net sections (that means, only cross sections perpendicular to grain are regarded). The appropriate characteristic strength for tension ($f_{t,k}$) or compression ($f_{c,k}$) in combination with the k_{mod} factor, which considers the duration of loads, and the partial safety factor γ_M leads to the design strength.
In the following the ULS verification will be shown exemplarily for a three layered CLT-element, illustrated in Figure 10. The verifications must be adopted analogously to CLT-elements with 5 or more layers.
Following conditions have to be fulfilled. Usually symmetry is given in thickness direction, resulting in $t_1=t_3$.

$$\sigma_{x,d} = \frac{|n_{x,d}|}{t_2} \le f_{CLT,k}\cdot\frac{k_{mod}}{\gamma_M}$$
$$\sigma_{y,d} = \frac{|n_{y,d}|}{t_1+t_3} \le f_{CLT,k}\cdot\frac{k_{mod}}{\gamma_M} \quad (10)$$

$f_{CLT,k}$ in above equation represents the appropriate strength value depending on tension ($f_{t,k}$) or compression ($f_{c,k}$), whatever is available.

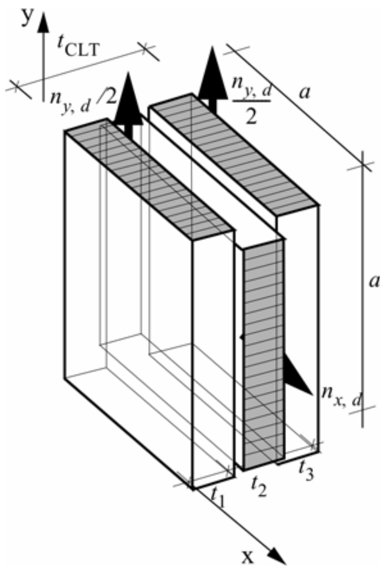


Figure 10: Design normal forces n_{xd} and n_{yd} of a 3-layered CLT

3.2 ULS verifications for shear force n_{xy}

Calculation of design shear stresses can be divided into two steps. In a first step the situation in the ideal RVSE element, which represents an infinite sequence of layers in thickness direction, is discussed (see 3.2.1). In a second subsequent step an extension to a real CLT-element with finite number of layers is carried out (see 3.2.2). Strength values are discussed in 3.2.3 and 3.2.4.

3.2.1 Design stresses for shear force n_{xy} in RVSE

As a single RVSE is part of an infinite sequence of RVSEs, it is not possible to establish an overall shear force n_{xy} in this theoretical case. It is only possible to calculate a proportional shear force $n_{xy,RVSE}$, which acts in one single RVSE. The nominal shear stress τ_0, associated with this RVSE, can be calculated with equation 11.

$$\tau_0 = \frac{V_{xy,RVSE}}{a \cdot t} = \frac{n_{xy,RVSE}}{t} \qquad (11)$$

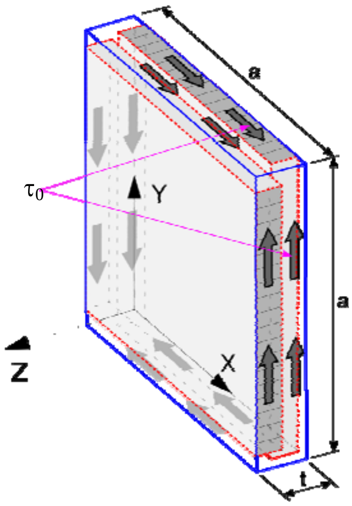


Figure 11: Nominal shear stress τ_0 in RVSE

The nominal shear stress τ_0 does not take into account the internal structure of the CLT-element. Shear stresses τ_0 act both on the cross sections and narrow faces of the boards (Figure 11). Up to now the internal structure of CLT remains unconsidered. In a CLT-element shear forces are only transmitted via cross sections perpendicular to grain from one RVSE to the next. An internal torsional moment, acting on both sides of the gluing interface, vanishes all shear stresses, located at the narrow faces of the boards (Figure 13). Simultaneously shear stresses, located in the cross sectional areas, are doubled. The final stress situation in a CLT-element is shown in Figure 12.
The effective shear stresses τ_v of a RVSE in the cross sectional areas can be calculated with equation 12.

$$\tau_V = 2 \cdot \tau_0 \qquad (12)$$

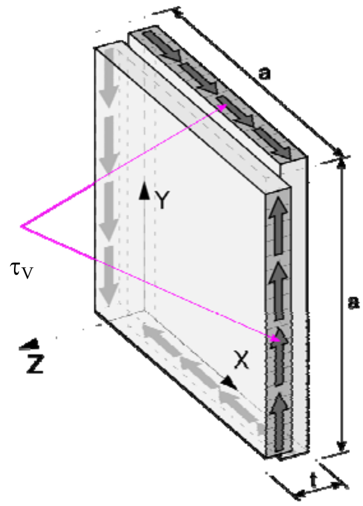


Figure 12: Real shear stress distribution in RVSE

The second verification must be carried out for the torsional stresses in the gluing interface due to Mechanism II (see Figure 13).

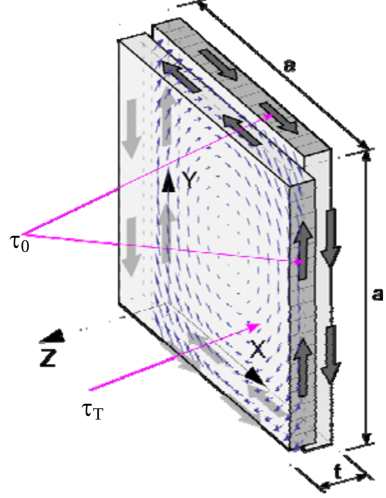


Figure 13: Torsional stresses in gluing interface of RVSE

The torsional moment can be calculated by

$$M_T = \tau_0 \cdot t \cdot a^2 \quad (13)$$

The maximal torsional stresses are defined by dividing the torsional moment M_T by the polar moment of resistance W_P.

$$\tau_T = \frac{M_T}{W_P} = \frac{\tau_0 \cdot t \cdot a^2}{\frac{a^3}{3}} = 3 \cdot \tau_0 \cdot \frac{t}{a} \quad (14)$$

τ_v and τ_M are the two shears stresses, which must be verified. The design values $\tau_{v,d}$ and $\tau_{T,d}$ are calculated by using the design stress $\tau_{0,d}$. The characteristic strength values are discussed in 3.2.3 and 3.2.4.

3.2.2 Design stresses for shear force n_{xy} in a CLT-element

When a CLT-element with its limited, odd number of layers is regarded, the following differences to the RVSE will occur:

- number of layers oriented in both main directions of the CLT-element is not the same.
- thickness of layers is not constant.
- plane of symmetry in the middle of the boards is lost due to boundary.

Verification of the CLT-element shall be carried by checking a series of ideal RVSEs, which are adjusted to the existing CLT-element. One ideal RVSE matches one gluing interface and both surrounding boards of the CLT-element. The question remains, how thick shall the thickness of the ideal RVSE be chosen? Here a conservative solution will be proposed. Checking the i[th] gluing interface of the CLT-element, it will be assumed, that always the thinner thickness of the two attached boards is the controlling thickness for the i[th] RVSE. One exception can be admitted. The outer boards, which are connected to the first or last gluing interface, are glued to only one board. Therefore, thickness of the first and last ideal RVSE with one outer board is either twice the thickness of the outer board or the ordinary thickness of the inner board, whatever is less.
A 5-layered CLT-element is illustrated in Figure 14. 4 ideal RVSEs, connected to the gluing interfaces, exist. The ideal thicknesses for each RVSE, denoted with t_i^* can be calculated as shown in Table 1:

Table 1: *thickness for ideal RVSE's of a 5 layered CLT-element*

# of RVSE	Ideal thickness t_i^*
1	t_1^*=min(2 t_1;t_2)
2	t_2^*=min(t_2;t_3)
3	t_3^*=min(t_3;t_4)
4	t_4^*=min(t_4;2 t_5)

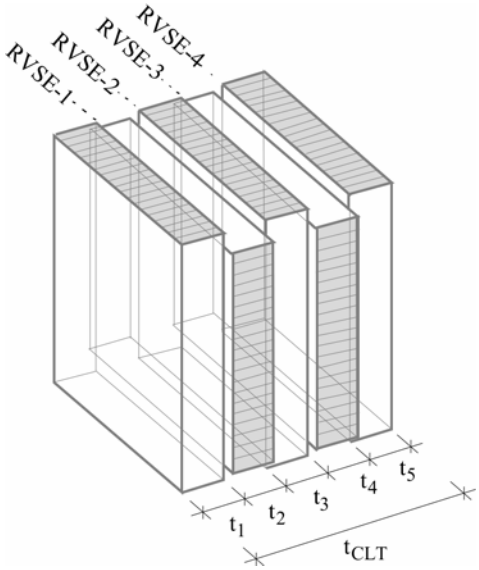


Figure 14: Ideal RVSE for a CLT-element with 5 layers

The overall thickness of all ideal RVSEs is denoted with Σt_i^* and is always smaller than or equal to the geometric overall thickness t_{CLT} of the CLT-element. Usually symmetry is given in thickness direction, resulting in $t_4=t_2$ and $t_5=t_1$.
Determination of ideal RVSEs thickness shall be carried out analogously in case of a 3-, 7- or more layered CLT-elements. Ideal thicknesses of the two RVSE are given exemplary in Table 2 for a 3-layered CLT-element.

Table 2: *thickness for ideal RVSE's of a 3 layered CLT-element*

# of RVSE	Ideal thickness t_i^*
1	t_1^*=min(2 t_1;t_2)
2	t_2^*=min(t_2;2 t_3)

The proportionate shear force $n_{xy,RVSE(i)}$ of the i[th] RVSE in an n-layered CLT-element can be determined by the following formula, which assumes a thickness-related participation of each RVSE in bearing the shear force n_{xy}.

$$n^*_{xy,RVSE(i)} = n_{xy} \cdot \frac{t_i^*}{\sum_{i=1}^{n-1} t_i^*} \quad (15)$$

The ideal nominal shear stress τ_0^* can be calculated by dividing the proportionate shear factor $n_{xy,RVSE(i)}$ through the thickness t_i^* of the i[th] RVSE. This leads to a constant nominal shear stress τ_0^* for all RVSEs (see following equation).

$$\tau^*_{0,RVSE(i)} = \frac{n_{xy} \cdot \frac{t_i^*}{\sum_{i=1}^{n-1} t_i^*}}{t_i^*} = \frac{n_{xy}}{\sum_{i=1}^{n-1} t_i^*} = \tau_0^* \quad (16)$$

Design shear stresses for verification of ULS can be calculated similar to ideal RVSE, given in 3.2.1. The nominal shear stress τ_0 must be replaced by the ideal nominal shear stress τ_0^*, given in equation 16. The shear stresses $\tau_{v,d}$ are equal for all ideal RVSEs. As the torsional shear stresses $\tau_{T,d}$ depend on the ratio (t/a), it can be concluded, that the controlling RVSE is the thickest one.

3.2.3 Shear strength values for ULS Verification

The charactzeristic shear strength $f_{v,k}$ for shear stress τ_v in the cross sections is actually in discussion. Generally $f_{v,k}$ for glulam was taken up to now, which can be expected to be approximately 3.0 up to 3.5 N/mm^2. A value of 5.2 N/mm^2 can be found in an actual ETA approval (ETA-06/0138). Tests in the laboratory of Graz University of Technology (TUG) have shown, that a significantly higher value for CLT shear strength can be expected. 20 tests were carried out at Graz University of Technology [2]. A symmetric test configuration with two fallible cross sections, as shown in Figure 15, was established.

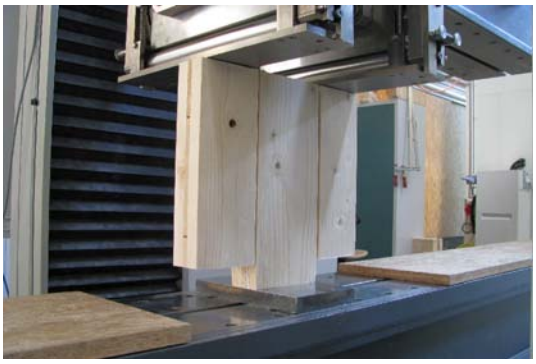


Figure 15: Test configuration for shear strength of CLT-elements

The two fallible cross sections due to shear are shown in Figure 16. As only one cross section can fail, the second one is still strength. Therefore the characteristic shear strength $f_{v,k}$ on basis of these tests will somewhat underestimate the real in plane shear strength of CLT.

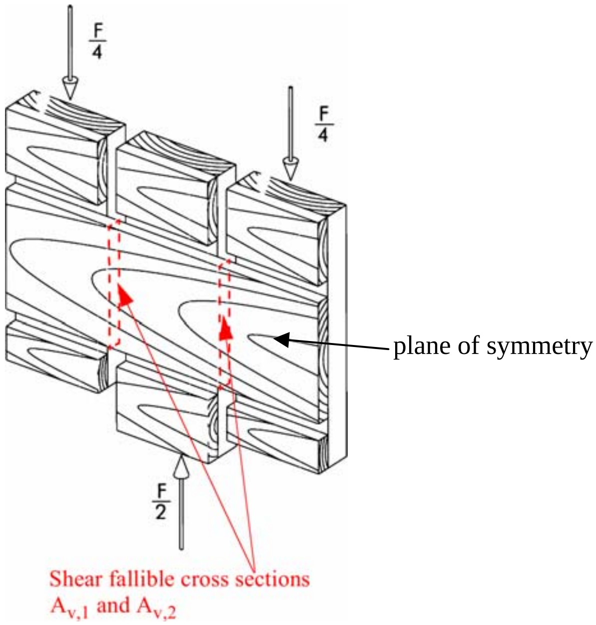


Figure 16: Fallible cross sections of TUG Test configuration

The force displacement curves of these tests are shown in Figure 17.

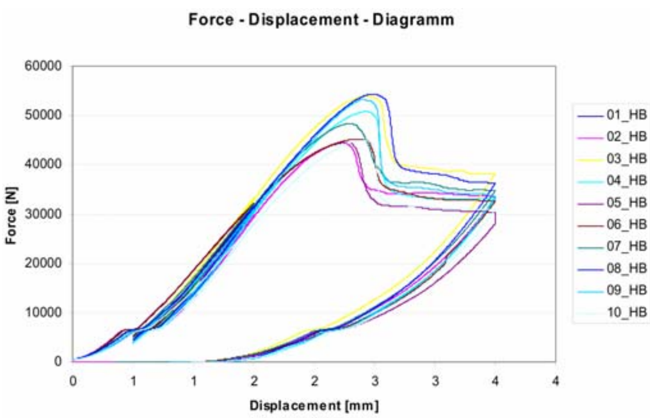


Figure 17: Force - displacement curves of shear tests

The vertical shift under the applied shear forces can be seen in detail in Figure 18.

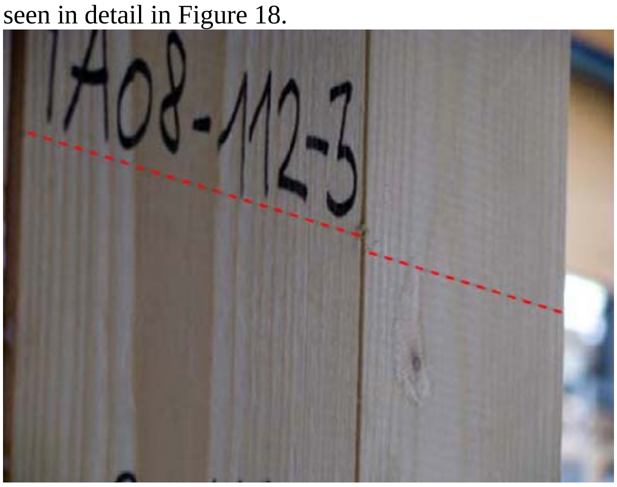


Figure 18: Vertical shift under shear loads

Results of these 20 tests [2] and proposal for $f_{v,k}$ are summarized in Table 3.

Table 3: Test results of TUG test configuration

Series	Value	
#	20	[-]
Height a	200	[mm]
Thickness t	10	[mm]
$f_{v,k}$ - mean value	12.8	[N/mm^2]
Standard deviation	1.45	[N/mm^2]
COV	11.3%	[-]
$f_{v,k}$ 5% - Quantile normal distribution	10.4	[N/mm^2]
$f_{v,k}$ 5% - Quantile log normal distribution	10.6	[N/mm^2]
$f_{v,k}$ 5% - Quantile EN 14358	10.3	[N/mm^2]

The 5% Quantile on basis of these tests is relatively high. A weakness of the proposed test configuration is the extreme distribution of thickness of the inner board in comparison to both outer ones. Whereas the middle layer has a thickness of only 10 mm, both outer layers are relatively thick (25 mm). In this case a relative clear shear failure occurs. If thicknesses of all layers are more balanced, a reduced shear strength $f_{v,k}$ could be expected. Tests and optimization of test configuration for almost same layer thicknesses are planned to be investigated in a diploma thesis at Graz University of Technology.

3.2.4 Torsional strength values for ULS Verification

The torsional strength $f_{T,k}$ in the gluing interface was investigated with large test series in a diploma thesis in 2004 at Graz University of Technology. The test configuration is illustrated in Figure 19.

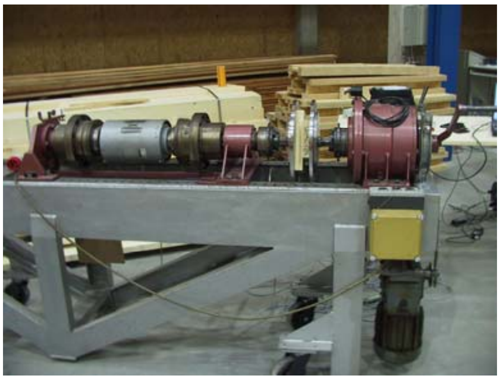


Figure 19: Test configuration for torsional shear strength in gluing interface of CLT-elements

The test specimen can be considered in detail in Figure 20.

Figure 20: Test specimen for torsional shear strength

3 different sizes of test specimen were used and geometry of gluing interface was varied from 100/145 mm^2 over 150/145 mm^2 up to 200/145 mm^2. Furthermore annual ring orientation (flat-grained versus edge-grained) was investigated. The complete test program can be seen in Figure 21.

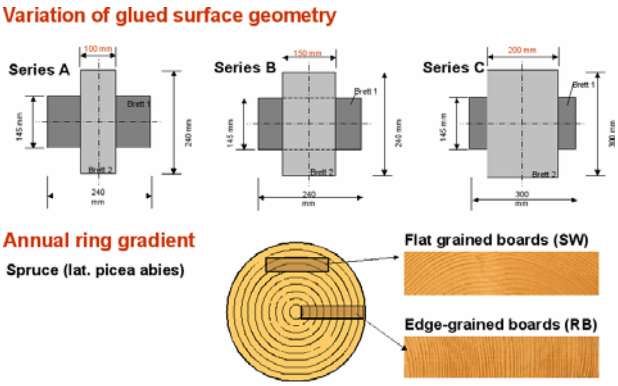


Figure 21: Parameter variation for torsional strength tests in gluing interface of CLT-elements

$6 \cdot 40 = 240$ tests were carried out in [4]. Regarding polar torsion theory without warping the maximum torsional shear strength can be evaluated with the following formula:

$$\tau_{\max} = \frac{M_T}{I_P} \cdot \frac{1}{2} \cdot a \qquad (17)$$

M_T is the torsional moment observed in the tests
I_P sectional moment of the gluing interface
a dimension of the gluing interface, which is identical to the larger board width.

Table 4: Test results of torsional strength tests

Series	Annual ring orient.	5% Quantile	
A	Edge-grained	3.67	[N/mm^2]
A	Flat grained	2.79	[N/mm^2]
B	Edge-grained	3.20	[N/mm^2]
B	Flat grained	2.69	[N/mm^2]
C	Edge-grained	2.98	[N/mm^2]
C	Flat grained	3.10	[N/mm^2]

Based on these and previous test results [5] a torsional shear strength value of $f_{T,k}$ = 2.50 N/mm^2 was proposed and is widely accepted.

4 EXAMPLE

The following example [6] shows the ULS verification of a overhanging CLT wall situated in the first floor of a single occupancy house. The location of the ULS verification in this example is illustrated with a red dot line (see Figure 22). The shear force is assumed to be constant there.

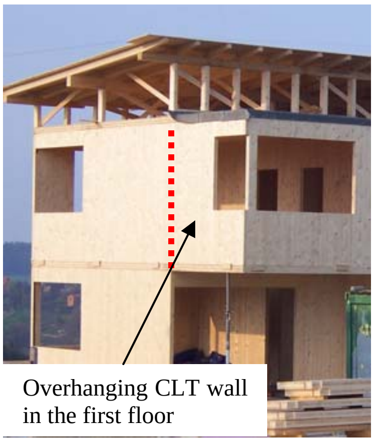


Figure 22: Test specimen for torsional shear strength

The design shear load along this line can be calculated with a constant value of $n_{xy,d}$=27.37 N/mm (Figure 23).

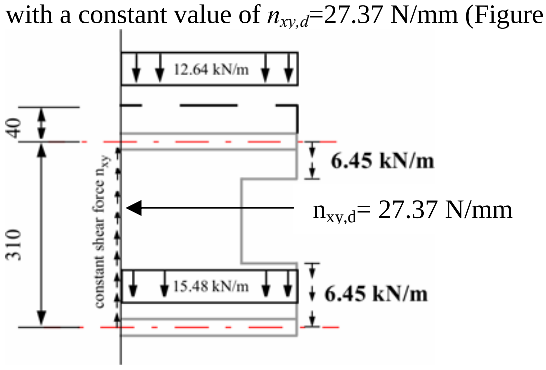


Figure 23: Shear load in the overhanging CLT wall

A short term action load case with k_{mod}=0.90 is regarded. The design shear strength $f_{v,d}$ and torsional strength value $f_{T,d}$ in N/mm^2 are assumed to be:

$$f_{v,d} = f_{v,k} \cdot \frac{k_{\text{mod}}}{\gamma_m} = 5.0 \cdot \frac{0.90}{1.25} = 3.60$$
$$f_{T,d} = f_{T,k} \cdot \frac{k_{\text{mod}}}{\gamma_m} = 2.5 \cdot \frac{0.90}{1.25} = 1.80 \qquad (18)$$

As the shear strength for CLT is still in discussion (3.2.3), a conservative value is used in this example. The wall is built up with a 3-layered CLT-element, where the layer thicknesses are $t_1/t_2/t_3$=30/34/30 mm. The board width of the CLT-element is assumed to be a=150 mm. The thicknesses of the two ideal RVSEs can be evaluated by rules given in Table 2. The thicknesses t_1^* and t_2^* are equal due to symmetry and can be determined with $t_1^* = t_2^*$=min(2·30;34)=34 mm. The ideal nominal shear stress $\tau_{0,d}^*$ can be calculated with

$$\tau_{0,d}^* = \frac{n_{xy,d}}{\sum_i t_i^*} = \frac{27.37}{34+34} = 0.403 \qquad (19)$$

The design stresses $\tau_{v,d}$ and $\tau_{M,d}$ in N/mm² can be estimated with

$$\tau_{v,d} = 2 \cdot \tau_{0,d}^* = 0.806$$
$$\tau_{M,d} = 3 \cdot \tau_0^* \cdot \frac{t_i^*}{a} = 3 \cdot 0.403 \cdot \frac{34}{150} = 0.274 \qquad (20)$$

The ULS verifications satisfy the well known verification formula, according to EC 5 to both mechanisms shear and torsion in the gluing interface.

$$\frac{\tau_{v,d}}{f_{v,d}} = \frac{0.806}{3.60} = 0.22 \le 1.0$$
$$\frac{\tau_{M,d}}{f_{M,d}} = \frac{0.274}{1.80} = 0.15 \le 1.0 \qquad (21)$$

Let us consider fire exposure now as an example for an accidental load case. It is assumed that thickness of layer 3 is reduced due to charring and is now t_3=6 mm instead of 30 mm. The thicknesses of the two ideal RVSE differ now. t_1^* remains with t_1^*=min(2·30;34)=34 mm, but t_2^* becomes t_2^*=min(2·6;34)=12 mm. Normally design forces in an accidental load case for fire exposure are usually lower than in ordinary load cases. But for better comparision, it is assumed, that the design shear force stays identical with $n_{xy,d}$=27.37 N/mm. The ideal nominal shear stress $\tau_{0,d}^*$ [N/mm^2] can be calculated for this accidental load case with

$$\tau_{0,d}^* = \frac{n_{xy,d}}{\sum_i t_i^*} = \frac{27.37}{34+12} = 0.595 \qquad (22)$$

The design stresses $\tau_{v,d}$ and $\tau_{M,d}$ in N/mm² can be estimated with

$$\tau_{v,d} = 2 \cdot \tau_0^* = 1.19$$
$$\tau_{M-1,d} = 3 \cdot \tau_0^* \cdot \frac{t_1^*}{a} = 3 \cdot 0.595 \cdot \frac{34}{150} = 0.405 \qquad (23)$$
$$\tau_{M-2,d} = 3 \cdot \tau_0^* \cdot \frac{t_2^*}{a} = 3 \cdot 0.595 \cdot \frac{12}{150} = 0.143$$

The design stresses for shear is increased by 47%. The torsional design stress is increased by 47% in RVSE-1, but reduced by the same in RVSE-2, where thickness is reduced by charring.

If shear stress $\tau_{v,d}$ is determined with the global net section, as it can be found in most technical approvals for CLT, the minimum thickness is 34 mm for the standard load case but also for the accidental load case. Shear verification can be verified for both load cases with

$$\tau_{v,d} = \frac{n_{xy}}{\min(t_1 + t_3; t_2)} = \frac{27.37}{34} = 0.806$$
$$\frac{\tau_{v,d}}{f_{v,d}} = \frac{0.806}{3.60} = 0.22 \leq 1.0 \qquad (24)$$

When thicknesses of the layers vary strongly, which might occur in an accidental load case like charring formulas, given in this paper and formulas, given in e.g. appropriate approvals, differ. Similar conclusion can be made for the torsional stresses (Mechanism II).

5 CONCLUSIONS

This paper deals with CLT walls under shear loads in plane. Basics for determination of shear stiffness were already given in [1] at WCTE 2006. The shear stiffness was presented for a theoretical CLT-element with an infinite number of layers (RVSE). Formulas for CLT stiffness of 3-, 5- and 7-layered CLT-elements are presented here as an enhancement. Additionally shear strength verifications are proposed. Determination of design shear stress and design torsional stress in the gluing interface are presented for the RVSE. Modifications of these formulas for 3-, 5- and higher layered CLT-elements are given in order to consider boundary effects and different layer thicknesses. Strength values for both mechanisms I+II are also presented here. Whereas the torsional strength is well accepted in the scientific community, the shear strength value is still under discussion. Currently values in approvals can be found with up to 5.2 N/mm², but even higher strength values can be expected. Further research is necessary in this field. Another open question remains in the case of high peaks of shear stresses, e.g. when openings are given in CLT walls.
It is still unclear, whether some internal stress redistribution is allowed (some ductility is present) or not (perfect brittle behaviour is assumed). If stress redistribution is not allowed (brittle behaviour), verification of CLT walls is determined by small areas with high shear stress gradients.

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