Introduction to CLT, Product Properties, Strength Classes

Reinhard Brandner
Graz University of Technology

Helene Bauer
Graz University of Technology

Introduction to CLT, Product Properties, Strength Classes

Gerhard Schickhofer
Professor, Head of Institute
Institute of Timber Engineering and Wood Technology, TU Graz
Graz, Austria

Reinhard Brandner
Assistant Professor, Deputy Head of Institute
Institute of Timber Engineering and Wood Technology, TU Graz
Graz, Austria

Helene Bauer
Project Assistant
Institute of Timber Engineering and Wood Technology, TU Graz
Graz, Austria

Summary

We introduce briefly the product cross laminated timber (CLT) and outline the development and basics of this European engineered timber product, innovated to be used as large-sized stand-alone structural element for load-bearing purposes. The main focus of our contribution is to present and discuss properties of side face bonded homogeneous CLT made of Norway spruce. A strength class system and corresponding characteristic properties of CLT exposed to loads in- and out-of-plane are presented. Background documents are referenced. In view of a concerted standardization system the characteristic properties are linked with adequate test configurations and reference dimensions of the base material and the product itself. The concertation of product properties, reference dimensions & conditions with adequate test configurations is a prerequisite and the basis for harmonization and international standardization of this innovative timber product of meanwhile global interest. Final remarks and an outlook conclude this contribution.

1. Introduction

In timber engineering more and more engineered wood products (EWPs) are used. These products allow using timber in dimensions multiple-times larger than typically known from sawn timber with the additional advantage of higher homogeneity in terms of lower dispersing properties and lower variation between products from different production batches and producers. These aspects are achieved by production processes which interlink the main steps (i) material classification, (ii) separation and (iii) innovative assembling to rigid composite structures via adhesive bonding.

Within the last decades various EWPs for load-bearing purposes entered the market; primary linear members, like glued laminated timber (glulam; GLT), (finger jointed) construction timber or duo- and trio-beams, but also two-dimensional products like laminated veneer lumber (LVL) and oriented strand boards (OSB). By tradition timber engineering mainly based on linear members; large hall structures with truss systems or solid-web girders, timber bridges and single- and multi-story houses, office and school buildings erected as light-frame timber structures with OSB or LVL as diaphragm component. The market share of timber structures, compared to that of mineral-based solid construction materials like masonry and reinforced concrete, was only a view percentage, at least in Europe.

In Central Europe and more than two decades ago a new EWP for load-bearing purposes was invented, called cross laminated timber (CLT). It constitutes a stand-alone laminar and large-sized plate-like structural element, which is commonly composed of an uneven number of layers (usually three, five or seven), each made of boards placed side-by-side, which are arranged crosswise to each other, usually at an angle of 90°. These elements, which can be used as whole floor and wall elements with and without openings, are capable of bearing loads in- and out-of-plane. Common dimensions of CLT elements are in length up to 18 or even 30 m, in width up to 3.0 or even 4.8 m and in thickness seldom above 300 to 400 mm; see e.g. [1,2]

The idea behind CLT is in principle not new and its basic structure comparable to common joinery and carpentry products with the same major advantage of high dimensional stability in-plane due to cross-wise layering. The innovative aspect of CLT is its thickness which allows using it as a stand-alone structural element with outstanding strength and stiffness properties. The large dimensions, its easy handling and versatile applicability opens new markets for timber engineering and allows architecture and engineering to realize (super)structures and monolithic buildings in timber. In fact, CLT is also a high-value alternative for reinforced concrete or other mineral-based solid construction materials whereby CLT acts as a serious competitor on the market [2]. Intensive research activities on CLT started 1990 in Graz / Austria and first residential buildings in CLT reflecting the current state-of-the-art were realized by Moser (1995) [3]. Meanwhile, CLT as innovative Central European product with about 500 TSD m^3 production volume per year in Europe, has become a product of global interest. Not only has it initiated research activities internationally but also the global establishment of production sites and activities in regard to standardization and harmonization, in particular in countries like Canada, United States, Japan, China and New Zealand. The solid structure of CLT allows also using timber species with lower mechanical properties than Norway spruce (*Picea abies*), the species typically used in Europe. Global interest and activities in conjunction with the ability to use local timber species lead to new CLT products with high local or regional added value, an important aspect when considering CLT as sustainable, CO_2-active construction material with a great chance to boost its international relevance further. Meanwhile great efforts are made in establishing the Solid Timber Construction Technique in Cross Laminated Timber, a building construction system which allows demonstration of the potential use as well as economic and competitive advantages of CLT.

Within this contribution we aim on presenting product properties in conjunction with a strength class system, providing the essential input parameters for the design process, as well as corresponding test configurations. With focus on Europe and the state-of-the-art we further concentrate on CLT of Norway spruce with homogeneous layup (all boards correspond to the same strength class) as a quasi-rigid composite structure with side face bonded layers.

2. Characteristic Properties of CLT and Test Configurations

2.1 General Comments and Definitions

2.1.1 Reference Dimensions for CLT Lamellas and CLT Elements

The European product standard for CLT, EN 16351 [4], allows layer thicknesses in the range of $t_\ell = 6$ to 45 mm and board or lamella widths within $w_\ell = 40$ and 300 mm. In view of standardization and construction tenders the widely accepted standard layer thicknesses in Central Europe are $t_\ell = 20$, 30 and 40 mm. Due to rolling shear stresses in layers of CLT loaded out-of-plane, a minimum width of $w_\ell \geq 4\,t_\ell$ is advised, otherwise a reduced rolling shear resistance has to be considered, see e.g. [5] and Section 2.3.2.

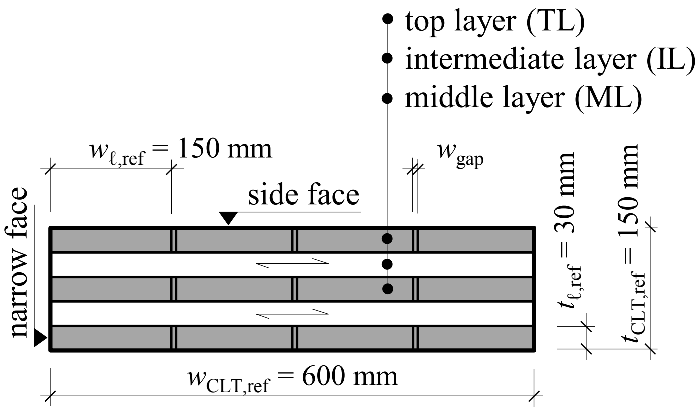


Fig. 1 Reference cross section of a CLT element and relevant terms

The heterogeneity of the raw material timber and potential influences during testing necessitate the standardization of reference dimensions and test conditions with the aim to allow for traceable and reliable product properties on a reference and comparable basis. In respect to the standard width of solid timber, $w_{\ell,\mathrm{ref}} = 150$ mm (EN 384 [6]), and the range of common CLT layer thicknesses, for lamellas of CLT a reference cross section of $w_{\ell,\mathrm{ref}} \times t_{\ell,\mathrm{ref}} = 150 \times 30$ mm² is proposed. To account for the laminar, plate-like structure of CLT and homogenization effects due to mutual (inter)action of lamellas and layers within the CLT structure, for a CLT element we propose a reference width equal to four-times the width of the reference lamella, with $w_{\mathrm{CLT,ref}} = 4\ w_{\ell,\mathrm{ref}} = 600$ mm. In view of a common number of layers between three and seven, for the reference thickness of a CLT element a five-layer element with homogeneous layup and layers in reference thickness are suggested, with $t_{\mathrm{CLT,ref}} = 5\ t_{\ell,\mathrm{ref}} = 150$ mm, see Fig. 1. Consequently, in the main axis of such a reference CLT element there are $N = 12$ lamellas (elements) running in the same direction which is roughly equal to the reference cross section of GLT where we have 15 lamellas, with $t_{\ell,\mathrm{GLT,ref}} = 40$ mm and $w_{\mathrm{GLT,ref}} \times d_{\mathrm{GLT,ref}} = 150 \times 600$ mm².

2.1.2 Proposed CLT Strength Class System and Background Information

Mechanical properties as well as density of CLT show significantly lower variability than corresponding properties of the base material, board or lamella. This circumstance is not new and one major advantage of EWPs in general. The reason therefore is the homogenization of base material’s (element’s) properties due to their common (inter)action in the serial, sub-parallel laminar structure of CLT where homogenization takes place within and between the individual layers. Although this (inter)action influences also the mean strengths and elastic and shear moduli, the major influence is on the variability which decreases remarkably. Consequently, with increasing number of interacting elements, product properties’ distributions concentrate more and more around their mean values and the lower quantiles, e.g. the 5 %-quantiles, rise. In fact, the higher the variability in base material’s properties, the higher the possible gain caused by homogenization [7]. Beside these homogenization effects, also known as stochastic system effects, there exist also mechanical system effects which may have also an influence on EWPs’ properties in relation to the base material’s properties. However, numerous investigations in the past conclude a dominance of stochastic system effects in the overall description of system properties based on element’s properties; a compilation of these investigations and modelling approaches can be found e.g. in [7].

These principal considerations are taken into account when discussing a possible strength class system for CLT. We suggest, in-line with the strength class system for GLT (see e.g. EN 14080 [8]), CLT strength classes which are related to the physical potential of the base material. Therefore, so called load-bearing models and models for elastic and shear moduli as well as density are required which describe CLT properties at reference conditions and dimensions in relation to reference base material’s properties. Furthermore, the name of a strength class should reflect the product, the reference product’s property(ies) and the principal layup or composition. In regard to GLT and [8] we suggest e.g. CL 28h or CL 28c, with “CL” as acronym for CLT, “28” as the corresponding characteristic (5 %-quantile) bending strength of CLT out-of-plane and “h” or “c” for a homogeneous (all layers of equal strength class) or combined (heterogeneous) layup of CLT, respectively, see e.g. [2,9]. Although CLT is capable bearing loads in- and out-of-plane we chose the characteristic bending strength out-of-plane as reference strength property (i) because it is one relevant product property, (ii) in reference to GLT and [8], and (iii) because the load-bearing model for CLT in bending out-of-plane was the first one for CLT and meanwhile has been multiple times confirmed (see [10]; Section 2.3.1). As outlined in [2] it is also meaningful to relate properties of CLT to that of GLT. This is a consequence of comparable reference cross section dimensions and number of elements in main direction, see Section 2.1.1. With the characteristic bending strength of CLT out-of-plane as reference strength class property, for the corresponding load-bearing model the tensile strength parallel to grain of the base material as main model parameter is required. The reason is that the edge bending stresses in CLT loaded out-of-plane primary cause tensile stresses parallel to grain in top layer's lamellas.

Back to the dominant role of stochastic system effects in EWP's properties' description: comprehensive investigations on tensile strength parallel to grain of lamellas from Norway spruce have shown that the variability in strength properties depends on the grading method and the number of classes the material was graded in. For visually graded sawn timber, irrespective if grading was performed in one or two strength classes plus rejection, the coefficient of variation usually found was $CV[f_{t,0}] = 35 \pm 5$ %. Boards graded mechanically in just one common grading class plus rejection, so that the boards with higher properties remained in the grading class, showed a comparable value for $CV[f_{t,0}]$. However, mechanical grading in more than one common grading class plus rejection reduces the variability due to higher accuracy in the mechanical grading process compared to visual grading and the outcome was found to be within $CV[f_{t,0}] = 25 \pm 5$ %, see [11]. Board material graded to a specific strength class showing high strength variability has a higher mean value than board material of the same strength class, with the same characteristic (5 %-quantile) strength value but with lower variability. Consequently, higher system effects and gain in resistance on the 5 %-quantile level can be achieved in EWPs by using base material of higher variability. We take this circumstance into account by defining a strength class system for CLT exemplarily based on a base material strength class T14 (see e.g. EN 14080 [8]), with $f_{t,0,\ell,k} = 14.0$ N/mm² and $E_{0,\ell,mean} = 11{,}000$ N/mm², as characteristic (5 %-quantile) tensile strength parallel to grain and mean elastic modulus parallel to grain, respectively. In general, strength properties are directly influenced by local growth characteristics, e.g. knots, knot clusters and grain deviation. This leads to a dependency of EWPs strength properties on the variability of strength properties of the base material, e.g. $CV[f_{t,0}]$. Known exceptions are e.g. shear as well as tension and compression strength perpendicular to grain; see e.g. [8]. In contrast, elastic EWP properties and density constitute average base material properties; a differentiation in respect to $CV[f_{t,0}]$ is not required.

Within the following sub-chapters and sections properties of CLT exposed to loads in- and out-of-plane are discussed. The presented values correspond to CLT made of Norway spruce, with side face bonded layers, homogenous layup and elements according to the specified reference dimensions (see Section 2.1.1) as well as the reference test conditions as specified e.g. in EN 408 [12], e.g. reference conditions with 20 °C and 65 % relative humidity which corresponds to an equilibrium reference moisture content of $u_{\mathrm{ref}} = 12$ %.

2.2 Density of CLT

The mean density of CLT, $\rho_{\mathrm{CLT,mean}}$, is the same as of the base material, with $\rho_{\mathrm{CLT,mean}} = \rho_{\ell,\mathrm{mean}}$, as far as the layer thicknesses are not too small so that the amount of adhesive used in production, usually with significantly higher density than the base material, has not any relevant influence. An influence of a few percentages can be expected when the layer thicknesses are below 10 mm.

Due to averaging effects in a CLT element the variability in density is much lower than in the base material. According to the Central Limit Theorem of probability theory, for a sufficiently large amount of boards or lamellas in a CLT element, N, the reduction in variability can be described by $\mathrm{CV}[\rho_{\mathrm{CLT}}] \approx \mathrm{CV}[\rho_\ell] / \sqrt{N}$. Tests have shown that there is sufficient agreement between theoretically calculated and experimentally observed values already in CLT elements in reference dimensions but also for three-layer CLT elements.

As consequence of these statements and with $\mathrm{CV}[\rho_\ell] = 8$ % (in general, 6 to 10 %; see [7]), the characteristic (5 %-quantile) product density of CLT in terms of base material's density and via normal approximation is given as

$$\rho_{\mathrm{CLT,k}} = \frac{1 - 1.645\,\mathrm{CV}[\rho_\ell]/\sqrt{N}}{1 - 1.645\,\mathrm{CV}[\rho_\ell]}\,\rho_{\ell,\mathrm{k}} \overset{N \geq 10}{\rightarrow} 1.10\,\rho_{\ell,\mathrm{k}}\,. \tag{1}$$

These regulations are in-line with [8] for GLT. However and as outlined in [13,14], in designing joints in side or narrow face of CLT, and considering density as the only material property indicating the embedment and withdrawal capacity of fasteners, in case of fasteners penetrating only one layer or lamella of CLT the density of the base material, $\rho_{\ell,\mathrm{k}}$, shall be used.

2.3 CLT out-of-plane: Strength Values, Moduli of Elasticity and Shear

2.3.1 Properties in Bending

In view of the load-bearing model for CLT in bending [10], the characteristic (5 %-quantile) bending strength out-of-plane, $f_{\mathrm{m,CLT,k}}$, as reference value for the proposed CLT strength class system, is regulated in dependency of the characteristic (5 %-quantile) tensile strength parallel to grain of the base material (boards), $f_{\mathrm{t},0,\ell,\mathrm{k}}$, and the corresponding coefficient of variation, $\mathrm{CV}[f_{\mathrm{t},0,\ell}]$, see

$$f_{\mathrm{m,CLT,k}} = k_{\mathrm{m,CLT}}\, f_{\mathrm{t},0,\ell,\mathrm{k}}^{0.8}, \text{ with } k_{\mathrm{m,CLT}} = k_{sys,\mathrm{m}}\, k_{\mathrm{CLT/GLT}}\, k_{\mathrm{h,CLT}}\, k_{\mathrm{CV\_t}}, \tag{2}$$

with $k_{\mathrm{sys,m}}$ as system effect due to mutually interacting lamellas in CLT element's main direction [15], $k_{\mathrm{CV\_t}}$ as factor which considers differences in $\mathrm{CV}[f_{\mathrm{t},0,\ell}]$ [11], $k_{\mathrm{h,CLT}}$ as depth factor equal to GLT according to [8] and $k_{\mathrm{CLT/GLT}}$ as factor which considers empirically determined differences in homogenization effects between CLT and GLT.

Table 1: CLT strength classes; characteristic values of CLT out-of-plane

	Base material T14; CV[$f_{t,0,\ell}$] =	25 ± 5 %	35 ± 5 %
Property [–]	**Symbol [–]**	**CL 24h**	**CL 28h**
Bending strength	$f_{m,CLT,k}$ [N/mm²]	24.0	28.0
Tensile strength perpendicular to grain	$f_{t,90,CLT,k}$ [N/mm²]	0.5	
Compression strength perpendicular to grain	$f_{c,90,CLT,k}$ [N/mm²]	3.0	
Shear strength	$f_{v,CLT,k}$ [N/mm²]	3.5	
Rolling shear strength	$f_{r,CLT,k}$ [N/mm²] $f_{r,lay,k}$ [N/mm²]	1.40, for w_ℓ / $t_\ell \geq 4$ 0.80, for w_ℓ / $t_\ell < 4$	
Modulus of elasticity parallel to grain	$E_{0,CLT,mean}$ [N/mm²] $E_{0,lay,mean}$ [N/mm²]	11,600	
Modulus of elasticity perpendicular to grain	$E_{90,CLT,mean}$ [N/mm²] $E_{90,lay,mean}$ [N/mm²]	300	
Modulus of elasticity in compression perp. to grain	$E_{c,90,CLT,mean}$ [N/mm²]	450	
Shear modulus	$G_{0,lay,mean}$ [N/mm²]	650	
Rolling shear modulus	$G_{r,lay,mean}$ [N/mm²]	100, for w_ℓ / $t_\ell \geq 4$ 65, for w_ℓ / $t_\ell < 4$	
Elastic & shear properties' 5 %-quantiles	$E_{CLT,05}$ [N/mm²] $E_{lay,05}$ [N/mm²] $G_{CLT,05}$ [N/mm²] $G_{lay,05}$ [N/mm²]	$E_{05} = 5/6\ E_{mean}$ $G_{05} = 5/6\ G_{mean}$	

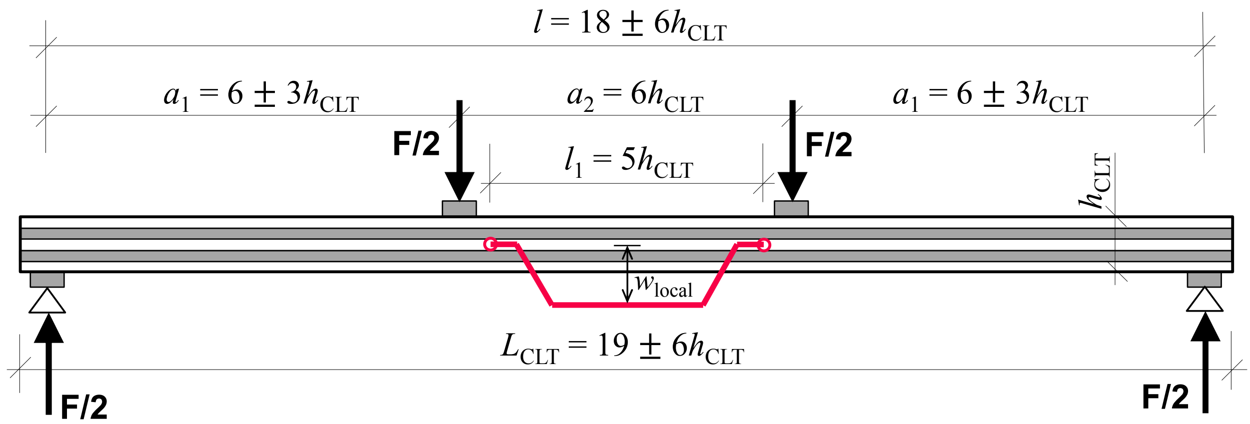
By using board material of strength class T14 but with different CV[$f_{t,0,\ell}$] the CLT strength classes, CL 24h and CL 28h, can be achieved, see Table 1.

For the modulus of elasticity parallel to grain the relationship

$$E_{0,\mathrm{CLT,mean}} = E_{0,\mathrm{lay,mean}} = 1.05\ E_{0,\ell,\mathrm{mean}} \tag{3}$$

is proposed which is conform with regulations for GLT in [8], see Table 1. Recent investigations have shown that the amount of system action on mean values in GLT in comparison to the elastic properties of the base material, as consequence of parallel and serial acting springs, is negligible [16]; the relationship $E_{0,\mathrm{CLT,mean}} = E_{0,\ell,\mathrm{mean}}$ would be more appropriate.

The determination of the bending properties of CLT, strength and modulus of elasticity, is carried out according to the four-point-bending test setup in [12]; see Fig. 2. To prevent rolling shear failures in this orthogonal laminar structure, it is suggested to increase the length a_1, as distance between support and load introduction, to $a_1 = 6 \pm 3\, h_{\mathrm{CLT}}$. Thus, a_1 depends on the CLT layup, the ratio w_ℓ / t_ℓ and the basic material properties. Based on experience with CLT made of Norway spruce an optimum length of $a_1 = 7.5\, h_{\mathrm{CLT}}$ was found. In-line with [12] it is proposed to measure the local deformations, w_{local}, at both narrow faces in the neutral axis and within the shear free area.



with:

h_{CLT}	… thickness of the specimen
l	… span of the specimen
l_1	… gauge length for measuring w_{local}
L_{CLT}	… length of the specimen
$w_{\ell,\mathrm{ref}}/t_{\ell,\mathrm{ref}}$	… reference width/thickness of single lamella

reference cross section for bending with

$t_{\ell,\mathrm{ref}} = 30$ mm; $w_{\ell,\mathrm{ref}} = 150$ mm

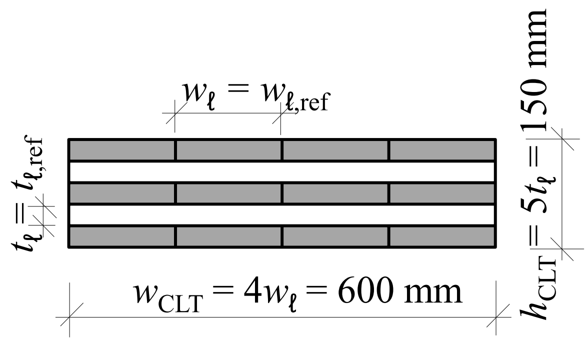


Fig. 2 Test setup for bending tests for loads out-of-plane

The calculation of the bending properties is based on the Timoshenko beam, assuming $E_0 = E_{0,\ell,\mathrm{mean}}$ and $E_{90} = 0$. Eqs. (4–6) show the calculation of the bending stiffness, K_{CLT}, the bending strength, $f_{\mathrm{m,CLT}}$, and the modulus of elasticity in bending, $E_{0,\mathrm{CLT}}$. Therein, $\Delta F / \Delta w$ is the relationship between changes in load and deformation, determined within the linear elastic range between 0.1 and 0.4 $F_{\max}$.

$$K_{\mathrm{CLT}} = \sum(E_{\mathrm{i}}\, I_{\mathrm{i}}) + \sum(E_{\mathrm{i}}\, A_{\mathrm{i}}\, e_{\mathrm{i}}^2) \tag{4}$$

$$f_{\mathrm{m,CLT}} = \frac{F_{\mathrm{max}}/2\,a_1}{K_{\mathrm{CLT}}}\, z\, E_0 \tag{5}$$

$$E_{0,\mathrm{CLT}} = \frac{a_1\, l_1^2}{16\,\frac{K_{\mathrm{CLT}}}{E_0}}\,\frac{\Delta F}{\Delta w} \tag{6}$$

2.3.2 Shear and Rolling Shear Properties

The shear strength of CLT against loads out-of-plane is regulated in compliance with GLT and [8], with $f_{\mathrm{v,CLT,k}} = 3.5$ N/mm².

For the shear modulus of CLT layers, $G_{0,\mathrm{lay,mean}}$, and in analogy to the modulus of elasticity in bending out-of-plane (see Section 2.3.1) we propose the same value as for the base material, with $G_{0,\mathrm{lay,mean}} = G_{0,\ell,\mathrm{mean}}$, see Table 1. This suggestion is also in-line with [8].

Due to the orthogonal layering, the transverse layers in CLT are exposed to rolling shear. The resistance against these stresses depends on the ratio w_ℓ / t_ℓ; the increasing amount of tension perpendicular to grain stresses combined with rolling shear stresses lead to a remarkable decrease in resistance; e.g. [5]. Other investigations on rolling shear strength were made e.g. by [17–20]. Recently, Ehrhart et al. [21] suggest a bi-linear approach for the characteristic (5 %-quantile) rolling shear strength, dependent on the ratio w_ℓ / t_ℓ, see

$$f_{\mathrm{r,CLT,k}} = \min\left\{0.2 + 0.3\,\frac{w_\ell}{t_\ell};\, 1.40\right\}. \tag{7}$$

For the ease of use the regulation of only two values, without bi-linear interaction, is recommended, with $f_{\mathrm{r,CLT,k}} = f_{\mathrm{r,lay,k}} = 1.40$ and 0.80 for $w_\ell / t_\ell \geq 4$ and $w_\ell / t_\ell < 4$, respectively.

The rolling shear modulus, $G_{\mathrm{r,lay}}$, also depends on the ratio w_ℓ / t_ℓ. Current technical assessment documents and past investigations outline a ratio $G_{\mathrm{r,lay,mean}} / G_{0,\mathrm{lay,mean}} = 1 / 10$ for $w_\ell / t_\ell \geq 4$. Recent investigations in [21] conclude a much higher rolling shear modulus, with $G_{\mathrm{r,lay,mean}} = 100$ and 65 N/mm² for $w_\ell / t_\ell \geq 4$ and $w_\ell / t_\ell = 2$, respectively, and a bi-linear approach, with

$$G_{\mathrm{r,CLT,mean}} = \min\left\{30 + 17.5\,\frac{w_\ell}{t_\ell};\, 100\right\}. \tag{8}$$

The reason for these higher values is that current European CLT products show an increasing amount of base material taken closer to the pith whereas in the past primary side-boards had been used. The significant relationship between rolling shear modulus and the annual ring pattern, i.e. the relative position of the board's center to the pith (e.g. [19,21,22]) leads in that case to higher values of rolling shear modulus. However, in respect to the ease of use we propose two fixed values instead of a bi-linear relationship, see Table 1.

Determination of the rolling shear properties is based on the shear test setup in [12]; see e.g. [20,21] and Fig. 3. The load is introduced at an angle of 14° to the loading plates which are made of steel or wood and rigidly glued on the test specimen. The relative displacement of the loading plates is measured on both sides and by displacement transducers. The advantage of this test configuration is that either single board segments, segments of CLT layers or even segments of whole CLT elements can be tested.

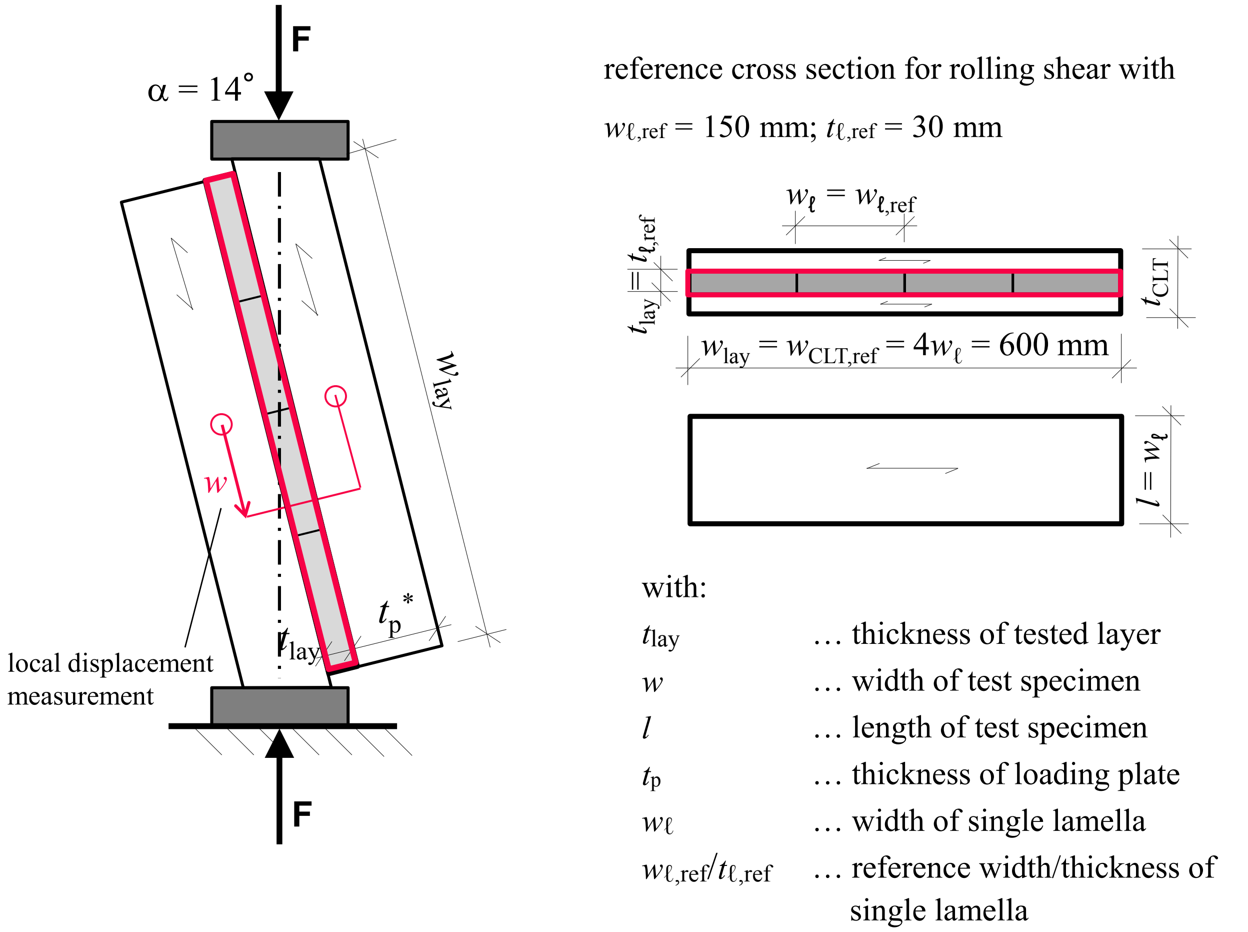


Fig. 3 Test setup for rolling shear tests

The calculation of the rolling shear properties, $f_{r,CLT(lay)}$ and $G_{r,CLT(lay)}$, can be done according to [12] and by means of Eqs. (9,10).

$$f_{r,lay} = \frac{F_{max} \cos 14^\circ}{l\ w} \tag{9}$$

$$G_{r,lay} = \frac{\Delta F \cos 14^\circ}{\Delta w} \frac{t_{lay}}{l\ w_{lay}} \tag{10}$$

2.3.3 Tension Perpendicular to Grain

The authors are not aware of any investigation on tensile properties of CLT elements perpendicular to grain. In some cases the strength property might be design relevant, e.g. in lap joints between floor elements. Based on an engineering judgement made by considering the laminar structure of CLT in analogy to GLT, for the product CLT we propose to use the same characteristic values as for GLT according to [8], see Table 1.

2.3.4 Compression Perpendicular to Grain

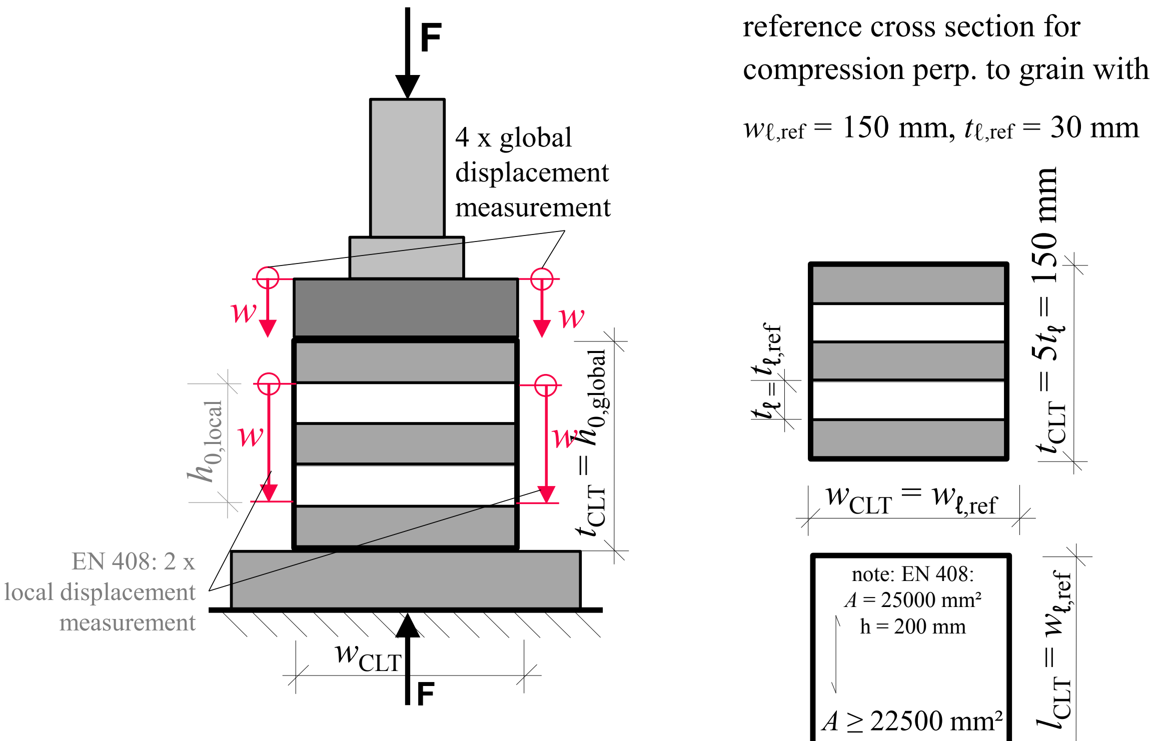
CLT as two-dimensional structural element opens new horizons in timber engineering. The dimensions and outstanding properties predestine CLT to be used in large-spanned and line or point-supported structures. Thus, properties in compression perpendicular to grain are of high relevance in designing CLT elements against loads out-of-plane. Several investigations concentrated on the basic product (single prism) and system properties (different load configurations) of CLT in compression perpendicular to grain, e.g. [23–28]. In comparison to GLT about 30 % higher elastic and strength properties were found for CLT [28]; see Table 1. The reason for this is the reinforcement by the transverse layers in the orthogonal structure of CLT reducing tensile stresses perpendicular to grain.

The determination of base properties of CLT in compression perpendicular to grain is suggested according to the test setup in [12]. Therein a centric load introduction on full-surface loaded prism is anchored. In contrast to the specifications in [12], a (global) displacement measurement is proposed via four displacement transducers arranged at the corners of the loading plate. Thus, the calculated modulus of elasticity is referenced to the whole thickness of the test specimen (gauge length $h_0 = t_{CLT}$) which allows determining a representative value for the given layup. Previous tests of numerous authors have shown that the base properties of CLT perpendicular to the grain are only to a small amount influenced by the layup. Of course, in respect to so far discussed reference dimensions for CLT test specimen a reference prism differing from specification in [12] is recommended, see Fig. 4.

The calculation of the properties for compression perpendicular to the grain, $f_{c,90,CLT}$ and $E_{90,CLT}$, can be done according to [12]; see Eqs. (11,12).

$$f_{c,90,CLT} = \frac{F_{c,90,max}}{l_{CLT}\ w_{CLT}} \tag{11}$$

$$E_{c,90,CLT} = \frac{h_0}{A}\frac{\Delta F}{\Delta w} \tag{12}$$



with:

t_{CLT}	… thickness of test specimen
w_{CLT}	… width of the test specimen
l_{CLT}	… length of the specimen
h_0	… gauge length: $h_{0,\mathrm{global}} = t_{\mathrm{CLT}}$ (global measurement); $h_{0,\mathrm{local}} = 0.6\ t_{\mathrm{CLT}}$ (local measurement according to EN 408 [12])
$w_{\ell,\mathrm{ref}}/t_{\ell,\mathrm{ref}}$	… reference width/thickness of single lamella

Fig. 4 Test setup for compression perpendicular to the grain

2.4 CLT in-plane: Strength Values and Shear Moduli

2.4.1 Properties in Tension Parallel to Grain

Properties of CLT in tension parallel to grain have not been investigated so far, not theoretically and nor via experiments. In engineering practice and on a conservative basis the same value for CLT as for the base material is used and only the lamellas oriented in load direction, i.e. the net cross section, A_{net}, is considered. However, the quasi-rigid composite structure of CLT consequence a mutual interaction of all boards in the CLT cross section oriented in load direction as far as the load is applied homogeneously. In view of a reference CLT cross section with $N = 12$ lamellas (three layers times four lamellas) and investigations on the system factor in tension parallel to grain (e.g. [15,29]) the following relationships are proposed ([2,9]):

$$f_{\mathrm{t,0,CLT,net,k}} = k_{\mathrm{sys,t,0}}\ f_{\mathrm{t,0,\ell,k}}\ , \tag{13}$$

with

$$k_{\mathrm{sys,t,0}} = \begin{cases} \min\left\{0.075\ln\left(N\right)+1;1.20\right\} & \text{... for } \mathrm{CV}\left[f_{\mathrm{t,0},\ell}\right] = 25\pm5\% \\ \min\left\{0.130\ln\left(N\right)+1;1.35\right\} & \text{... for } \mathrm{CV}\left[f_{\mathrm{t,0},\ell}\right] = 35\pm5\% \end{cases}. \tag{14}$$

This approach bases again on A_{net} but additionally takes into account the homogenization effects within the parallel acting system as function of CV[$f_{\mathrm{t,0},\ell}$], see Table 2. The values are slightly lower than for GLT according to [8] which regulates the characteristic tensile strength parallel to grain to be equal to 80 % of the characteristics bending strength, but higher than for CLT according to the Austrian National regulations for Eurocode 5 (ÖNORM B 1995-1-1 [30]) which allows only to apply a k_{sys}-factor on a single layer, which is in the reference case of four parallel acting boards equal to $k_{\mathrm{sys}} = 1.09$; compare: $k_{\mathrm{sys,t}}$ for $N = 4$ according to Eq. (7) yields 1.10 and 1.18 for base material's strength classes with low and high variability, respectively.

Table 2: CLT strength classes; characteristic values of CLT in-plane

	Base material T14; CV[$f_{\mathrm{t,0},\ell}$] =	25 ± 5 %	35 ± 5 %
Property [–]	**Symbol [–]**	**CL 24h**	**CL 28h**
Tensile strength parallel to grain	$f_{\mathrm{t,0,CLT,net,k}}$ [N/mm²]	16.0	18.0
Compression strength parallel to grain	$f_{\mathrm{c,0,CLT,net,k}}$ [N/mm²]	24.0	28.0
Shear strength in-plane (shear & torsion)	$f_{\mathrm{v,net,k,ref}}$ [N/mm²] $f_{\mathrm{v,gross,k}}$ [N/mm²] $f_{\mathrm{T,node,k}}$ [N/mm²]	5.5 3.5 2.5	
Shear modulus in-plane	$G_{\mathrm{CLT,mean}}$ [N/mm²]	450 [a)] 650 [b)]	
Shear properties' 5 %-quantiles	$G_{\mathrm{CLT,05}}$ [N/mm²]	$G_{05} = 5/6\ G_{\mathrm{mean}}$	

a) simplified value for CLT without narrow face bonding or with cracks or checks; more detailed approach provided by [31]

b) CLT with narrow face bonding; edge bonding has to be secured over the entire lifetime

2.4.2 Properties in Compression Parallel to Grain

Equal to the tensile properties of CLT parallel to grain, also for compression there are no investigations available so far. Current engineering practice is analog to the approach in tension; however, the mutual interacting layers and lamellas indicate again potentially higher characteristic (5 %-quantile) strength properties in CLT than in the base material, expressible by a system factor $k_{sys,c}(N) \geq 1.00$ as multiplier on the compression strength $f_{c,0,\ell,k}$, see e.g. [9]. For the ease of use, we propose to regulate compression strength parallel to grain of CLT, $f_{c,0,CLT,net,k}$, analog to GLT and according to [8], with $f_{c,0,CLT,net,k} = f_{m,CLT,k}$, see Table 2.

2.4.3 Shear Properties of CLT in-plane

The properties of CLT elements against loads in-plane have been subject of numerous investigations. According to [31–34], three different failure mechanisms have to be distinguished for CLT with and without adhesive bonding on the narrow face: (i) gross-shear failure of the CLT element by longitudinal shearing of all layers of CLT with narrow face bonding, and in CLT without narrow face bonded layers (ii) net-shear failure by exceeding the shear resistance in-plane in layers oriented in CLT's weak direction (e.g. [32,36–38]), and (iii) torsion failure in the gluing-interfaces between the orthogonal layers [17,39,40]. However, a reliable achievement of gross- and net-shear failures in CLT elements failed and the possibility to extrapolate the outcomes from single node testing was not verified so far.

In a comprehensive test campaign using the test configuration of [41] failures in gross- and net-shear could be reliably achieved; [42]. Based on a parameter study in [42] the following characteristic shear properties were derived (see Table 2):

- for CLT elements without narrow face bonding, usually failing in net-shear, a reference characteristic (5 %-quantile) net-shear strength of $f_{v,net,k,ref} = 5.5$ N/mm² applies as far as the thickness of layers in weak axis, $t_{\ell,fail}$, is smaller or equal to 40 mm and the width of gaps between adjacent lamellas within one layer, w_{gap}, is smaller or equal to 6 mm; this strength value is referenced to the net cross section of a CLT element, A_{net}, which is equal to the length of a diaphragm times the sum of layer thicknesses in weak direction, t_{net}, given as

  $$t_{net} = \min\left\{\sum t_{\ell,L}; \sum t_{\ell,T}\right\}, \tag{15}$$

  with $t_{\ell,L}$ and $t_{\ell,T}$ as layer thicknesses parallel and transverse the orientation of the top layers, respectively;

- for CLT elements without narrow face bonding with $t_{\ell,fail}$ below 40 mm but in the range of 20 to 40 mm higher shear strengths were observed. In rare cases of layup parameters $\sum t_{\ell,T} / \sum t_{\ell,L} \geq 0.8$ net-shear failures in top and middle layers instead in intermediate layers may occur. Due to boundary effects lower shear strength of top layers equal to a nominal 10 mm thicker layer was found.

- for simplification, in CLT elements without narrow face bonded layers an average shear modulus of $G_{CLT,mean} = 450$ N/mm² applies. For cases requiring a more detailed calculation the approach according to Bogensperger et al. [31] is proposed;

- for CLT elements with narrow face bonding, usually failing in gross-shear, a characteristic (5 %-quantile) gross-shear strength of $f_{v,gross,k} = 3.5$ N/mm², dedicated to the entire cross section, A_{gross}, and a mean shear modulus of $G_{CLT,mean} = 650$ N/mm² apply. Both values correspond to values for GLT according to [8] and can be used as long as the narrow face bonding is secured. The possibility of cracks due to swelling and shrinkage, at least in the top layers, has to be considered.

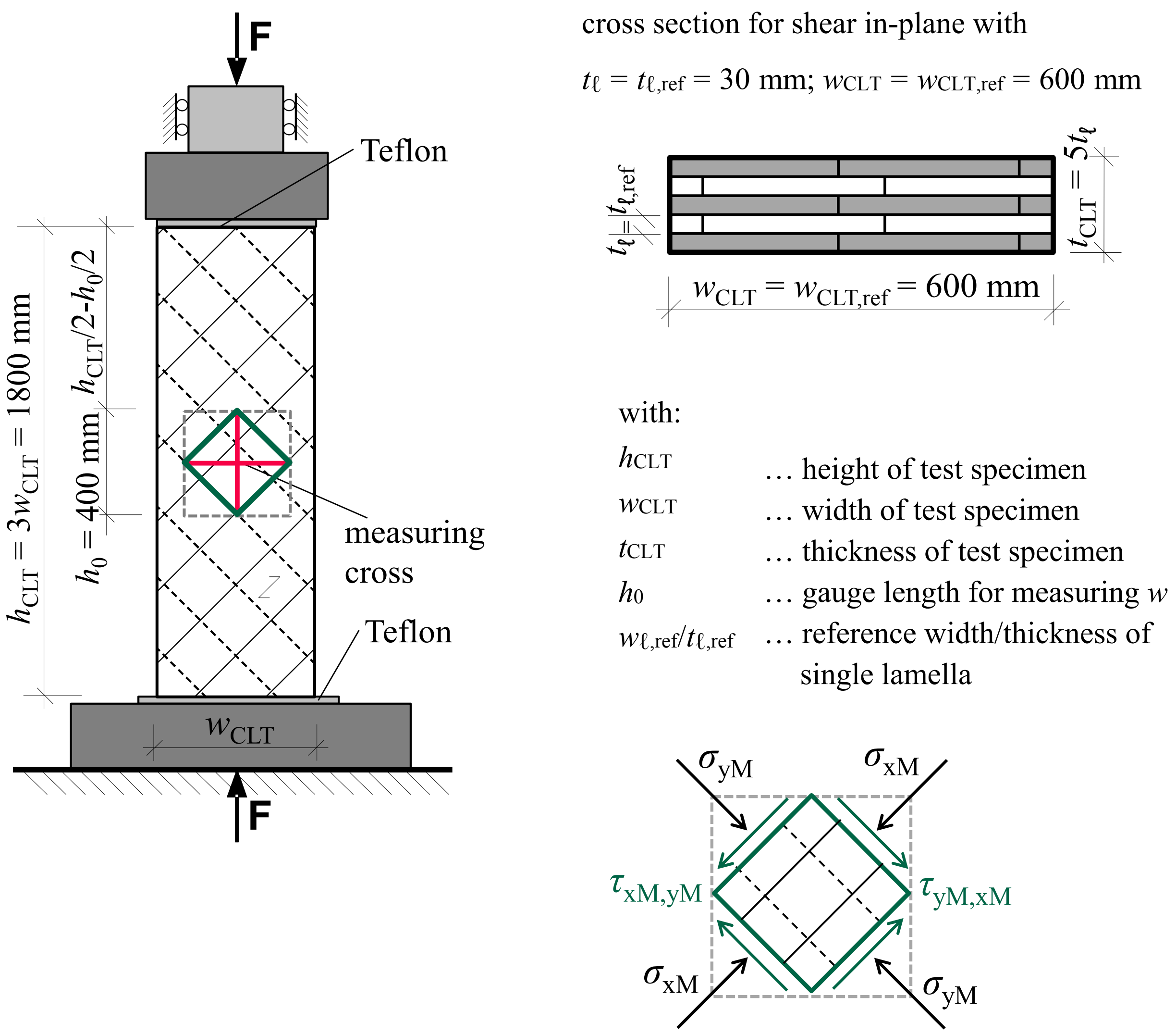


Fig. 5 Test setup for determination of the properties for shear in-plane

The characteristic (5 %-quantile) shear strength against the torsion failure mechanism is based on single node tests and was found with $f_{T,node,k} = 2.5$ N/mm², see Table 2.

Recently, [42] the successful applicability of the test configuration according to [41] was demonstrated. This configuration allows determining shear properties of CLT diaphragms with specifications mirroring current product parameter's variety. The configuration is based on a simple compression test conducted at an angle of 45° to layer orientation, see Fig. 5. The use of specimen with a ratio $h_{CLT} = 3\ w_{CLT}$ is suggested; see [42]. To minimize possible influences by friction Teflon strips may be arranged between specimen and loading and support. The local deformation measurement can be done via four strain transducers situated centrically on both side faces, vertically and horizontally, with gauge lengths $h_0 = 400$ mm. In case of very slender test specimen which are prone to fail in buckling the use of centrically placed horizontal supports is recommended.

The shear stress at maximum load, $\tau_{xM,yM}$, is calculated by

$$\tau_{\mathrm{xM,yM}} = \frac{F_{\max}}{2\ w_{\mathrm{CLT}}\ t_{\mathrm{CLT}}}. \tag{16}$$

In calculation of the shear strength, $f_{v,CLT}$, differentiation in CLT with and without narrow face bonding is required as the typical failure mechanism is either gross- or net-shear.

In case of CLT with narrow face bonding Eqs. (17,18) apply; with σ_{90} as compression stress in y_M-direction, E_{90} as modulus of elasticity perpendicular to the grain of the base material (top layer), E_{yM} as weighted modulus in elasticity in y_M-direction (intermediate layer), E_0 as modulus of elasticity parallel to the grain of the base material, and $t_{\ell,T} / t_{\ell,L}$ as ratio between the sum of layer thicknesses in weak and strong diaphragm direction.

$$f_{\mathrm{v,gross}} = \tau_{\mathrm{xM,yM}} + 1.15\,\sigma_{90} + 0.13\,\sigma_{90}^2, \text{ with } \sigma_{90} = \tau_{\mathrm{xM,yM}} \frac{E_{90}}{E_{\mathrm{yM}}} \tag{17}$$

$$E_{\mathrm{yM}} = \frac{\sum t_{\ell,\mathrm{yM}}\ E_0 + \sum t_{\ell,\mathrm{xM}}\ E_{90}}{t_{\mathrm{CLT}}}\ ;\ t_{\mathrm{CLT}} = \sum t_{\ell,\mathrm{xM}} + \sum t_{\ell,\mathrm{yM}} \text{ and } \sum t_{\ell,\mathrm{L}} \geq \sum t_{\ell,\mathrm{T}} \tag{18}$$

In case of CLT without narrow face bonding with and without gaps, Eqs. (19,20) apply; with σ_{90} as compression stress in x_M-direction, E_{90} as modulus of elasticity perpendicular to the grain of the base material, E_{xM} as weighted modulus of elasticity in x_M-direction (top layer), E_0 as modulus of elasticity parallel to the grain of the base material and t_{net} as sum of the layer thicknesses in weak diaphragm direction.

$$f_{\mathrm{v,net}} = \tau_{\mathrm{xM,yM}} \frac{t_{\mathrm{CLT}}}{t_{\mathrm{net}}} + 1.15\,\sigma_{90} + 0.13\,\sigma_{90}^2, \text{ with } \sigma_{90} = \tau_{\mathrm{xM,yM}} \frac{E_{90}}{E_{\mathrm{xM}}} \tag{19}$$

$$E_{\mathrm{xM}} = \frac{\sum t_{\ell,\mathrm{xM}}\ E_0 + \sum t_{\ell,\mathrm{yM}}\ E_{90}}{t_{\mathrm{CLT}}}\ ;\ t_{\mathrm{net}} = \sum t_{\ell,\mathrm{T}} \tag{20}$$

For CLT diaphragms with or without narrow face bonding the shear modulus, G_{CLT}, can be determined according to Eq. (21); in case of specimen featuring a ratio h_{CLT} / w_{CLT} > 3 a shear correction factor α_{G} = 1.0 can be applied.

$$G_{\mathrm{CLT}} = \alpha_{\mathrm{G}}\ \frac{h_0}{2\ w_{\mathrm{CLT}}\ t_{\mathrm{CLT}}}\ \frac{\Delta F}{\Delta w_{\mathrm{G,mean}}} \tag{21}$$

3. Conclusions and Outlook

3.1 Topics for Research and Development

Due to appearance and mechanical reasons as well as aspects of building physics the trend in CLT is towards minimizing the gaps between lamellas within layers and optimization of appearance quality. Apart from standardized layups with standard layer thicknesses of t_ℓ = 20, 30 and 40 mm, the demand on other layups which are optimized for CLT hybrid structural elements, e.g. ribbed floor elements and box-beams, will increase. In that respect also the utilization of diverse timber species, e.g. for rising the stiffness by target-oriented stiffness grading and the use of high-capacity timber species, e.g. birch, will make it easier to fulfill the requirements in serviceability limit state (SLS) design, i.e. limits in deflection and vibration.

Testing and design prerequisite correction factors for the adjustment of characteristic product properties, determined and applicable for CLT elements with reference dimensions and tested at reference conditions, to CLT elements of other dimensions and exposed to other conditions. Factors enabling these adjustments, e.g. as part of load-bearing models for CLT and in respect to size, system (homogenization), stress distribution, moisture content and temperature, are required; further research is needed.

3.2 Standardization

Although the European CLT product standard, EN 16351 [4], has just been released, it is recommended to commence the work for its revision. We propose to address in particular the following aspects:

- The establishment of a CLT strength class system with reference to the base material's (board or lamella) potential (for example based on T-strength classes according to [8] and reference conditions (e.g. moisture content, cross section, layup, etc.) are proposed. Nomination of CLT strength classes CLxxh and CLxxc according to glulam strength classes GLxxh and GLxxc in [8] is suggested.
- The analyses of all test configurations currently anchored in [4] in respect to their applicability and adequacy for determination of characteristic properties

is necessary. If required, the amendment of existing and supplement of to date missing test configurations together with adequate design approaches and with concerted examination procedures for determination of characteristic product properties are seen as relevant for the establishment of the CLT strength class system. At the end, implementation of these test configurations in EN 408 [12] is seen as meaningful.

- It is deemed to be important to consider all timber species with a relevant market potential for the production of CLT, with focus on European softwood species (e.g. Norway spruce, pine, fir, larch). However, also other species of international importance should be considered, e.g. Japanese cedar (Sugi), Radiata pine.

4. Acknowledgements

The research work was conducted at the Institute of Timber Engineering and Wood Technology at the Graz University of Technology as well as at the Competence Centre Holz.Bau Forschungs GmbH in the framework of the COMET K-Project "focus solid timber solutions (focus_sts)". We would like to express our thanks to all partners involved. The publication, as part of the proceedings from the Joint Conference of FP1402 & FP1404 "Cross Laminated Timber – a competitive wood product for visionary and fire safe buildings" held on the 10th March 2016 at KTH / Stockholm, was written in the framework of the COST Action FP1402 "Basis of Structural Timber Design – from research to standards", chaired by Philipp Dietsch, Technische Universität München (www.costfp1402.tum.de).

5. References

[1] Schickhofer G., Bogensperger T., and Moosbrugger T. (eds.), *BSPhandbuch: Holz-Massivbauweise in Brettsperrholz – Nachweise auf Basis des neuen europäischen Normenkonzepts* [BSPhandbuch: solid timber construction technique with cross laminated timber – verification based on the new European standardization concept], Verlag der Technischen Universität Graz, Graz, 2010, p. 384 (in German).

[2] Brandner R., Flatscher G., Ringhofer A., Schickhofer G., and Thiel A., "Cross laminated timber (CLT): overview and development", *European Journal of Wood and Wood Products*, 2016, DOI 10.1007/s00107-015-0999-5.

[3] Moser K., "Dickholz durch Vakuum [Dickholz through vacuum]", *Bauen mit Holz*, 1995, Vol. 11, pp. 941–947 (in German).

[4] EN 16351, *Timber structures – Cross laminated timber – Requirements. Draft version*, European Committee for Standardization (CEN), 2014.

[5] Kreuzinger, H., and Scholz, S., *Schubtragverhalten von Brettsperrholz* [Shear behavior in cross laminated timber], Research report, 2001, Technische Universität München, Munich (in German).

[6] EN 384, *Structural timber – Determination of characteristic values of mechanical properties and density*, European Committee for Standardization (CEN), 2010.

[7] Brandner, R., *Stochastic System Actions and Effects in Engineered Timber Products and Structures*, Verlag der Technischen Universität Graz, Graz, 2013, p. 467*,* dx.doi.org/10.3217/978-3-85125-263-7.

[8] EN 14080, *Timber structures – Glued laminated timber and glued solid timber – Requirements*, European Committee for Standardization (CEN), 2013.

[9] Unterwieser, H., and Schickhofer, G., *Characteristic values and test configurations of CLT with focus on selected properties*, In: R. Harris, A. Ringhofer and G. Schickhofer (eds.) Focus Solid Timber Solutions – European Conference on Cross Laminated Timber (CLT), The University of Bath, 2013, Bath.

[10] Jöbstl, R.A., Bogensperger, T., Moosbrugger, T., and Schickhofer, G., *A contribution to the design and system effect of cross laminated timber (CLT)*, 39th CIB-W18 Meeting, 2006, Florence, Italy.

[11] Brandner, R., Schickhofer, G., "Glued laminated timber in bending: new aspects concerning modelling", *Wood Science and Technology*, 2008, Vol. 42, No. 5, pp. 401–425.

[12] EN 408, *Timber structures – Structural timber and glued laminated timber – Determination of some physical and mechanical properties*, European Committee for Standardization (CEN), 2012.

[13] Blaß, H.J., and Uibel, T., *Tragfähigkeit von stiftförmigen Verbindungsmitteln in Brettsperrholz* [Load carrying capacity of joints with dowel type fasteners in solid wood panels], Karlsruher Berichte zum Ingenieurholzbau, 2007, Universitätsverlag Karlsruhe, Karlsruhe (in German).

[14] Ringhofer, A., Brandner, R., and Schickhofer, G., "Withdrawal resistance of self-tapping screws in unidirectional and orthogonal layered timber products", *Materials and Structures*, 2015, doi:10.1617/s11527-013-0244-9.

[15] Brandner, R., and Schickhofer, G., *System effects of structural elements – determined for bending and tension*, 9th World Conference on Timber Engineering (WCTE 2006), 2006, Portland, Oregon, United States.

[16] Brandner, R., and Schickhofer, G., "Probabilistic models for the modulus of elasticity and shear in serial and parallel acting timber elements", *Wood Science and Technology*, 2015, Vol. 49, pp.121–146, doi:10.1007/s00226-014-0689-1.

[17] Blaß, H.J., and Görlacher, R., "Zum Trag- und Verformungsverhalten von Brettsperrholz – Elementen bei Beanspruchung in Plattenebene: Teil 2 [Contribution to the deformation behavior of cross laminated timber elements

in-plane: Part 2]", *Bauen mit Holz*, 2002, Vol. 12, pp. 30–34 (in German).

[18] Wallner, G., *Versuchstechnische Ermittlung der Verschiebungskenngrößen von orthogonal verklebten Brettlamellen* [Experimental determination of displacement properties from two orthogonally bonded board segments], Diploma thesis, 2004, Graz University of Technology (in German).

[19] Jakobs, A., *Zur Berechnung von Brettlagenholz mit starrem und nachgiebigem Verbund unter plattenartiger Belastung unter besonderer Berücksichtigung des Rollschubes und der Drillweichheit* [Calculation of laminar laminated timber as rigid and flexible composite loaded out-of-plane with particular consideration of rolling shear and twisting], Dissertation, Universität der Bundeswehr, 2005 (in German).

[20] Mestek, P., Kreuzinger, H., and Winter, S., *Design Concept for CLT – reinforced with Self-Tapping Screws*, 44th CIB-W18 Meeting, 2011, Alghero, Italy.

[21] Ehrhart, T., Brandner, R., Schickhofer, G., and Frangi, A., *Rolling shear properties of some European timber species with focus on cross laminated timber (CLT): test configuration and parameter study*, 2nd INTER-Meeting, 2015, Sibenik, Croatia.

[22] Görlacher, R., "Ein Verfahren zur Ermittlung des Rollschubmoduls von Holz [A method for determining the rolling shear modulus of timber]", *Holz als Roh- und Werkstoff*, 2002, Vol. 60, pp. 317–322 (in German).

[23] Halili, Y., *Versuchstechnische Ermittlung von Querdruckkenngrößen für Brettsperrholz* [Experimental determination of compression perpendicular to grain properties of cross laminated timber], Diploma thesis, 2008, Graz University of Technology (in German).

[24] Salzmann, C., *Ermittlung von Querdruckkenngrößen für Brettsperrholz (BSP)* [Determination of compression perpendicular to grain properties of cross laminated timber (CLT)], Master's thesis, 2010, Graz University of Technology (in German).

[25] Serrano, E., and Enquist, B., *Compression strength perpendicular to grain in cross-laminated timber (CLT)*, 11th World Conference on Timber Engineering (WCTE 2010), 2010, Riva del Garda, Italy.

[26] Bogensperger, T., Augustin, M., and Schickhofer, G., *Properties of CLT-panels exposed to compression perpendicular to their plane*, 44th CIB-W18 Meeting, 2011, Alghero, Italy.

[27] Ciampitti, A., *Untersuchung ausgewählter Einflussparameter auf die Querdruckkenngrößen von Brettsperrholz* [Investigations on selected influencing parameters on the mechanical properties in compression perpendicular to the grain of cross laminated timber], Master's thesis, 2013, Graz University of Technology (in German).

[28] Brandner, R., and Schickhofer, G., *Properties of cross laminated timber (CLT) in compression perpendicular to grain*, 1st INTER-Meeting, 2014, Bath, United Kingdom.

[29] Jeitler, G., and Brandner, R., *Modellbildung für DUO-, TRIO- und QUATTRO-Querschnitte* [Modelling of DUO-, TRIO- and QUATTRO-beams], In: G. Schickhofer and R. Brandner (eds.) 7. Grazer Holzbau-Fachtagung (7.GraHFT'08): Modellbildung für Produkte und Konstruktionen aus Holz – Bedeutung von Simulation und Experiment, Verlag der Technischen Universität Graz, 2008, Graz (in German).

[30] ÖNORM B 1995-1-1 *Eurocode 5: Design of timber structures – Part 1-1: General – Common rules and rules for buildings – National specifications, national comments and national supplements concerning ÖNORM EN 1995-1-1*, Austrian Standards Institute (ASI), 2014.

[31] Bogensperger, T., Moosbrugger, T., and Silly, G., *Verification of CLT-plates under loads in plane*, 11th World Conference on Timber Engineering (WCTE2010), 2010, Riva del Garda, Italy.

[32] Bogensperger, T., Moosbrugger, T., and Schickhofer, G., *New test configuration for CLT-wall-elements under shear load*, 40th CIB-W18 Meeting, 2007, Bled, Slovenia.

[33] Flaig, M., and Blaß, H.J., *Shear strength and shear stiffness of CLT-beams loaded in plane*, 46th CIB-W18 Meeting, 2013, Vancouver, Canada.

[34] Brandner, R., Bogensperger, T., and Schickhofer, G., *In plane shear strength of cross laminated timber (CLT): test configuration, quantification and influencing parameters*, 46th CIB-W18 Meeting, 2013, Vancouver, Canada.

[35] Bosl, R., *Zum Nachweis des Trag- und Verformungsverhaltens von Wandscheiben aus Brettsperrholz* [Contribution to the load and displacement behavior of cross laminated timber diaphragms], Dissertation, 2001, Military University Munich (in German).

[36] Jöbstl, R.A., Bogensperger, T., and Schickhofer, G., *In-plane shear strength of cross laminated timber*, 41st CIB-W18 Meeting, 2008, St. Andrews, Canada.

[37] Hirschmann, B., *Ein Beitrag zur Bestimmung der Scheibenschubfestigkeit von Brettsperrholz* [A contribution to the determination of in-plane shear strength of cross laminated timber], Master's thesis, 2011, Graz University of Technology (in German).

[38] Andreolli, M., Rigamonti, M.A., and Tomasi, R., *Diagonal compression test on cross laminated timber panels*, 13th Word Conference on Timber Engineering (WCTE 2014), 2014, Quebec, Canada.

[39] Jeitler, G., *Versuchstechnische Ermittlung der Verdrehungskenngrößen von orthogonal verklebten Brettlamellen* [Experimental determination of torsion properties of orthogonally bonded board segments], Diploma thesis, 2004, Graz University of Technology (in German).

[40] Jöbstl, R.A., Bogensperger, T., Schickhofer, and G., Jeitler, G., *Mechanical behaviour of two orthogonally glued boards*, 8th World Conference on Timber Engineering (WCTE 2004), 2004, Lahti, Finland.

[41] Kreuzinger, H., and Sieder, M., "Einfaches Prüfverfahren zur Bewertung der Schubfestigkeit von Kreuzlagenholz / Brettsperrholz [Simple test setup for assessment of shear strength of cross laminated timber]", *Bautechnik*, 2014, Vol. 90, No. 5, pp. 314–316 (in German).

[42] Brandner, R., Dietsch, P., Dröscher, J., Schulte-Wrede, M., Kreuzinger, H., Sieder, M., Schickhofer, and G., Winter, S., *Shear properties of cross laminated timber (CLT) under in-plane load: Test configuration and experimental study*, 2nd INTER-Meeting, 2015, Sibenik, Croatia.