DOI: https://doi.org/10.14256/JCE.2071.2017



Primljen / Received: 11.4.2017.
Ispravljen / Corrected: 13.10.2017.
Prihvaćen / Accepted: 30.10.2017.
Dostupno online / Available online: 10.3.2018.

# Cross-laminated timber (CLT) – a state of the art report

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Subject review

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## Cross-laminated timber (CLT) – a state of the art report

Cross laminated timber is an innovative plate-shaped product presenting a laminated structure and excellent physicomechanical properties. Due to its high stiffness and in-plane and out-of-plane bearing capacity, it is most often used in form of wall or floor panels. Favourable environmental, aesthetic and energy properties further enhance its qualities. The paper is a summary of CLT research conducted so far, with an emphasis on the need to harmonise existing regulations and include this product in the European standard for timber structures Eurocode 5.

Key words:
cross laminated timber, CLT, composite material, material properties, carrying capacity analysis, Eurocode 5

Pregledni rad

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## Križno lamelirano drvo (CLT) - pregled stanja područja

Križno lamelirano drvo (eng. *Cross Laminated Timber* – CLT) inovativni je pločasti proizvod slojevite strukture i izvrsnih fizikalno-mehaničkih svojstava. Zbog velike krutosti i nosivosti u ravnini i okomito na ravninu elementa najčešće se primjenjuje u obliku zidnih ili stropnih panela. Povoljna ekološka, estetska i energetska svojstva dodatno ga pospješuju. Rad prikazuje sumarni pregled dosad provedenih istraživanja CLT-a, s naglaskom na potrebnu harmonizaciju postojećih propisa i njegovo uključivanje u europsku normu za drvene konstrukcije Eurokod 5.

Ključne riječi:
križno lamelirano drvo, CLT, kompozitni materijal, materijalne karakteristike, analiza nosivosti, Eurokod 5

Übersichtsarbeit

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## Brettsperrholz (CLT) – Verwendungsübersicht

Brettsperrholz (eng. *Cross Laminated Timber* – CLT) ist ein innovatives plattenförmiges Produkt mit einer geschichteten Struktur und hervorragenden physikalisch-mechanischen Eigenschaften. Aufgrund der hohen Steifigkeit und Tragfähigkeit in Ebene und senkrecht zur Ebene des Elements wird es meistens in Form von Wand- oder Deckenpaneelen verwendet. Die günstigen ökologischen, ästhetischen und energiewirtschaftlichen Eigenschaften verbessern dieses noch zusätzlich. Die Abhandlung gibt eine zusammenfassende Übersicht über die bisherigen Untersuchungen des CLT mit Betonung auf der erforderlichen Harmonisierung der bestehenden Vorschriften und dessen Integration in die europäische Norm Eurocode 5 für Holzkonstruktionen.

Schlüsselwörter:
Brettsperrholz, CLT, Verbundmaterial, Materialeigenschaften, Analyse der Tragfähigkeit, Eurocode 5

## 1. Introduction

Throughout the history, traditional timber structures have mostly been used as lightweight framework systems with linear solid-wood elements of limited span. In the early twentieth century, steel and concrete became more readily available and cost-effective, and thus timber was largely replaced with reinforced concrete. The interest for timber structures re-emerged in the mid-1960s after introduction of a novel wood based product called the engineered wood product (EWP). Products such as glued laminated timber (GLT) enabled construction of more complex and highly robust linear larger-span structures. The first plate-shaped products such as the laminated veneer lumber (LVL) or oriented strand boards (OSB) were for the most part used as secondary elements in the lining and protection of structures. In the scope of subsequent development incentives, a new composite product called cross laminated timber (CLT) was patented in the mid-1990s. CLT is a stiff plate-shaped product composed of an appropriate number of layers (mostly odd-numbered: 3, 5 or 7), where each layer is made of boards/lamellae placed adjacent to one another, and where neighbouring layers are most often glued at an angle of 90° to one another. This multi-layered and highly optimised structure provides such in-plane and out-of-plane carrying capacity, so it can be used as wall and floor panels. The product is characterised by a high level of prefabrication and hence the on-site work is rapid, mostly involving only assembly and connection of individual panels. From the aspect of building physics, the material exhibits excellent energy efficiency and high capacity for storing moisture and thermal energy [1]. Small self-weight facilitates foundation work, and enables its use even in earthquake-prone areas [2]. Workability, slenderness, and diverse possibilities of incorporation in large-size panels, pose almost no limitations to architectural shaping of this product. Favourable natural and environmental properties, accompanied by aesthetically pleasing surfaces, are the reason for the rising exposure of CLT in recent years, as witnessed by the growing number of residential and office buildings, ever increasing in size and creativity, through which a new return of timber to urban surroundings has been intensified over the past several years [3] (Figure 1).

Besides high-rise construction, CLT also offers great potential with regard to its use in bridge building, where it can be used either independently or in combination with other wood- and/or steel-based materials in the construction of ribbed and/or box girders (Figure 2). CLT properties have rapidly been recognized even outside of Europe in the countries such as Canada or the USA, but also in the countries exposed to frequent seismic activities, such as Japan, China or New Zealand, all of which resulted in progressive increase of its production over the past several years, with an annual increase of 15-20 % [9].

In order to realize the full potential of this material, it also proved indispensable to intensify activities in the field of standardisation and harmonisation of existing regulations and standards. CLT properties were initially defined by national regulations (since 1998) and, subsequently, as from 2006, through the work of international technical committees (International European Technical Approval – ETA). Although the first European standard for CLT, EN16351 [10], was introduced in 2015, it currently regulates only limitations related to production and construction and, even there, a uniform design procedure is still lacking. The design procedure can be found in some national annexes to the European standard such as [11, 12], although it is still not included in the European standard for timber structures EN 1995-1-1 [13]. In the meantime, engineers have been using various technical regulations and manufacturer-issued specifications for CLT related calculations. Several books and manuals now offer recommendations and design procedures based on the results

**Figure 1. CLT element with 5 layers (top left) [4]; exhibition pavilion "The Smile" in London (top centre) [4]; Brock Commons Project in Vancouver (top right) [5]; Dalston Lane Project in London (bottom left) [6]; Wohnbau Wagramer Strasse Project in Vienna (bottom centre) [7]; Treet Project in Bergen (bottom right) [8]**

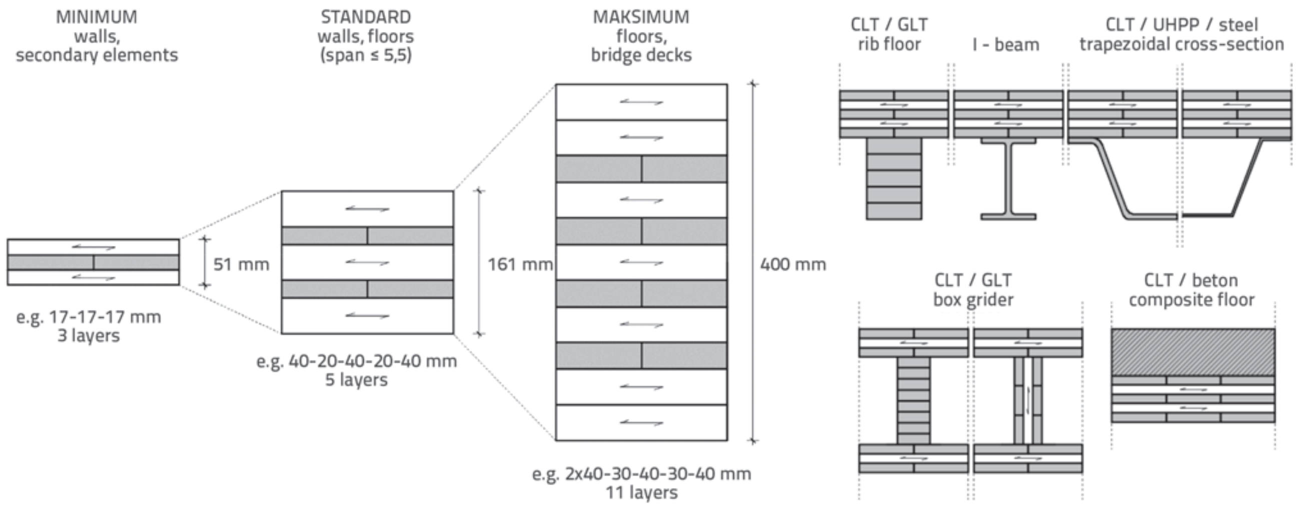



**Figure 2. Cross sections of typical CLT girders (left); examples of composite structures based on CLT, LLD, steel, concrete or ultra-high-performance plywood (UHPP) (right) [14]**

presented in a huge number of research projects conducted so far. Notable examples are the manual by Schickhofer from 2010 [14] or the manual by Wallner-Novak from 2013 [15] for the CLT use in Europe, as well as manuals for Canadian [16] and US [17] markets.
The following paper focuses on the most significant CLT aspects related to its manufacturing process, methodology used for defining its material characteristics, and design procedure for specific design situations. An overview of the still open and yet unexplored areas is also given. At that, the paper mostly concentrates on European achievements and provides an overview of European standards and European types of softwood used in the homogeneous CLT structure.

## 2. CLT manufacturing technology

### 2.1. General notions on manufacturing procedure

The CLT manufacturing procedure/technology, shown in Figure 3, presents a number of similarities with the LLD process. The terminology and marks used in this paper, with standard geometrical data, are presented in Figure 4. The manufacturing procedure can roughly be divided into two basic steps:
- preparation and treatment of basic material (first three sub-steps from Figure 3)
- arranging and gluing of basic material (final three sub-steps from Figure 3).

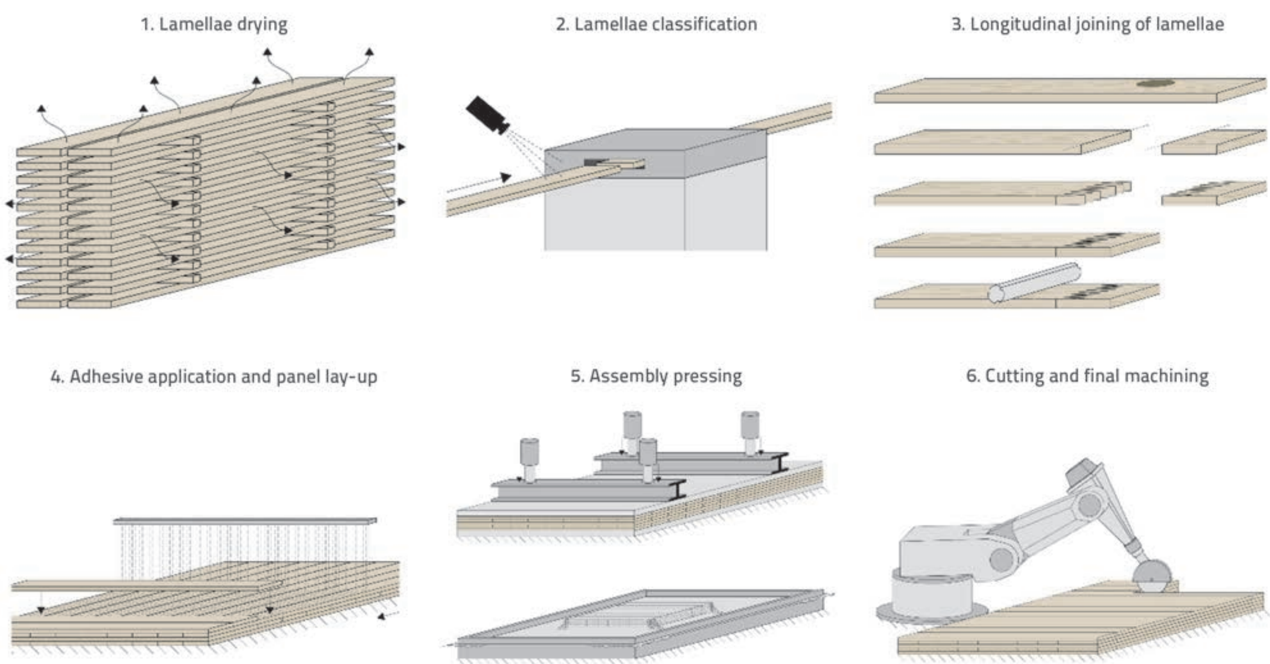



**Figure 3. CLT manufacturing procedure [18]**

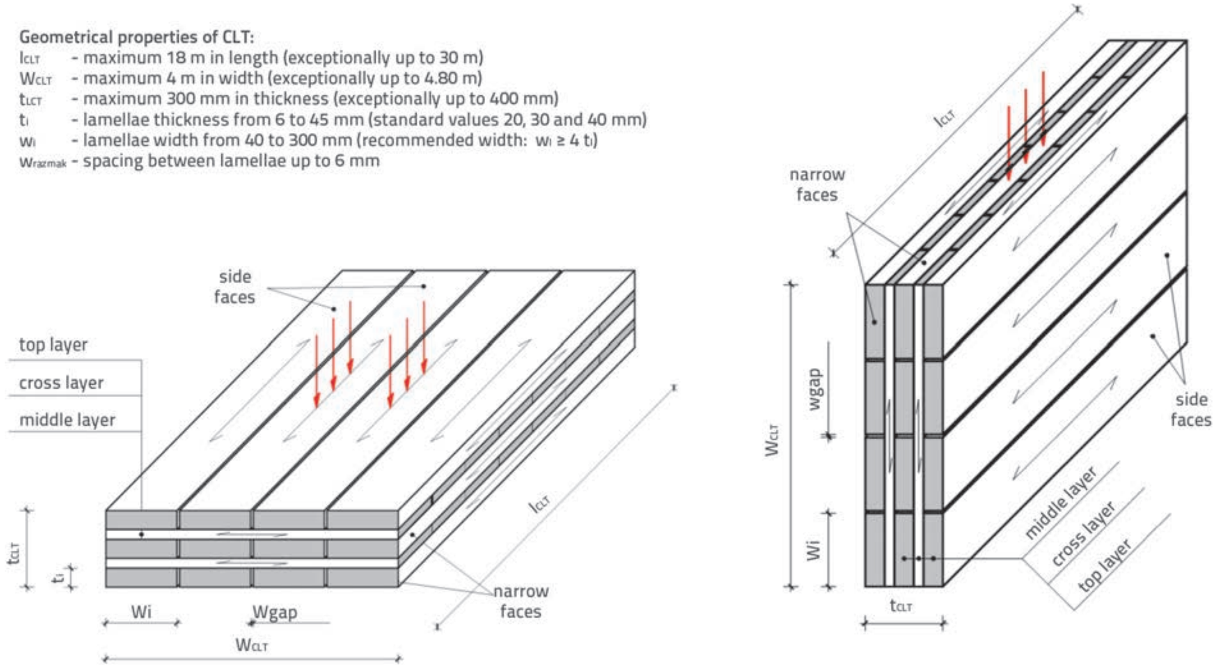



**Figure 4. Geometrical properties of CLT elements for loads out-of-plane (left) and loads in-plane (right)**

## 2.2. First manufacturing step: Preparation and treatment of basic material

The first manufacturing step involves drying and classification of raw material, and then planing, cutting and longitudinal joining using finger joints. Moisture tolerances of the basic material are 12 ± 2 %. Once this is achieved, the material is classified either visually or by machine according to EN14081-1 [19] or DIN4074-1 [20]. The timber class C24 compliant with EN 338 [21] is normally used in the case of homogeneous CLT sections, while a somewhat lower grade C16/18 is allowed in the case of combined sections in vertical layers. Soft types of wood are mainly used, although an appropriate use can also be made of local types with poorer mechanical properties [22]. After classification of material, lamellae are connected longitudinally using finger joints according to the specification and technology corresponding to that used for LLD girders. Some manufacturers offer joining involving entire CLT elements, using large-size finger joints 45 mm in minimum length [9]. Such joints are realised on earlier made CLT elements, and it should however be noted that such connection may result in the reduction of mechanical properties [23]. When realising such finger joints it is necessary to use an appropriate adhesive compliant to, for instance, EN 301 [24] or EN 15425 [25] and to take into account technical requirements for the use of such joints (moisture, temperature, quantity, duration and intensity of pressure during application, etc.). It is recommended to use adhesive substances presenting mechanical properties similar to those of the basic material. Most frequently used adhesives include melamine-urea-formaldehyde (MUF), single-component polyurethane adhesive (1K-PUR), and emulsion polymer isocyanate adhesive (EPI). After completion of finger joints, lamellae are finally cut to dimensions needed for fabrication of CLT elements.

## 2.3. Second manufacturing step: arranging and gluing of basic material

The second manufacturing step involves arranging and gluing the previously treated lamellae to form the CLT product. Attempts are generally made during CLT manufacturing to minimise the spacing between lamellae so as to take into account building physics requirements (fire resistance, airtightness or sound insulation), aesthetic requirements, and specific board joining requirements. However, 6 mm maximum spacing is specified in many technical regulations, EN 16351 included [10]. If CLT elements are manufactured without spacing, some manufacturers first produce individual CLT layers by gluing narrow edges of lamellae, and then these layers are glued together along wide sides to form a final element. However, the contribution of applying glue along narrow sides of lamellae is questionable and it is generally recommended that it can be neglected or at least limited to internal layers of the element [9]. This is due to the expected occurrence of irregular cracks on the surface of the element as a result of timber shrinkage and swelling caused by change in temperature and moisture. If the manufacturing procedure does not include production of individual layers, then the previously prepared lamellae are directly arranged and glued along wide sides to form the CLT element composite. As a general rule, recommendations and requirements given by the glue manufacturer must be observed. Here the most significant parameters such as gluing pressure, quality, moisture and glue thickness, are related to the LLD girder gluing practise. Glue types similar to those used in the fabrication of finger joints are applied. Board gluing is conducted by applying an appropriate pressure. The values range from 0.10 to 1.0 N/mm$^2$ if hydraulic jacks are used, while the corresponding values vary from 0.05 to 0.10 N/mm$^2$ for vacuum jacks, and the values range from 0.01 to 0.20 N/mm$^2$ for pressure exerted by bolts, clamps and nails. Nevertheless, a uniform gluing compression value has still not been defined in the corresponding regulations. This is discussed in greater detail in [9]. After gluing, the product is cut to final dimensions. In addition, appropriate geometrical corrections are made as needed prior to delivery of the product. Such final product is adequately protected against outside weather conditions as soon as it is ready for transport and placing.

## 3. Material properties of CLT

### 3.1. General

A reliable CLT design procedure depends on the reliably defined material properties, and the latter are currently not defined in EN 16351 [10]. Furthermore, they have not been consistently regulated between technical regulations. Two approaches for the determination of material properties have been formulated [26]:

- an approach based on mechanical properties tested on basic material in combination with the load carrying model
- the approach based on mechanical properties tested on full-scale CLT elements.

The research conducted so far in order to determine individual mechanical properties is presented below, and a summary overview of recommended nominal values is given at the end of the section.

### 3.2. Loads out-of-plane of CLT elements

#### 3.2.1. Bending strength

The model for determining bending resistance out-of-plane of CLT is proposed by Jöbstl et al. [27] based on experimental testing conducted in parallel on CLT and LLD girders. The proposed carrying capacity model is based on the homogeneous reference CLT section presented in Figure 5, which served for defining two strength classes, CL 24h and CL 28h, based on lamellae belonging to strength class T14 as defined in EN 14080 [28].

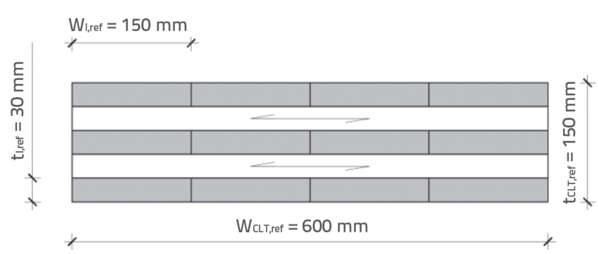



**Figure 5. Designations and dimensions of reference CLT section [27]**

The model takes into account homogenisation of material properties of CLT, expressed in reduced variability of mechanical characteristics of the entire element, as compared to the variability of basic material. The proposed model takes into account four influence factors by which the characteristic tensile strength parallel to grain is translated into the characteristic bending strength out-of -plane of CLT according to expression (1) based on [27]:

$$f_{m,CLT,k} = k_{m,CLT} \times f_{t,0,l,k}^{0,8}; \quad k_{m,CLT} = k_{sys,m} \times k_{CLT/GLT} \times k_{h,CLT} \times k_{CV\_t} \tag{1}$$

where:
$f_{m,CLT,k}$ - characteristic value of bending strength,
$f_{t,0,l,k}$ - characteristic value of tensile strength parallel to grain,
$k_{sys,m}$ - coefficient that takes into account the systemic effect at bending due to interaction of a number of lamellae,
$k_{CLT/GLT}$ - coefficient that takes into account difference in homogenisation influence between CLT and LLD,
$k_{h,CLT}$ - CLT height coefficient corresponding to that of LLD,
$k_{CV\_t}$ - coefficient depending on variation of basic material.

#### 3.2.2. Shear strength

Bending loads out-of-plane of CLT element causes shear stress in fibre direction in longitudinal layers, while shear stress perpendicular to the fibre direction occurs in transverse layers (Figure 6). The basic material value compliant with EN 14080 [28] must be used for the typical shear strength $f_{v,CLT,k}$ and for the mean shear stiffness $G_{CLT,mean}$ parallel to grain, as recommended in [26, 29].

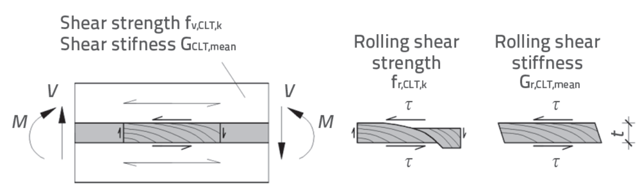



**Figure 6. Shear strength designation for loads out-of-plane of CLT element**

Several studies have so far been made with regard to the determination of the rolling shear strength $f_{r,CLT,k}$ and rolling shear stiffness $G_{r,CLT,mean}$ perpendicular to grain, as critical carrying capacity and serviceability parameters for CLT [30-37]. Most studies were conducted using standard European types of softwood [38, 39] although activities have been intensified in recent years with regard to the use of non-standard types [40, 41], with an emphasis on possible uses of hardwood species [42]. Erhart et al. conducted in 2015 an extensive experimental testing involving more than 200 specimens. This testing was conducted using standard procedure presented in Figure 7, in accordance with EN 408 [43]. The contribution of the following parameters was analysed:

- type of wood
- geometry of lamellae taking into account their width to thickness ratio $w_l$ / $t_l$
- type of lamella cutting as a function of distance from the heartwood.

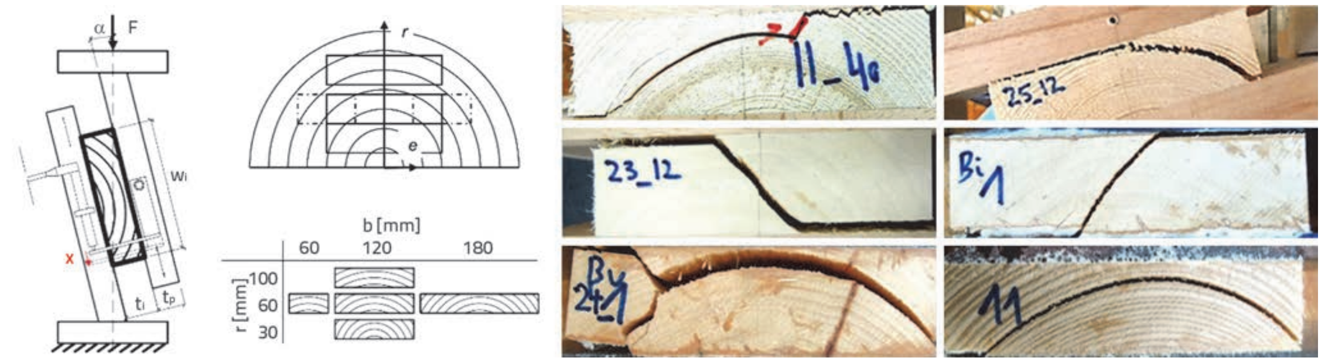


**Figure 7. Experimental configuration, varied parameters and typical type of failure according to [38] (from left to right)**

Based on this testing, the authors made the following conclusions that are generally compliant with those made in earlier studies:

- shear strength and stiffness greatly depend on the type of wood and the values are much lower for softer types compared to harder types of wood,
- the lamella $w_l$ / $t_l$ ratio greatly influences the strength and stiffness values, where reduction of the ratio causes reduction in carrying capacity due to increase in tensile and shear stress perpendicular to grain
- the greater the distance of lamella from the heartwood the lower the shear stiffness, with no clear change in strength. A bilinear model as a function of the width to thickness ratio $w_l$ / $t_l$ is presented in expressions (2) and (3).

$$f_{r,CLT,k} = \min \begin{cases} 0{,}2 + 0{,}3 \times \frac{w_l}{t_l}; & w_l/t_l = 2 \rightarrow f_{r,CLT,k} = 0{,}80\,\mathrm{N/mm^2} \\ 1{,}40 & w_l/t_l = 4 \rightarrow f_{r,CLT,k} = 1{,}40\,\mathrm{N/mm^2} \end{cases} \quad (2)$$

$$G_{r,CLT,mean} = \min \begin{cases} 30 + 17{,}5 \times \frac{w_l}{t_l}; & w_l/t_l = 2 \rightarrow G_{r,CLT,mean} = 65\,\mathrm{N/mm^2} \\ 100 & w_l/t_l = 4 \rightarrow G_{r,CLT,mean} = 100\,\mathrm{N/mm^2} \end{cases} \quad (3)$$

### 3.2.3. Tension strength perpendicular to grain

As research is lacking in the field of tension perpendicular to grain for CLT, it is recommended – according to engineering judgment based on similarity of CLT and LLD elements – that the CLT tensile strength perpendicular to grain should be considered similar to that of LLD, i.e. $f_{t,90,CLT,k}$ = $f_{t,90,k}$, in accordance with EN 14080 [28].

### 3.2.4. Compression strength perpendicular to grain

Mechanical properties for compression perpendicular to grain are determined based on experimental testing of small prismatic specimens the surfaces of which are exposed to homogeneous and uniform stress, which is compliant to the testing according to EN 408 [43] and EN 16351 [10]. Several studies have been conducted so far with the purpose of determining the reference compressive strength and elastic modulus perpendicular to grain [44-49]. Halili [44] conducted in 2008 an experimental testing of CLT and LLD prisms. After the testing, he established that greater strength and stiffness values of CLT prisms are due to the so called "locking effect" where transverse CLT sample layers act as a strengthening. They thus reduce lateral deformation of the specimen and assume tensile stress occurring in the process. Salzmann [45] conducted in 2010 a testing on reference prisms and various CLT element configurations. He analysed the influence of the position of point load and linear load. The greatest carrying capacity was obtained in the case of CLT specimens subjected to central load, as the propagation of stress was possible in all four directions, while the smallest carrying capacity was obtained for specimens subjected to load at corners, as the propagation of stress was prevented at two free sides of the specimen. Serrano and Enquist [46] analysed in 2010 linear load by which a connection of wall and floor elements was simulated. Bogensperger et al. [47] conducted in 2011 an extensive numerical analysis of CLT specimens based on a 3D numerical model, where several different point load and linear load situations were simulated for CLT elements. Based on this analysis, the authors concluded that a linear dependence

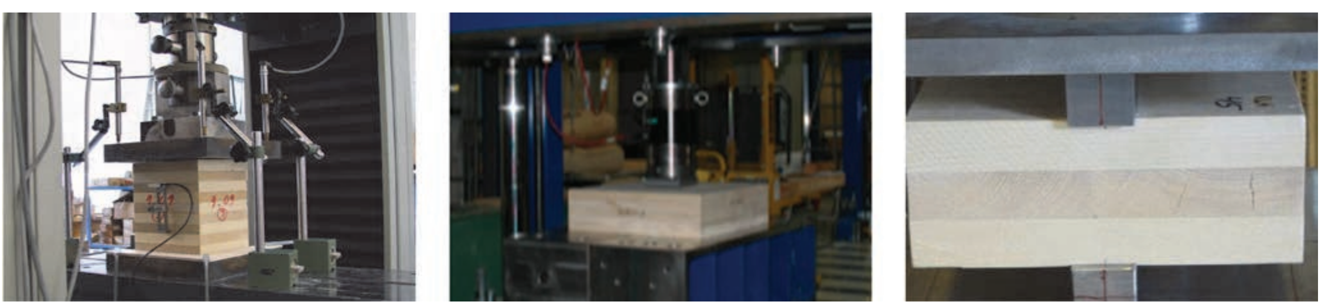


**Figure 8. Experimental samples for testing compressive strength perpendicular to grain: Halili [44] (left), Salzmann [45] (centre) and Serrano [46] (right)**

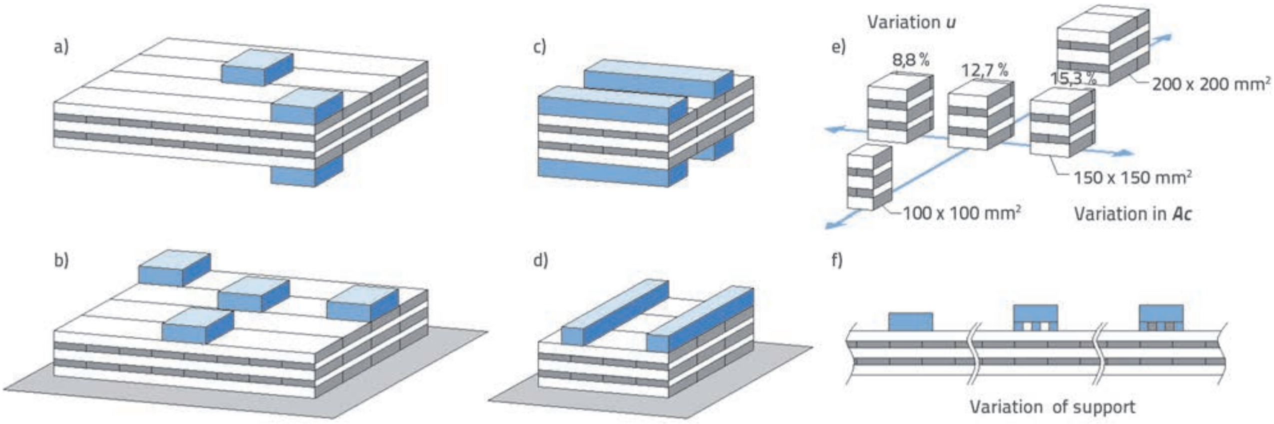



**Figure 9. Experimental testing of parameters according to [49]: a) point load and point support; b) point load and flat support; c) linear load and linear support; d) linear load and plane support; e) variation in area and moisture of tested prisms; f) support variation in case of linear load**

exists between the sample thickness and the stress distribution depth.

In 2014, Brandner and Schickhofer [49] analysed experimental results as related to parameters shown in Figure 9:
- influence of dimensions of the reference prism contact area
- difference in behaviour in case of point, linear, and plane loading of CLT elements
- influence of moisture on the strength and elastic modulus.

The following conclusions were made:
- there is a linear increase in strength and stiffness with an increase in contact area of reference prisms
- the strength and stiffness decrease in case of CLT elements subjected to point and linear load as a result of increase in contact area
- the strength and stiffness decrease with an increase in material moisture.

Based on this testing, the authors proposed the reference value of characteristic compressive strength perpendicular to grain, namely $f_{c,90,CLT,k,ref}$ = 3,0 N/mm², and the mean elastic modulus amounting to $E_{c,90,CLT,mean,ref}$ = 400 N/mm².

A summary of compressive strength experimental testing perpendicular to grain, as conducted on reference CLT prisms, is presented in Table 1, where *n* is the number of tested samples, *l* is the length, *b* is the width, and *h* is the height of reference prisms; at that, characteristic strength and modulus values were obtained using log-normal distribution according to EN 14358 [50].

## 3.3. Loads in-plane of CLT elements

### 3.3.1. Tension strength parallel to grain

CLT properties in case of exposure to tension parallel to grain have not as yet been sufficiently studied, and this neither theoretically nor experimentally. Using the engineering approach on the side of safety, only the net area of cross section $A_{net}$ is taken into account in calculation, and the carrying capacity involves only those layers that are parallel to external load [14]. Nevertheless, the influence of homogenisation must also be taken into account due

**Table 1. Mechanical properties of CLT prisms perpendicular to grain direction**

| Author / year | n | l x b x h [mm] | $f_{c.90.CLT.mean}$ [N/mm²] | $f_{c.90.CLT.k}$ [N/mm²] | $E_{c.90.CLT.mean}$ [N/mm²] | $E_{c.90.CLT.k}$ [N/mm²] |
|---|---|---|---|---|---|---|
| Halili 2008 [44] | 217 | 160 x 160 x 200 | 3.31 | 2.94 | 485 | 404 |
| Salzmann 2010 [45] | 15 | 160 x 160 x 150 | 3.52 | 3.01 | 440 | 346 |
| | 35 | 160 x 160 x 160 | 3.34 | 2.86 | 367 | 280 |
| | 27 | 160 x 160 x 165 | 3.33 | 2.69 | 435 | 338 |
| | 10 | 160 x 160 x 197 | 3.43 | 2.96 | 387 | 287 |
| Serano & Enquist 2010 [46] | 15 | 200 x 200 x 120 | 3.33 | 2.86 | - | - |
| Brandner & Schickhofer 2014 [49] | 10 | 100 x 100 x 150 | 3.26 | 2.97 | 380 | 325 |
| | 29 | 150 x 150 x 150 | 3.48 | 3.10 | 391 | 311 |
| | 10 | 200 x 200 x 150 | 3.87 | 3.51 | 436 | 382 |

to parallel action of a greater number of lamellae within a single girder layer. The expression (4) is proposed in [26] for calculating characteristic tensile strength parallel to grain of CLT:

$$f_{t,0,CLT,net,k} = k_{sys,t,0} \times f_{t,0,l,k} \tag{4}$$

$$k_{sys,t,0} = \begin{cases} \min(0{,}075 \times \ln N) + 1;\ 1{,}20 & \rightarrow\ CV\left[f_{t,0,l}\right] = 25 \pm 5\% \\ \min(0{,}130 \times \ln N) + 1;\ 1{,}35 & \rightarrow\ CV\left[f_{t,0,l}\right] = 35 \pm 5\% \end{cases}$$

where:

$f_{t,0,CLT,net,k}$ - characteristic value of CLT tensile strength parallel to grain

$k_{sys,t,0}$ - coefficient that takes into account the systemic effect in tension due to interactive action of a greater number of lamellae

N - number of parallel oriented longitudinal lamellae (for reference cross-section N = 12)

$CV[f_{t,0,l}]$ - coefficient of tensile strength variation parallel to grain of the basic material.

### 3.3.2. Compression strength parallel to grain

Research is also scarce with regard to compressive strength parallel to grain. In engineering practice, this value is determined in the way similar to the determination of tensile strength parallel to grain. Accordingly, the coefficients $k_{sys,c} \geq 1.0$ are proposed as they take into account an interactive compressive action of a greater number of parallel oriented lamellae [26]. However, a conservative recommendation would be to take compressive strength parallel to grain as being equal to the out-of-plane bending strength $f_{c,0,CLT,net,k} = f_{m,CLT,k}$.

### 3.3.3. Shear strength

In case if CLT panels are loaded in-plane, a general requirement is to check three shear failure mechanisms (FM) shown in Figure 10 [51, 52]:

- shear failure along gross cross-section of CLT, relevant in case narrow lamella sides are glued, failure at $f_{v,gross}$
- shear failure along net cross-section of CLT, relevant in case of no contact at narrow sides of lamellae, failure at $f_{v,net}$
- shear failure due to torsion and uniaxial shear stress at the contact between two orthogonally glued lamellae, failure at $f_{tor}$ and $f_r$.

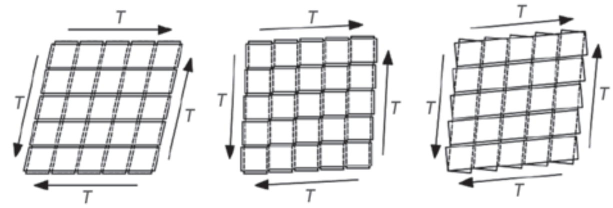



**Figure 10. Shear failure mechanisms for CLT elements loaded in-plane [52] FM I (left), FM II (centre), FM III (right)**

Complex stress state and complex interaction between individual failure mechanisms are the reasons behind non-existence of a uniform experimental configuration and reference specimen for determining shear strength of CLT. In case narrow sides of lamellae are glued, it is recommended to assume, for proving carrying capacity for failure mechanism FM I, the typical shear strength of $f_{v,gross,k}$ = 3,5 N/mm² and the mean shear modulus of $G_{CLT,mean}$ = 650 N/mm² in accordance with EN 14080 [28]. If there is no contact between narrow sides of adjecent lamellae, which is most frequently the case with CLT, the proof of carrying capacity is ambiguous and it is necessary to separately check FM II and FM III. Several studies have been conducted on this topic and, in this respect, a general distinction can be made between the testing conducted on small specimens made of individual nodes of orthogonally glued lamellae, and the testing on large CLT specimens. The research on small specimens is mainly conducted to determine FM II [51, 53, 54] or FM III [31, 55, 56]. The tests on large specimens have been oriented toward determination of FM II [57-59]. Figure 11 shows experimental setups from small models, and Figure 12 shows specimens from large models. Summary

**Table 2. CLT test results (FM III)**

| Author / year | Test description and varied parameters | n | $f_{tor.mean}$ [N/mm²] | $f_{tor.k}$ [N/mm²] | $f_{r.mean}$ [N/mm²] | $f_{r.k}$ [N/mm²] |
|---|---|---|---|---|---|---|
| Blaß i Görlacher 2002 [31] | One contact area, size: 40 x 40 mm, 62 x 95 mm. 62 x 75 mm. 64 x 64 mm. 64 x 100 mm | 57 | 3.59 | 2.82 | - | - |
| Jöbstl 2004 [55] | One contact area, size: 100 x 145 mm, 150 x 145 mm. 200 x 145 mm | 81 | 3.46 | 2.71 | - | - |
| Walner 2004 [60] | Two contact areas, size: 100 x 150 mm, 150 x 150 mm. 200 x 150 mm | 122 | - | - | 1.51 | 1.18 |
| Blaß & Flaig 2010 [52] | Bending of CLT beam 150 mm in height, thickness 27-27-27 mm and 30-20-30 mm | 12 | 4.67 | 2.68 | 1.99 | 1.15 |
| Blaß & Flaig 2013 [52] | Two contact areas, size: 75 x 150 mm | 6 | - | - | 1.43 | 1.18 |
| Blaß & Flaig 2014 [56] | One contact area, size: 165 x 165 mm | 24 | 3.03 | - | 1.28 | - |

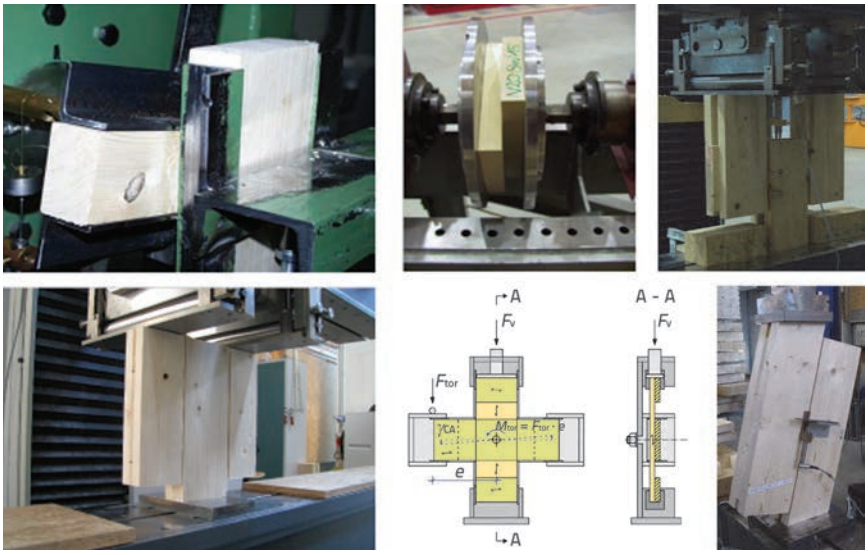



Figure 11. Experimental configurations of small CLT specimens: Blaß [31] (top left), Jöbstl [55] (top centre), Walner [60] (top right), Jöbstl [53] (bottom left), Flaig [56] (bottom centre), Brandner [51] (bottom left)

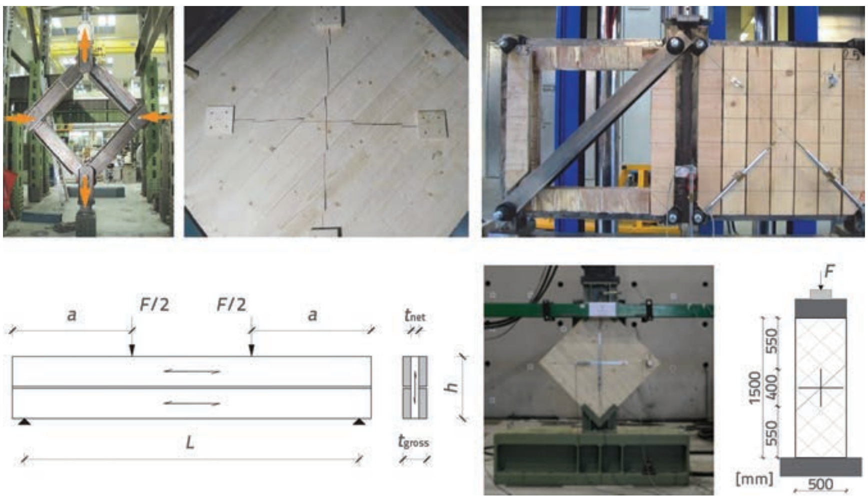



Figure 12. Experimental configurations of large CLT specimens: Bosl [61] (top left), Bogensperger [57] (top right), Jöbstl [53] (bottom left), Andreolli [58] (bottom centre), Brandner [59] (bottom right)

results with brief description of experimental testing are presented in Tables 2 and 3. Table 2 concerns small specimens and verification of FM III, while Table 3 involves large specimens and FM II.

An extensive experimental testing was conducted by Brandner et al. [59] in 2015 on prisms subjected to compression load, as shown in Figure 12. Test results and varied experimental parameters are shown in Table 3. Main conclusions are:

- the shear strength decreases with an increase in spacing between lamellae
- lamella width contributes only slightly and has no clear influence on shear strength
- the carrying capacity reduces significantly with an increase in layer thickness
- the influence of the number of girder layers is not significant
- the carrying capacity of each element must be checked separately for CLT elements having the thickness ratio of longitudinal and transverse layers of more than 0.80.

Based on test results, the authors recommend the reference characteristic net value of $f_{v,net,k,ref}$ = 5.5 N/mm² for lamella thickness up to $t_l$ = 40 mm and lamella spacing up to $w_{gap}$ = 6 mm. For lamella thicknesses $t_l$ between 20 and 40 mm, the authors propose expression (5) for strength increase, but in the maximum amount of up to 20 %.

$$f_{v,net,k} = f_{v,net,k,ref} \times \min\begin{cases}(40/t_l)^{0.3}\\ 1{,}20\end{cases} \tag{5}$$

### 3.4. Recommended reference values for mechanical properties of CLT

As reference values of CLT mechanical properties are not as yet provided in EN 16351 [10], appropriate recommended values for loads in- and out-of-plane can be found in in [26, 29]. These values are shown in Table 4. They are given on the basis of research conducted so far and, in the absence of standard values, they may be used by engineers in practical work. Values given in the table are valid for homogeneous CLT sections made of standard European type of softwood.

## 4. Design of CLT elements

### 4.1. General

The CLT design procedure is currently not included in the European standard EC5 [13], but is present in some national annexes such as [11, 12]. There are presently several manuals in Europe, such as [14, 15] in which design is regulated in keeping with the known European reliability concept. According to this concept, the material safety factor $\gamma_M$, and the property modification factor $k_{mod}$, must be defined so as to obtain design material properties of the material. The material safety factor amounting to $\gamma_M$ = 1.25 is proposed for CLT and, at that, the value of the property modification factor $k_{mod}$ – which takes into account the microclimate of the area and duration of load – is considered equal to the values applied for solid wood and LLD, where the CLT use is limited to service class 1 and 2 [26].

**Table 3. CLT test results (FM II)**

| Author / year | Test description and varied parameters | n | $f_{v,gross,mean}$ [N/mm²] | $f_{v,net,mean}$ [N/mm²] |
|---|---|---|---|---|
| Bosl 2002 [61] | Diagonal tension test of CLT specimen rotated at 45°. Size: 1200 x 1200 x 85 mm³ (thickness: 5 x 17 mm). Failure did not occur by reaching of the net shear strength. | 4 | 2.30 | 5.60 |
| Bogensperger et al. 2007 [57] | Square CLT specimen exposed to bending, size: 560 x 560 x 120 mm³ (thickness 30 + 60 + 30 mm). Failure did not occur by reaching of the net shear strength. | 5 | - | 6.00 |
| Jöbstl 2008 [53] | Bending of CLT beams,7 test series height from 260 to 400 mm. Failure did not occur by reaching of the net shear strength. | 90 | - | 8.40 |
| Jöbstl 2008 [53] | Small shear specimens with two shear surfaces 200 x 200 mm. Failure by reaching of the net shear strength. | 20 | - | 12.8 |
| Andreolli & Tomasi 2012 [62] | Bending of CLT beam series with span of 3000 mm, height of 600 mm and varied thickness: 90 mm (30-30-30), 130 mm (29-21-29-21-29), 135 mm (5 x 27) and 144 mm (34-21-34-21-34). Failure did not occur by reaching of the net shear strength | 4 | 4.74 | 9.04 |
| Andreolli & Tomasi 2014 [58] | Diagonal compression test of CLT specimen rotated at 45°. Only one sample failed by reaching of the net shear strength. | 4 | - | 12.7 |
| Brandner et al. 2013 [51] | Small shear specimen rotated at 14° with varying lamella width (150 and 200 mm), lamella thickness (10, 20 and 30 mm) and lamella spacing (1,5, 5 i 25 mm) Failure by reaching of the net shear strength. | 80 | - | 8.98 |
| Brandner et al. 2015 [59] | CLT prism with layers glued at 45° tested for compression. Size: 1500 x 500 x t mm³, lamella width (80, 160 and 240 mm), thickness (20, 30 and 40 mm) and number of layers (3, 5 and 7). Failure by reaching of the net shear strength. | 112 | 3.80 | 7.44 |

**Table 4. Recommended reference values of strength and modulus in N/mm² and density in kg/m³**

| Strength class of basic material T14, $f_{t,0,l,k}$ = 14,0 , $E_{0,l,mean}$ = 11000 | | **CV [$f_{t,0,l}$], 25 ± 5 %** | |
|---|---|---|---|
| **Author / year** | **Material properties of CLT** | **CLT strength class** | |
| | | **CL 24 h** | **CL 28 h** |
| Unterwieser & Schickhofer 2013 [26] | Bending strength $f_{m,CLT,k}$<br>* values determined on reference specimen | **24*** | **28*** |
| Unterwieser & Schickhofer 2013 [26] | Tensile strength parallel to grain $f_{t,0,CLT,net,k}$<br>* values determined on reference specimen | **16*** | **18*** |
| EN 14080 [28] | Tensile strength perpendicular to grain $f_{t,90,CLT,k}$ | **0.5** | |
| EN 14080 [28] | Compressive strength parallel to grain $f_{c,0,CLT,net,k}$ | **24** | **28** |
| Brandner & Schickhofer 2014 [49] | Compressive strength perpendicular to grain $f_{c,90,CLT,k}$ | **3.0** | |
| Brandner et al. 2015 [59] | Net shear strength of in-plane loaded CLT $f_{v,net,k,ref}$ | **5.5** | |
| Flaig & Blaß 2013 [52] | Gross shear strength of in-plane loaded CLT $f_{v,gross,k}$ | **3.5** | |
| Blaß & Görlacher 2002 [31] | Torsional strength of in-plane loaded CLT $f_{v,tor,k}$ | **2.5** | |
| EN 14080 [28] | Shear strength parallel to grain $f_{v,CLT,k}$ | **3.5** | |
| Ehrhart et al. 2015 [38] | Rolling shear strength $f_{r,CLT,k}$ | **0.8 - 1.4** | |
| EN 14080 [28] | Elastic modulus parallel to grain $E_{0,CLT,mean}$<br>$E_{0,CLT,mean} = 1.05 \cdot E_{0,l,mean}$ ; $E_{05,CLT} = 5/6 \cdot E_{0,CLT,mean}$ | **11600** | |
| EN 14080 [28] | Elastic modulus perpendicular to grain $E_{90,CLT,mean}$ | **300** | |
| Brandner & Schickhofer 2014 [49] | Elastic modulus for compression out-of-plane $E_{c,90,CLT,mean}$ | **450** | |
| Brandner et al. 2015 [58] | Shear modulus parallel to grain $G_{CLT,mean}$ (* without gluing narrow sides of lamellae [59], ** with gluing narrow sides of lamellae) | **450***<br>**650**** | |
| Ehrhart et al. 2015 [38] | Rolling shear modulus $G_{r,CLT,mean}$ | **65 - 100** | |
| EN 14080 [28] | Density $\rho_{CLT,mean}$<br>$\rho_{CLT,mean} = \rho_{l,mean}$, $\rho_{CLT,k} = 1.10\ \rho_{l,k}$ | **420** | |

### 4.2. Ultimate limit states – loads out-of-plane

#### 4.2.1. Bending

The shear flexibility of vertical girder layers must be adequately taken into account when proving resistance to bending out-of-plane. Considering the limitation of the Euler-Bernoulli theory that does not take into account shear deformations, the carrying capacity analysis requires the use of other methods such as γ-method [63], shear analogy method [64], or Timoshenko's exact method [65]. Comparative analysis of these methods is given by Bogensperger et al. [66]. Based on this analysis, it was concluded that they do not greatly differ for practical spans $l_{CLT}$ / $t_{CLT}$ ≥ 15, and that each of these methods can in fact be applied. Although CLT elements can take over load in two directions, in each of the methods they are designed as strip girders of unit width. The modified γ - method has been well accepted and is often used by engineers, as it was created through adjustment of the basic γ-method that is already present in EC 5 [13]. The method relies on the Euler-Bernoulli theory and the shear flexibility is indirectly included in the calculation through effective bending stiffness. The method can be applied for CLT elements with 3 and 5 layers, but it can also be extended to include 7 and 9 layers. The effective bending stiffness $EI_{eff}$ is calculated according to expression (6), and the flexibility factor $\gamma_i$ according to expression (7):

$$EI_{eff} = \sum_i \left(E_i \times b_i \times t_i^3 / 12\right) + \sum_i \left(\gamma_i \times E_i \times b_i \times t_i \times z_i\right) \tag{6}$$

$$\gamma_i = \left(1 + \frac{\pi^2 \times E_i \times b_i \times t_i}{L_{eff}^2 \times \left(G_{j,90} \times b_j\right) / t_j}\right)^{-1} \tag{7}$$

where:
- $E_i$ - elastic modulus of each girder layer (for longitudinal layers $E_i = E_0$, and for vertical layers $E_i = E_{90} = 0$)
- $b_i$ - unit girder width (1 m)
- $t_i$ - thickness of each layer *i*
- $z_i$ - distance between the centre of each layer and the centre of the entire cross-section
- $\gamma_i$ - flexibility factor that has unit value for the central longitudinal layer,
- $L_{eff}$ - effective spacing between zero points of bending moment
- $G_{j,90}$ - shear modulus perpendicular to grain
- $j$ - perpendicular layer between the i-th and central longitudinal layer.

Further design procedure includes calculation of stress and proving carrying capacity, and is not presented here in full detail as it is similar to that used in the basic γ-method presented in EC5 [13]. The bending stiffness can be obtained based on Timoshenko theory by using expression (7) and by adopting the value $\gamma_i$ = 1,0 for all layers, and the value $E_i = E_{90} \neq 0$ for vertical layers. An advantage of Timoshenko method lies in the fact that it is not dependent on the number of layers, nor on the number of girder spans, and can therefore be also used for static systems of continuous girders.

Probably the most accurate but also the most time consuming is the shear analogy method, which implies combination of two connected beams with equal vertical deformations in each point along the girder span. The first beam (A) takes into account bending stiffness of each layer individually, which constitutes the first part of expression (6), with the condition of $E_i = E_{90} \neq 0$ for vertical layers of the girder. The bending stiffness of the second beam (B) corresponds to the second part of expression (6) with the condition that $\gamma_i$ = 1.0 for all layers and, hence, the sum of stiffness values of both beams corresponds to the stiffness according to Timoshenko theory. It's advantage lies in that it can also take into account, through interaction of two beams, highly complex stress distribution phenomena even if a direct external load is not present. The proof of carrying capacity according to this method will not be further elaborated in the paper, as a more detailed account can be found in [16]. A simplified carrying capacity model according to Timoshenko theory was proposed by Schickhofer et al. [14]. Effective stiffness of girder $EI_{eff}$ is calculated according to expression (8) where the elastic modulus of vertical layers of girder $E_{90} \approx 0$ is neglected due to high elastic modulus ratio in the direction of fibres, and perpendicular to the direction of fibres $E_0/E_{90} \approx 30$.

$$EI_{eff} = \sum_i \left(E_i \times b_i \times t_i^3 / 12\right) + \sum_i \left(E_i \times b_i \times t_i \times z_i\right) \tag{8}$$

Distribution of normal stresses σ(z) along the CLT height from the bending moment along the girder span M(x) is presented in Figure 13 and is calculated using expression (9). The proof of carrying capacity – involving verification of maximum calculated normal stresses $\sigma_{max,d}$ - is given in expression (10).

$$\sigma(z) = \frac{M(x)}{EI_{eff}} \times z_i \times E_i(z_i) \tag{9}$$

$$\frac{\sigma_{max,d}}{f_{m,CLT,d}} \leq 1,0 \tag{10}$$

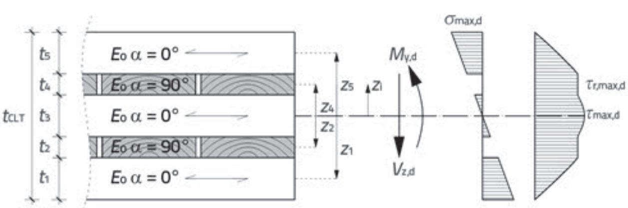



**Figure 13. Stress distribution for CLT element loaded out-of-plane**

#### 4.2.2. Shear

When CLT element is loaded out-of-plane, the proof of shear resistance is made separately for longitudinal and transverse layers. Shear stress distribution along the height of the cross-section $\tau_d$ (z) is presented in Figure 13. It is calculated using expression (11), while the carrying capacity proof is given in expression (12) [67]:

$$\tau_d(z) = \frac{V_{z,d} \times \int_A E_i(z) \times S_i(z)}{EI_{eff} \times b} \quad (11)$$

$$\frac{\tau_{max,d}}{f_{v,CLT,d}} \leq 1{,}0; \quad \frac{\tau_{r,max,d}}{f_{r,CLT,d}} \leq 1{,}0 \quad (12)$$

where:
$V_{z,d}$ - design value of transverse force
$S_i(z)$ - static moment of resistance along girder height
$\tau_{max,d}$ - maximum design value of shear stress parallel to grain
$\tau_{r,max,d}$ - maximum design value of shear stress perpendicular to grain.

### 4.2.3. Compression perpendicular to grain

In case of point or linear support of CLT girders, the resistance to compression perpendicular to grain must be proven according to expression (13)) [67]:

$$\frac{\sigma_{c,90,CLT,d}}{k_{c,90,CLT} \times f_{c,90,CLT,ref,d}} \leq 1{,}0; \quad \frac{F_{c,90,d}}{A_c \times k_{c,90,CLT} \times f_{c,90,CLT,ref,d}} \leq 1{,}0 \quad (13)$$

where:
$\sigma_{c,90,CLT,d}$ - design value of compressive stress perpendicular to grain
$F_{c,90,d}$ - design value of compressive force perpendicular to grain
$A_c$ - area in which compression load is applied
$k_{c,90,CLT}$ - stress dispersion factor
$f_{c,90,CLT,ref,d}$ - design value of compressive strength perpendicular to grain as defined on reference prisms.

Brandner et al. [49] propose a stress dispersion model in which stress is applied at an angle of 45° in longitudinal layers and 15° in transverse layers, where the modified compressive strength of CLT perpendicular to grain $f_{c,90,CLT}$ is calculated according to expression (14) and as per marks/designations given in Figure 14.

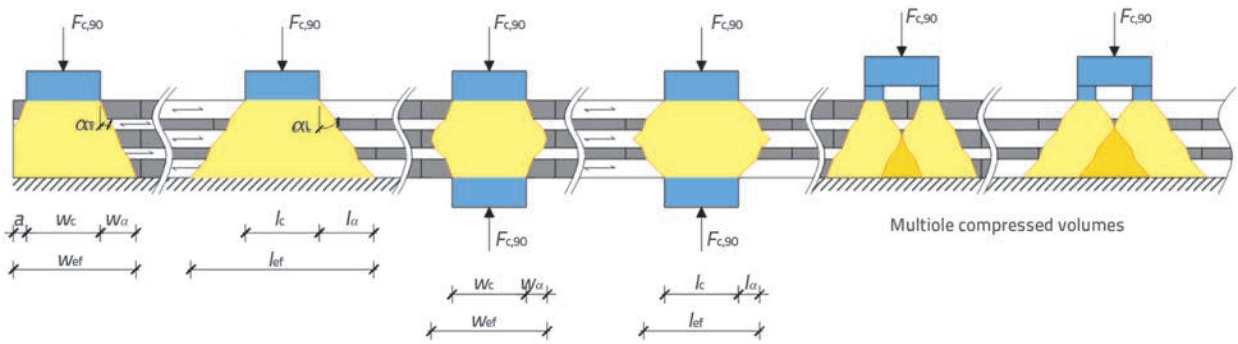
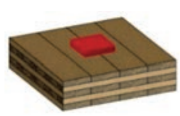
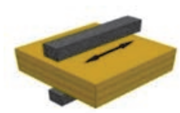
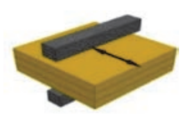
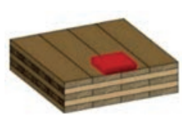
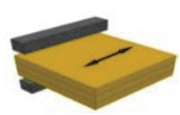
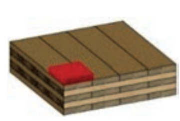
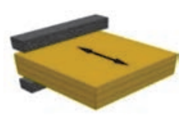



**Figure 14. Distribution of compression stress perpendicular to grain for point load and point, linear or plane support of CLT elements at αL = 45° and αT = 15° according toa [49]**

**Table 5. Proposed values of coefficient $k_{c,90,CLT}$ for different load and support situations [68]; [1]point or linear support; [2]continuous plane support**

| Number of layers | Point load | $k_{c.90.CLT}$ [1] | $k_{c.90.CLT}$ [2] | Linear load | $k_{c.90.CLT}$ [1] | $k_{c.90.CLT}$ [2] |
|---|---|---|---|---|---|---|
| 3 |  | 1.14 - 1.37 | 1.27 - 1.76 |  | 1.04 - 1.14 | 1.08 - 1.27 |
| 5 | | 1.29 - 1.63 | 1.49 - 2.26 | | 1.09 - 1.25 | 1.18 - 1.46 |
| 7 | | 1.52 - 1.88 | 2.04 - 2.77 | | 1.17 - 1.35 | 1.33 - 1.62 |
| 3 |  | 1.11 - 1.29 | 1.23 - 1.57 |  | 1.09 - 1.21 | 1.18 - 1.38 |
| 5 | | 1.19 - 1.47 | 1.38 - 1.91 | | 1.14 - 1.30 | 1.27 - 1.55 |
| 7 | | 1.41 - 1.64 | 1.79 - 2.24 | | 1.25 - 1.40 | 1.46 - 1.71 |
| 3 |  | 1.09 - 1.26 | 1.18 - 1.51 |  | 1.02 - 1.07 | 1.04 - 1.14 |
| 5 | | 1.17 - 1.44 | 1.33 - 1.86 | | 1.05 - 1.13 | 1.09 - 1.23 |
| 7 | | 1.35 - 1.61 | 1.68 - 2.20 | | 1.09 - 1.17 | 1.16 - 1.31 |
| 3 |  | 1.07 - 1.18 | 1.13 - 1.35 |  | 1.05 - 1.10 | 1.09 - 1.19 |
| 5 | | 1.12 - 1.30 | 1.23 - 1.57 | | 1.07 - 1.15 | 1.13 - 1.28 |
| 7 | | 1.25 - 1.41 | 1.48 - 1.78 | | 1.13 - 1.20 | 1.23 - 1.36 |

$$f_{c,90,CLT,d} = f_{c,90,CLT,ref,d} \times \sqrt{\frac{A_{ef}}{A_c}} = f_{c,90,CLT,ref,d} \times \sqrt{\frac{l_{ef} \times w_{ef}}{l_c \times w_c}} \rightarrow k_{c,90,CLT} = \sqrt{\frac{A_{ef}}{A_c}} \quad (14)$$

where:
$w_c$ and $l_c$ - width and length of support
$w_{ef}$ and $l_{ef}$ - effective width and effective length of stress.

Thiel and Brandner [68] give recommendations and spans for the coefficient $k_{c,90,CLT}$, as shown in Table 5. Nevertheless, the authors propose a more detailed calculation according to analytical model [49] and expression (14) in case compressive stresses perpendicular to grain are relevant from the aspect of carrying capacity.

## 4.3. Ultimate limit state – loads in-plane

### 4.3.1. Tension parallel to grain

In case of tension parallel to grain, the recommendation is to take into account only those girder layers that are oriented in the direction of external load, i.e. to calculate with the net area of cross-section $A_{net}$ [14]. The carrying capacity is proven according to the following expression (15):

$$\frac{\sigma_{t,0,net,d}}{f_{t,0,CLT,net,d}} \leq 1{,}0; \quad \frac{N_{t,d}}{A_{net} \times f_{t,0,CLT,net,d}} \leq 1{,}0 \quad (15)$$

where:
$\sigma_{\tau,0,net,d}$ - design value of tensile stress parallel to grain
$N_{t,d}$ - design value of tensile force parallel to grain.

### 4.3.2. Compression parallel to grain

The carrying capacity with regard to compression parallel to grain must be proven at the level of cross-section according to expression (16) using the net area of cross section $A_{net}$ and taking into consideration only those layers that are in the direction of the action [14].

$$\frac{\sigma_{c,0,net,d}}{f_{c,0,CLT,net,d}} \leq 1{,}0; \quad \frac{N_{c,d}}{A_{net} \times f_{c,0,CLT,net,d}} \leq 1{,}0 \quad (16)$$

where:
$\sigma_{c,0,net,d}$ - design value of compressive stress parallel to grain
$N_{c,d}$ - design value of compressive force parallel to grain.

In addition to proof needed at the cross-sectional level, it is also necessary to check stability of girders at the level of elements. The bending proof can be made according to the equivalent member theory by determining bending coefficient, or using the second order theory on the deformed system, which is considered in more detail in [69, 70].

### 4.3.3. Shear

The resistance to shear is proven using two distinct analytical models. One of them is used for the analysis of wall girders, and the other for the analysis of beams. In both models, recommendation is made to check three earlier described failure mechanisms shown in Figure 10. Moosbruger et at. [71] proposed in 2006 an analytical model based on the representative volume element (RVE), which is the smallest reference section through the thickness of CLT element, and which can additionally be reduced to the representative volume sub-element (RVSE) composed of the section of only two orthogonally glued lamellae shown in Figure 15. There are three model assumptions:
- uniform state of shear stress
- equal thickness of all girder layers
- absence of contact at narrow sides of lamellae.

The calculation of stress is based on an idealised nominal shear stress $\tau_0$, which is relevant only in case of glued narrow sides of lamellae, as follows:

$$\tau_{0,d} = \frac{n_{xy,RVSE,d}}{a \times t_l} \quad (17)$$

$$\tau_{net,d} = 2 \times \tau_{0,d} \quad (18)$$

$$\tau_{tor,d} = \frac{M_{tor,d}}{I_p} \times \frac{a}{2} = 3 \times \tau_{0,d} \times \frac{t_l}{a} \quad (19)$$

where:
$n_{xy,RVSE,d}$ - external design load reduced to one RVSE
$a$ - RVSE lamella width
$t_l$ - RVSE thickness
$M_{tor,d}$ - design value of torsional moment on the glued contact of orthogonal lamellae
$I_p$ - polar torsional moment on the glued contact of orthogonal lamellae.

When proving carrying capacity, each stress must be compared with the corresponding strength according to relevant failure mechanisms, as follows:

$$\textbf{(FM I)}\ \frac{\tau_{0,d}}{f_{v,gross,d}} \leq 1{,}0; \ \textbf{(FM II)}\ \frac{\tau_{net,d}}{f_{v,net,d}} \leq 1{,}0; \ \textbf{(FM III)}\ \frac{\tau_{tor,d}}{f_{v,tor,d}} \leq 1{,}0 \quad (20)$$

Using numerical parametric analysis on RVSE, Bogensperger et al. [54, 57] additionally defined expressions for shear stiffness of CLT panels as a function of shear stiffness of base material by varying dimensions, thickness and spacing of lamellae.
Another analytical calculation method for the analysis of beams was proposed in 2013 by Flaig and Blass [52] based on the theory of composite girders. For proving FM I and FM II the authors propose the use of the Euler-Bernoulli theory taking into account the gross and net shear thickness in the calculation

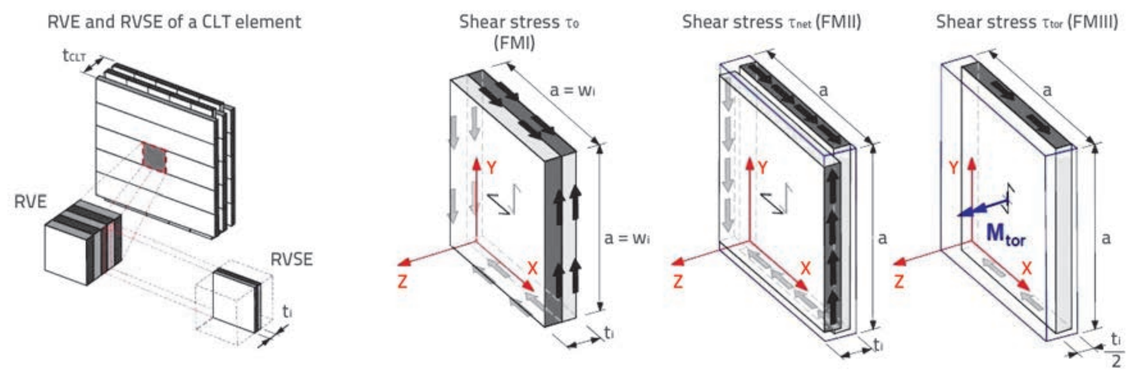



**Figure 15. Distribution of shear stress on RVSE element [71]**

of shear stress $\tau_{xy}$ according to marks shown in Figure 16 and expressions (21) and (22):

$$\tau_{xy,gross,d} = \frac{V_{y,d} \times S_{z,gross}}{I_{z,gross} \times t_{gross}} \Rightarrow \tau_{xy,gross,max,d} = 1{,}50 \times \frac{V_{y,d}}{h \times t_{gross}} \quad (21)$$

$$\tau_{xy,net,d} = \frac{V_{y,d} \times S_{z,net}}{I_{z,net} \times t_{net}} \Rightarrow \tau_{xy,net,max,d} = 1{,}50 \times \frac{V_{y,d}}{h \times t_{net}} \quad (22)$$

where:
$V_{y,d}$ - design value of transverse force
$S_z$ - static moment of the area around the z-z axis
$I_z$ - axial moment of inertia around the z-z axis
h - beam height
t - beam thickness
*gross* - gross section of the girder
*net* - net section of the girder.

Capacity proofs FM I and FM II include verification of the expression (23):

$$\textbf{(FM I)}\ \frac{\tau_{xy,gross,max,d}}{f_{v,gross,d}} \leq 1.0; \ \textbf{(FM II)}\ \frac{\tau_{xy,net,max,d}}{f_{v,net,d}} \leq 1.0 \quad (23)$$

In case of FM III, the theory of composite girders is used to calculate three components of shear stress according to expressions (24), (25) and (26):

$$\tau_{zx,d} = \frac{6 \times V_{y,d}}{b^2 \times n_{CA}} \times \left(\frac{1}{m^2} - \frac{1}{m^3}\right) \quad (24)$$

$$\tau_{zy,d} = \frac{q_{y,d}}{m \times b} \quad (25)$$

$$\tau_{tor,d} = \frac{3 \times V_{y,d}}{b^2 \times n_{CA}} \times \left(\frac{1}{m} - \frac{1}{m^3}\right) \quad (26)$$

where:
$\tau_{zx,d}$ - design value of uniaxial shear stress in the direction of girder axis
$\tau_{zy,d}$ - design value of uniaxial shear stress perpendicular to girder axis
$\tau_{tor,d}$ - design value of torsional stress at glued contact of orthogonal lamellae
b - lamella width
$n_{CA}$ - number of glued surfaces at the contact between longitudinal and transvers layers in the direction of girder thickness
m - number of lamellae in the direction of girder height
$q_{y,d}$ - design value of external load in kN/m.

Capacity proof FM III includes verification of two interactions, according to expression (27):

$$\textbf{(FM III-A)}\ \frac{\tau_{tor,d}}{f_{v,tor,d}} + \frac{\tau_{zx,d}}{f_{r,d}} \leq 1{,}0; \ \textbf{(FM III-B)}\ \frac{\tau_{tor,d}}{f_{v,tor,d}} + \frac{\tau_{zy,d}}{f_{r,d}} \leq 1{,}0 \quad (27)$$

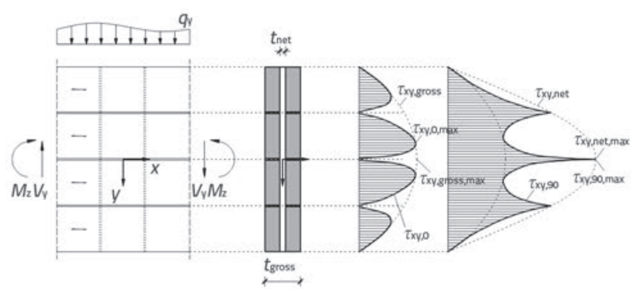



**Figure 16. Distribution of shear stress τxy along the CLT section height by longitudinal layers (left) and vertical layers (right) [52]**

Proposed analytical method assumes a uniform distribution of torsional shear stress $\tau_{tor}$ in beam height and width direction, wherein recent studies based on 3D numerical analysis indicate non uniform distribution in beam height [72, 73] and beam width direction [74], respectively.

## 4.4. Serviceability limit state

### 4.4.1. Deflections and deformations

In CLT girders loaded out-of-plane, the proof of serviceability is more often relevant compared to the proof of bearing capacity. In this case verification of deflection and vibrations is of high significance. Shear flexibility of vertical layers is the reason why shear stiffness of the girder must be included in the calculation of deflection and deformations. The effective shear stiffness $GA_{eff}$ is calculated according to expression (28), and the cross-sectional distortion coefficient is calculated according to expression (29) [67]:

$$GA_{ef} = \kappa \times GA = \kappa \times \sum_i (G_i \times b_i \times t_i) \tag{28}$$

$$\kappa = \frac{EI_{eff}^2}{GA \times \int_z \frac{S^2(z,E(z))}{G(z) \times b(z)} dz} \tag{29}$$

where:

$G_i$ - shear modulus of individual layers (for longitudinal layers $G_i = G_0$, and for vertical layers $G_i = G_{90}$)

κ - shear stress factor that takes into account distortion of cross section; it varies from 0.25 to 0.35 [2].

In case of long-term actions, the influence of creep and service class must also be taken into account using the deformation coefficient $k_{def}$ where, due to lack of relevant investigations, the value for plywood may be recommended [75].

### 4.4.2. Vibrations

In case of CLT elements exceeding 4.0 m in span, vibrations may often be a relevant design parameter. There are currently several distinct calculation methods such as the method given in EC5 [13], method proposed by Hamm and Richter [76], modified method by Hamm and Richter [77] or the method by Hu [16]. Generally, all these methods check natural frequencies, stiffness criterion, and acceleration due to vibrations. When proving vibrations, it is also important to differentiate between the type of support, i.e. between hinged, partly fixed of fully fixed panels. In this case, the intensity of load transferred via walls to lower storeys and influencing stiffness of connection between panels, is also quite important. Natural frequency of freely supported CLT girder, which may be considered to be hinged to its two edges, is calculated according to expression (30) [67] and, depending on building requirements, it must be greater than the minimum value given in Table 6.

$$f_{l,beam} = \frac{k_m}{2\pi \times l^2} \sqrt{\frac{(EI)_{l,ef}}{m}} \ [\text{Hz}] \tag{30}$$

where:

$f_{l,beam}$ - natural frequency of CLT element in static system of a freely supported beam

$(EI)_{l,ef}$ - effective bending stiffness in longitudinal direction of CLT

$k_m$ - coefficient that takes into account is own forms of oscillation and various boundary conditions for CLT support

m - CLT mass

l - CLT girder span

If CLT element is supported on all four edges, natural frequency can be obtained using the following expression (31) [67]:

$$f_{l,plate} = f_{l,beam} \times \sqrt{1 + \frac{2D_{xy}^*}{(EI)_{l,ef}} \times \frac{l^2}{b^2} + \frac{(EI)_{b,ef}}{(EI)_{l,ef}} \times \frac{l^4}{b^4}} \ [\text{Hz}] \tag{31}$$

where:

$f_{l,plate}$ - natural frequency of CLT element supported on all four edges

$(EI)_{b,ef}$ - effective bending stiffness in the direction perpendicular to CLT

b - CLT girder span in vertical direction

$D_{xy}^*$ - reduced distortion stiffness of CLT girder for the case without gluing narrow sides of lamellae.

According to stiffness criterion, it must be proven that the vertical deflection due to force F = 1 kN does not exceed, at any zone of the CLT girder, the allowed vales shown in Table 6. The shear flexibility $GA_{ef}$ and the load distribution $b_f$ must be taken into account in an appropriate manner. The maximum deflection in mid span can be obtained for the simple supported CLT element according to expression (32) and, at that, the distribution of load is taken into account using (33) according to [67].

**Table 6. Critical values of serviceability limit state from the vibration proving aspect**

| Verification criterion | Method used | High requirements | Normal requirements |
|---|---|---|---|
| Natural frequency $f_{crit}$ | EN 1995-1-1 [13] | 8 Hz | |
| | Hamm/Richter [76] | 8 Hz | 6 Hz |
| | Modified Hamm/Richter [77] | 8 Hz | 6 Hz |
| Stiffness criterion $w_{crit.1kN}$ | EN 1995-1-1 [13] | 1 mm | 2 mm |
| | Hamm/Richter [76] | 0.25 mm | 0.25 mm |
| | Modified Hamm/Richter [77] | | |
| Criterion of acceleration due to vibration $a_{crit}$ | EN 1995-1-1 [13] | 0.05 m/s² | 0.05 m/s² |
| | Hamm/Richter [76] | | |
| | Modified Hamm/Richter [77] | | |

$$w = \frac{F \times l^3}{48 \times (EI)_{l,ef} \times b_f} + \frac{F \times l}{4 \times (GA)_{ef} \times b_f} \quad (32)$$

$$b_f = \frac{l}{1,1} \times \sqrt[4]{\frac{(EI)_{b,ef}}{(EI)_{l,ef}}} \quad (33)$$

If the natural frequency $f_l$ lies between the critical value given in Table 6 and minimum value $f_{min}$ = 4,5 Hz, then the criterion of acceleration due to vibrations must also be checked. In this case, the obtained acceleration must be lower that the critical value $a_{crit}$ given in Table 6. The acceleration due to vibrations can be obtained using expression (34) [67]:

$$a = \frac{0,4 \times \left(\frac{F_0 \times \alpha_{i,f_l}}{M_{gen}}\right)}{\sqrt{\left(\left(\frac{f_1}{f_f}\right)^2 - 1\right)^2 + \left(2 \times \zeta \times \frac{f_1}{f_f}\right)^2}} \quad (34)$$

where:
$M_{gen}$ - effective generalized mass of the CLT panel
$f_f$ - excitation frequency
$f_l$ - natural frequency
$\alpha_{i,fl}$ - Fourier coefficient of dominant harmonic oscillation
$F_0$ - self-weight of excitation load (700 kN)
$\zeta$ - damping coefficient which ranges from 2.5 to 3.5 % for CLT floors.

## 5. Specific sections of CLT

### 5.1. Fire resistance of CLT

Design for fire resistance is currently carried out using the reduced cross-section method (RCSM) given in EN 1995-1-2 [78]. The method is based on determination of the charring depth $d_{char}$ which, in case of CLT, depends on several factors:
- charring velocity $\beta$
- type of adhesive substance
- existence and type of fire protection.

Two charring velocity values have been defined based on whether there is a spacing between lamellae within girder layers:
- $\beta$ = 0.65 mm/min is adopted for CLT without spacing or with spacing of up to 2 mm
- $\beta$ = 0.80 mm/min for CLT with spacing ranging from 2 to 6 mm.

The reduced cross-section of CLT is graphically presented in Figure 17 in which girder thickness $t_{CLT}$ is reduced for the charring depth $d_{char}$ according to expression (35), where $k_0$ linearly changes from 0 to 1 during first 20 minutes of fire. The full value of $d_o$ = 7mm is adopted after 20 minutes for the layer of thermally modified material without bearing capacity, and this is added to the charring depth $d_{char}$.

$$d_{ef} = d_{char} + k_0 \times d_0; \quad k_0 = \min\begin{cases} t/20 \\ 1,0 \end{cases} \quad (35)$$

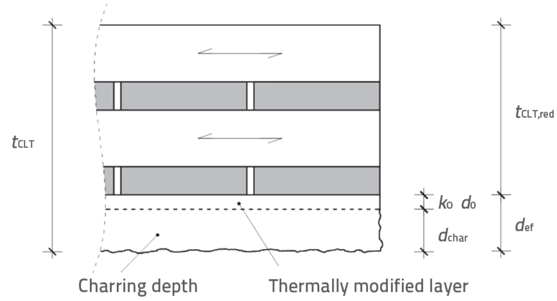



**Figure 17. Marks showing reduced cross-section of CLT due to fire**

A detailed analysis and state-of-the-art review is given by Klippel et al. [79] for CLT girders loaded out-of-plane and exposed to fire. A modified method for calculating an "effective cross-section" is proposed and this by using a thermally modified layer of material $d_0$ whose value is not constant, which is not the case in the method given in EN 1995-1-2 [78]. Based on experimental research, Frangi et al. [80] additionally emphasize the importance of selecting an appropriate adhesive substance as it was observed that, in case glue nonresistant to high temperature is used, the charred part of the girder separates at the point of glued contact between layers. It was therefore recommended to use a double value of charring velocity $\beta$ in the design. However, such assumption does not apply in case of CLT girders subjected to in-plane load [79]. Additional research aimed at defining charring velocity $\beta$ and thickness of thermally modified layer of material $d_o$ was conducted by Schmidt [81] and Fragiacomo [82] for the case of CLT plates, i.e. by Schmidt et al. [83] for the case of CLT panels. General conclusion was that, in the foreseeable future, the work should be focused on optimisation of the value $d_0$, as related to the required fire resistance time for CLT (30, 60 and 90 minutes), or as related to the CLT composition (thickness, arrangement and number of layers). The state-of-the-art in this field was presented by Werther et al. [84] for the case of fire resistance of CLT connections. Here the authors emphasize the key role of connections in preventing passage of heat when providing for fire resistance of the entire building.

### 5.2. Seismic resistance of CLT

Considerable stiffness in the element plane and relatively small self-weight are two main reasons behind an excellent behaviour of CLT even in case of seismic action. Based on EN 1998-1-1 [85] and the seismic resistance design procedure involving behaviour factor q, a considerable number of experimental and numerical tests have so far been made in order to determine seismic resistance of CLT elements. These tests can generally be classified into the wall panel tests and tests for entire CLT structures. The wall panel testing has been in the focus of interest of Dujič et al. [86], Ceccotti et al. [87], Popovski et al. [88], Seim et al. [89], Flatscher et al. [90], Gavrić et al. [91], and Tomasi et al. [92]. This testing involves variation of a great number of parameters, the most important being:

- dimensions, content and composition of CLT
- boundary conditions and connection types
- experimental configuration and load application method.

It can generally be concluded that regardless of the CLT content, number of panels and composition, the carrying capacity has not been limited by the carrying capacity of the material, but rather and every time by the carrying capacity and ductility of CLT connections. In most cases, the connections are realized as point connections or linear connections using metallic angle brackets and supports in combination with connection accessories such as nails, screws and full or partially threaded self-tapping screws. Connections/joints have in fact been proven critical even in the case of seismic resistance of hybrid systems involving CLT and structural glass [93]. Numerous research has been made in the sphere of dimensioning and optimization of connections, both for normal and seismic design situations. Notable papers include the ones proposed by Uibel et al. [94], Schneider et al. [95], Ringhofer et al. [96], Gavrić et al. [97, 98], and Izzi et al. [99]. In addition to the use of standard connection types, several recent studies involving innovative new connections have shown great potential for practical use (Kraler et al. [100] and Polastri et al. [101]. Global behaviour of entire CLT structures has been tested on the earthquake shaking table in the scope of the SOFIE project (*Sistema Costruttivo Fiemme*) by Ceccotti et al. [102] and SERIES project (*Seismic Engineering Research Infrastructures for European Synergies*) by Flatscher and Schickhofer [103]. This research served as the basis for proposing the CLT behaviour factor $q$ ranging between 2.0 and 3.0. Regardless of the differences between the experimental models, in both cases the influence of connections has proven to be a critic parameter with regard to bearing capacity. Therefore, if there are no data on connection devices and connection method, it is highly recommended to use a lower value of this behaviour factor q, i.e. $q = 2.0$ [104].

### 5.3. Open and insufficiently studied issues

Although a considerable research has been made to this date for various design situation involving CLT, some open or poorly investigated issues still remain, including the ones related to specific actions, or those concerning specific CLT configurations and compositions. These areas are:

- concentrated load on CLT plates (Mestek [34], Bogensperger [48])
- concentrated load on CLT wall girders (Thiel and Brandner [68])
- ribbed floors as CLT and GLT girder composites (Thiel and Brandner [68])
- large openings in CLT wall and floor girders (Dujič [105], Kawai [106])
- openings and side cuts in CLT beams (Flaig [56], Bejtka [107])
- heterogeneous CLT systems involving the use of hardwoods
- stability problems
- connections/joints and strengthening
- stress interactions

## 6. Conclusion

As an innovative composite product, CLT has undoubtedly highly contributed over the last decade to the popularisation and increased use of wooden structures, replacing traditionally well-established linear systems with new and modern solid forms. Taking into account current developments and an increased interest of all participants in construction industry, further CLT globalisation may be expected in the near future, with additional strengthening of influence in overseas countries such as Canada, Japan, and the US. That is why additional efforts aimed at CLT standardisation must be made in the near future to realize the full potential of this outstanding product. This standardisation activity includes harmonisation of existing manufacturing-related regulations, reference tests, design procedure, providing solutions for details, construction of structures, and their subsequent use. From the standpoint of manufacturing, a further harmonisation among manufactures is anticipated, which is expected to result in creation of standardised prefabricated modular elements. As to mechanical properties, activities have intensified over the last several years to define their reference values and reference testing procedures. Recently published EN 16351 [10] provides only some test procedures, but without reference values. Further work on the definition of CLT strength classes will also be encouraged in the oncoming period. In addition, hybrid systems for optimisation of CLT, based on the use of hardwoods or locally available softwoods, should also be covered by regulations, as these systems have shown a great potential for practical application albeit on a limited number of tests. As to CLT calculation, future version of the European standard for timber structures Eurocode 5 (EN 1995-x-x), which is currently being revised, is expected to include CLT with the design procedure for all relevant states of stress, from the in-plane to out-of-plane action. At that a special emphasis should be placed on connections, which in most cases define behaviour of the entire structure, especially in accidental design situations such as those relating to earthquake or fire. An emphasis is placed on the lack of an appropriate type of connection that would be adjusted to CLT elements, as mostly point-based types such as metallic L sections - taken from wooden frame systems - are now dominantly used for CLT. The serviceability and vibrations in CLT elements are also an open issue revealing an insufficient number of investigations, particularly concerning CLT use in highrise buildings. Current regulations and limitations are insufficient and require further action. Weather effects such as moisture, creep and shrinkage of CLT, are also quite considerable and, due to absence of research, CLT is considered by applying the values used for other similar materials. Behaviour in extraordinary situations such as earthquake or fire has so far been investigated mostly on individual elements, and it is therefore quite disputable whether the results can be applied to the entire CLT structures. Good knowledge on the behaviour of connections at the wall and plate contacts has proven to be of crucial significance in this respect, but is unfortunately lacking.

In conclusion, it can be stated that innovative composites such as CLT contribute to the development and further broadening of construction possibilities, not only in the case of wooden structures but, on a larger scale, in the entire construction sector as well. CLT potential is currently mostly realized in the case of environment-friendly and energy-efficient multistorey residential and office buildings. In this way, as a representative of wooden structures, CLT offers a high-quality solution as a sound alternative to concrete or masonry structures, which is expected to further strengthen its position in the near future.

## REFERENCES


[1] Ferk, H.: Some building science aspects for building with CLT, Focus solid timber solutions - European conference on cross laminated timber (CLT), Bath, pp. 207-250 , 2013.

[2] Brandner, R., Flatscher, G., Ringhofer, A., Schickhofer, G., Thiel, A.: Cross laminated timber (CLT): overview and development, European Journal of Wood and Wood Products, 74 (2016) 3, pp. 331-351.

[3] Ringhofer, A., Schickhofer, G.: Timber in town - current examples for residentail buildings in CLT, Focus solid timber solutions - European conference on cross laminated timber (CLT), Bath, pp. 185-206 , 2013.

[4] London Design Festival - The Smile, www.londondesignfestival.com/smile, 04.04.2017.

[5] Brock Commons Tallwood House, www.actonostry.ca/project/brock-commons-tallwood-house/, 04.04.2017.

[6] Dalston Lane - The world's largest CLT building, www.waughthistleton.com/dalston-lane/, 04.04.2017.

[7] Wohnbau Wagramer Strasse, www.binderholz.com/bauloesungen/wohnbau/wohnbau-wagramer-strasse-wien-oesterreich/, 04.04.2017.

[8] Treet: The tallest timber-framed building in the world, http://treetsameie.no/, 04.04.2017.

[9] Brandner, R.: Production and technology of cross laminated timber (CLT): State-of-the-art-report, Focus solid timber solutions - European conference on cross laminated timber (CLT), Bath, pp. 3-36, 2013.

[10] EN 16351 Timber Structures - Cross Laminted Timber - Requirements, European Committee for Standardization (CEN), Brussels, Belgium, 2015.

[11] DIN EN 1995-1-1/NA National Annex - Nationally determined parameters - Eurocode 5: Design of timber structures - Part 1-1: General - Common rules and rules for buildings, Deutsches Institut für Normung (DIN), 2013.

[12] ÖNORM B 1995-1-1/NA Eurocode 5: Design of timber structures - Part 1-1: General - Common rules and rules for buildings - National specifications for the implemntation of ÖNORM B 1995-1-1, national comments and national supplements, Austrian Standards Institute (ASI), Vienna, Austria, 2014.

[13] EN 1995-1-1 Eurocode 5: Design of timber structures - Part 1-1: General rules and rules for buildings, European Committee for Standardization (CEN), Brussels, Belgium, 2004.

[14] Schickhofer, G., Bogensperger, T., Moosbrugger, T.: BSPhandbuch: Holz- Massivbauweise in Brettsperrholz: Nachweise auf Basis des neuen europäischen Normenkonzepts, Graz University of Technology, Graz, 2010.

[15] Wallner-Novak, M., Koppelhuber, J., Pock, K.: Cross-Laminated Timber Structural Design - Basic design and engineering principles according to Eurocode, proHolz Austria, Vienna, 2013.

[16] Gagnon, S., Pirvu, C.: CLT Handbook: cross laminated timber - Canadian edition, FPInnovations, Quebec, 2011.

[17] Karacabeyli, E., Douglas, B.: CLT Handbook: cross laminated timber - U.S. edition, FPInnovations, Pointe-Claire, 2013.

[18] Mestek, P., Werther, N., Winter, S.: Building with Cross Laminated Timber - Load-bearing solid wood components for walls, ceilings and roofs, Studiengemeinschaft Holzleimbau e.V., Wuppertal, 2010.

[19] EN 14081-1 Timber structures - Strength gradaed structural timber with rectangular cross section - Part 1: General Requirements, European Committee for Standardization (CEN), Brussels, Belgium, 2005.

[20] DIN 4074-1 Strength grading of wood - Part 1: Coniferous sawn timber, 2012.

[21] EN 338 Structural timber - strength classes, European Committee for Standardization (CEN), Brussels, Belgium, 2009.

[22] Crawford, D., Hairstans, R., Smith, R.E.: Feasibility of cross laminated timber production from UK sitka spruce, Focus solid timber solutions - European conference on cross laminated timber (CLT), Bath, pp. 37-52, 2013.

[23] Blaß, H.J., Flaig, M.: Keilgezinkte Rahmenecken und Satteldachträger aus Brettsperrholz, KIT Scientific Publication, Karlsruhe, 2015.

[24] EN 301 Adhesives, phenolic and aminoplastic, for load-bearing timber structures - Classification and performance requirements, European Committee for Standardization (CEN), Brussels, Belgium, 2006.

[25] EN 15425 Adhesives - One component polyurethane adhesives for load-bearing timber structures - Classification and performance requirements, European Committee for Standardization (CEN), Brussels, Belgium, 2008.

[26] Unterwieser, H., Schickhofer, G.: Characteristic values and test configurations of CLT with focus on selected properties, Focus solid timber solutions - European conference on cross laminated timber (CLT), Bath, pp. 53-73, 2013.

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

[28] EN 14080 Timber structures - glued laminated timber and glued solid timber - requirements, European Committee for Standardization (CEN), Brussels, Belgium, 2013.

[29] Schickhofer, G., Brandner, R., Bauer, H.: Introduction to CLT - product properties - strength classes, Proceedings of the Joint Conference of COST Actions FP1402 & FP1404, Cross laminated timber - a competitive wood product for visionary and fire safe buildings, Stockholm, pp. 9-32 , 2016.

[30] Aicher, S., Dill-Langer, G.: Basic consideration to rolling shear modulus in wooden boards, Otto-Graf-Journal, 11, 2000.

[31] Blaß, H.J., Görlacher, R.: Zum Trag- und Verformungsverhalten von LIGNOTREND Elementen bei Beanspruchung in Plattenebene, Bauen mit Holz, 104 (2002) 11, pp. 34-41.

[32] Görlacher, R.: Ein Verfahren zur Ermittlung des Rollschubmoduls von Holz, Holz als Roh- und Werkstoff, 60 (2002) 5, pp. 317-322.

[33] Fellmoser, P., Blaß, H.J.: Influence of rolling shear modulus on strength and stiffness of structural bonded timber elements, Proceedings of 37th CIB-W18 Meeting, Edinburgh, 2004.

[34] Mestek, P., Kreuzinger, H., Winter, S.: Design of Cross Laminated Timber CLT, Proceedings of 10th World Conference on Timber Engineering (WCTE2008), Miyazaki, 2008.

[35] Flores, E.I.S., Saavedra, K., Hinojosa, J., Chandra, Y., Das, R.: Multi-scale modelling of rolling shear failure in cross-laminated timber structures by homogenisation and cohesive zone models, International Journal of Solids and Structures, 81 (2016), pp. 219-232, https://doi.org/10.1016/j.ijsolstr.2015.11.027

[36] Franzoni, L., Lebee, A., Lyon, F., Foret, G.: Influence of orientation and number of layers on the elastic response and failure modes on CLT floors: modeling and parameter studies, European Journal of Wood and Wood Products, 74 (2016) 5, pp. 671-684.

[37] Blaß, H.J., Görlacher, R.: Zum Trag- und Verformungsverhalten von LIGNOTREND Decken und Wandsystemen aus Nadel-schnittholz, Bauen mit Holz, 103 (2001) 4, pp. 37-40.

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

[39] Sikora, K.S., McPolin, D.O., Harte, A.M.: Effects of the thickness of cross-laminated timber (CLT) panels made from Irish Sitka spruce on mechanical performance in bending and shear, Construction and Building Materials, 116 (2016), pp. 141-150, https://doi.org/10.1016/j.conbuildmat.2016.04.145

[40] Zhou, Q., Gong, M., Chui, Y.H., Mohammad, M.: Measurement of rolling shear modulus and strength of cross laminated timber fabricated with black spruce, Construction and Building Materials, 64 (2014), pp. 379-386, https://doi.org/10.1016/j.conbuildmat.2014.04.039

[41] Li, M., Lam, F., Li, Y.: Evaluating rolling shear strength properties of cross laminated timber by torsional shear tests and bending tests, Proceedings of 13th World Conference on Timber Engineering (WCTE2014), Quebec, 2014.

[42] Aicher, S., Hirsch, M., Christian, Z.: Hybrid cross-laminated timber plates with beech wood cross-layers, Construction and Building Materials, 124 (2016), pp. 1007-1018, https://doi.org/10.1016/j.conbuildmat.2016.08.051

[43] EN 408 Timber structures - Structural timber and glued laminated timber - Determination of some physical and mechanical properties, European Committee for Standardization (CEN), Brussels, Belgium, 2012.

[44] Halili, Y.: Versuchstechnische Ermittlung von Querdruckkenngrößen für Brettsperrholz, Master Thesis, Institute of Timber Engineering and Wood Technology, Graz University of Technology, Graz, Austria, 2008.

[45] Salzmann, C.: Ermittlung von Querdruckkenngrößen für Brettsperrholz (BSP), Master Thesis, Institute of Timber Engineering and Wood Technology, Graz University of Technology, Graz, Austria, 2010.

[46] Serrano, E., Enquist, B.: Compression strength perpendicular to grain in cross-laminated timber (CLT), Proceedings of 11th World Conference on Timber Engineerig (WCTE2010), Riva del Garda, 2010.

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

[48] Bogensperger, T., Jöbstl, R.: Concentrated load introduction in CLT elements perpendicular to plane, Proceedings of 1st INTER-Meeting, Bath, 2014.

[49] Brandner, R., Schickhofer, G.: Properties of cross laminated timber (CLT) in compression perpendicular to grain, Proceedings of 1st INTER-Meeting, Bath, 2014.

[50] EN 14358 - Timber structures - Calculation and verification of characteristic values, European Committee for Standardization (CEN), Brussels, Belgium, 2006.

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

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

[53] Jöbstl, R., Bogensperger, T., Schickhofer, G.: In plane shear strength of cross laminated timber, Proceedings of 41th CIB-W18 Meeting, St. Andrews, 2008.

[54] Bogensperger, T., Moosbrugger, T., Silly, G.: Verification of CLT-plates under loads in plane, Proceedings of 11th World Conference on Timber Engineerig (WCTE2010), pp. 885-898, Riva del Garda, 2010.

[55] Jöbstl, R., Bogensperger, T., Schickhofer, G., Jeitler, G.: Mechanical behaviour of two orthogonally glued boards, Proceedings of 8th World Conference on Timber Engineering (WCTE2004), Portland, 2004.

[56] Flaig, M.: Design of CLT beams with rectangular holes or notches, Proceedings of 1st INTER-Meeting, Bath, 2014.

[57] Bogensperger, T., Moosbrugger, T., Schickhofer, G.: New test configuration for CLT wall elements under shear load, Proceedings of 40th CIB-W18 Meeting, Bled, 2007.

[58] Andreolli, M., Rigamonti, M.A., Tomasi, R.: Diagonal compression test on cross laminated timber panels, Proceedings of 13th World Conference on Timber Engineering (WCTE2014), Quebec, 2014.

[59] Brandner, R., Dietsch, P., Dröscher, J., Schilte-Wrede, M., Sieder, M.: Scheibenschub von Brettsperrholz: Verifizierung einer Prüfkonfiguration und Parameterstudie, Bautechnik, 92 (2015) 11, pp. 759-769.

[60] Wallner, G.: Versuchstechnische Ermittlung der Verschiebungskenngrößen von orthogonal verklebten Brettlamellen, Master Thesis, Graz University of Technology, Graz, Austria, 2004.

[61] Bosl, R.: Zum Nachweis des Trag- und Verformungsverhaltens von Wandschiben aus Brettsperholz, PhD Thesis, Institute for structural engineering, Military University of Munich, 2002.

[62] Andreolli, M., Tomasi, R.: Experimental investigation on in-plane behaviour of cross-laminated timber elements, Proceedings of 45th CIB-W18 Meeting, Växjö, 2012.

[63] Möhler, K.: Die Bemessung der Verbindungsmittel bei zusammengesetzten Biege- und Druckgliedern im Holzbau, Bauen mit Holz, 68 (1966), pp. 162-164.

[64] Kreuzinger, H.: Verbundkonstruktionen aus nachgiebig miteinander verbundenen Querschnittsteilen, Proceedings of Ingenieurholzbau Karlsruher Tage, Bruderverlag Karlsruhe, 2000.

[65] Timoshenko, S.P.: On the correction factor for shear of the differential equation for transverse vibrations of bars of uniform cross-section, Phil Mag, 41 /1921), pp. 744-746.

[66] Bogensperger, T., Silly, G., Schickhofer, G.: Comparison of methods of approximate verification procedures for cross laminated timber, Research report, holz.bau forschungs gmbh: Graz, Austria, 2012.

[67] Thiel, A.: ULS and SLS design of CLT and its implementation in the CLT designer, Focus solid timber solutions - European conference on cross laminated timber (CLT), University of Bath, Bath, pp. 77-102, 2013.

[68] Thiel, A., Brandner, R.: Ultimate limit states design of CLT elements - Basis and some special topics, Proceedings of the Joint Conference of COST Actions FP1402 & FP1404, Cross laminated timber - a competitive wood product for visionary and fire safe buildings, Stockholm, 2016.

[69] Thiel, A., Krenn, H.: Buckling loads for cross-laminated timber elements under uniaxial in-plane compression, Proceedings of 14th World Conference on Timber Engineering (WCTE2016), Vienna, 2016.

[70] Perret, O., Lebee, A., Douthe, C., Sab, K.: The Bending-Gradient theory for the linear buckling of thick plates: Application to Cross Laminated Timber panels, International Journal of Solids and Structures, 87 (2016), pp. 139-152, https://doi.org/10.1016/j.ijsolstr.2016.02.021

[71] Moosbrugger, T., Guggenberger, W., Bogensperger, T.: Cross-laminated timber wall segments under homogeneous shear - with and without openings, Proceedings of 9th World Conference on Timber Engineering (WCTE2006), Portland, 2006.

[72] Jeleč, M., Strukar, K., Rajčić, V.: Structural analysis of in-plane loaded CLT beams, Electronic Journal of the Faculty of civil engineering Osijek - e-GFOS, 14, pp. 30-40, 2017.

[73] Jeleč, M., Rajčić, V., Danielsson, H., Serrano, E.: Structural analysis of in plane loaded CLT beams with holes: FE-analyses and parameter studies, Proceedings of 3rd INTER-Meeting, Graz, 2016.

[74] Danielsson, H., Serrano, E., Jeleč, M., Rajčić, V.: In-plane loaded CLT beams - Tests and analysis of element lay-up , Proceedings of 4th INTER-Meeting, Kyoto, 2017.

[75] Jöbstl, R., Schickhofer, G.: Comparative examination of creep of GLT and CLT slabs in bending, Proceedings of 40th CIB-W18 Meeting, Bled, 2007.

[76] Hamm, P., Richter, A., Winter, S.: Floor vibrations – new results, Proceedings of 11th World Conference on Timber Engineerig (WCTE2010), Riva del Garda, 2010.

[77] Thiel, A., Schickhofer, G.: Design methods for Cross Laminated timber concering floor vibrations: a comparability study, Research report, holz.bau forschungs gmbh, Graz, Austria, 2012.

[78] EN 1995-1-2 Eurocode 5: Design of timber structures - Part 1-2: General - Structural fire design, European Committee for Standardization (CEN), Brussels, Belgium, 2004.

[79] Klippel, M., Schmidt, J., Frangi, A.: Fire Design of CLT – comparison of design concepts, Proceedings of the Joint Conference of COST Actions FP1402 & FP1404, Cross laminated timber - a competitive wood product for visionary and fire safe buildings, Stockholm, 2016.

[80] Frangi, A., Fontana, M., Knobloch, M., Bochicchio, G.: Experimental analysis of cross-laminated timber panels in fire, Fire Safety Journal, 44 (2009) 8, pp. 1078-1087.

[81] Schmid, J., König, J., Kohler, J.: Fire-exposed cross-laminated timber – modelling and tests, Proceedings of 11th World Conference on Timber Engineerig (WCTE2010), Riva del Garda, 2010.

[82] Fragiacomo, M., Menis, A., Clemente, I., Bochicchio, G.: Fire Resistance of Cross-Laminated Timber Panels Loaded Out of Plane, Journal of Structural Engineering, 139 (2013) 12, https://doi.org/10.1061/(ASCE)ST.1943-541X.0000787

[83] Schmid, J., Menis, A., Fragiacomo, M., Clemente, I., Bochicchio, G.: Behaviour of Loaded Cross-Laminated Timber Wall Elements in Fire Conditions, Fire Technology, 51 (2015) 6, pp. 1341-1370.

[84] Werther, N., Denzel, J.K., Stein, R., Winter, S.: Detailing of CLT with respect to fire resistance, Proceedings of the Joint Conference of COST Actions FP1402 & FP1404, Cross laminated timber - a competitive wood product for visionary and fire safe buildings, Stockholm, 2016.

[85] EN 1998-1:2004 + AC + A1 Eurocode 8: design of structures for earthquake resistance -part 1: general rules, seismic actions and rules for buildings, European Committee for Standardization (CEN), Brussels, Belgium, 2013.

[86] Dujič, B., Zarnić , R., Aicher, S., Racking of wooden walls exposed to different boudary conditions, Proceedings of 38th CIB-W18 Meeting, Karlsruhe, 2005.

[87] Ceccotti, A.: SOFIE Project - Cyclic Tests on Cross-Laminated Wooden Panels, Proceedings of 9th World Conference on Timber Engineering (WCTE2006), Portland, 2006.

[88] Popovski, M., Schneider, J., Schweinsteiger, M.: Lateral load resistance of cross-laminated wood panels, Proceedings of 11th World Conference on Timber Engineerig (WCTE2010), Riva del Garda, 2010.

[89] Seim, W., Hummel, J., Vogt, T.: Earthquake design of timber structures - Remarks on force-based design procedures for different wall systems, Engineering Structures, 76 (2014), pp. 124-137, https://doi.org/10.1016/j.engstruct.2014.06.037

[90] Flatscher, G., Bratulić, K., Schickhofer, G.: Experimental tests on cross-laminated timber joints and walls. Proceedings of the Institution of Civil Engineers - Structures and Buildings,168 (2015) 11, pp. 868-877, https://doi.org/10.1680/stbu.13.00085

[91] Gavrić, I., Fragiacomo, M., Ceccotti, A.: Cyclic Behavior of CLT Wall Systems: Experimental Tests and Analytical Prediction Models, Journal of Structural Engineering, 141 (2015) 11, https://doi.org/10.1061/(ASCE)ST.1943-541X.0001246

[92] Tomasi, R., Smith, I.: Experimental Characterization of Monotonic and Cyclic Loading Responses of CLT Panel-To-Foundation Angle Bracket Connections, Journal of Materials in Civil Engineering, 27 (2015) 6, https://doi.org/10.1061/(ASCE)MT.1943-5533.0001144

[93] Stepinac, M., Rajčić, V., Žarnić, R.: Timber structural glass composite systems in earthquake environment, Građevinar, 68 (2016) 3, pp. 211-219.

[94] Uibel, T., Blaß, H.J.: Joints with dowel type fasteners in CLT structures, Focus solid timber solutions - European conference on cross laminated timber (CLT), Bath, pp. 119-136 , 2013.

[95] Schneider, J., Shen, Y., Stiemer, S.F., Tesfamariam, S.: Assessment and comparison of experimental and numerical model studies of cross-laminated timber mechanical connections under cyclic loading, Construction and Building Materials, 77 (2015), pp. 197-212, https://doi.org/10.1016/j.conbuildmat.2014.12.029

[96] Ringhofer, A., Brandner, R., Schickhofer, G.: Withdrawal resistance of self-tapping screws in unidirectional and orthogonal layered timber products, Materials and Structures, 48 (2015) 5, pp. 1435-1447.

[97] Gavrić, I., Fragiacomo, M., Ceccotti, A.: Cyclic behaviour of typical metal connectors for cross-laminated (CLT) structures, Materials and Structures, 48 (2015) 6, pp. 1841-1857.

[98] Gavrić, I., Fragiacomo, M., Ceccotti, A.: Cyclic behavior of typical screwed connections for cross-laminated (CLT) structures, European Journal of Wood and Wood Products, 73 (2015) 2, pp. 179-191.

[99] Izzi, M., Flatscher, G., Fragiacomo, M., Schickhofer, G.: Experimental investigations and design provisions of steel-to-timber joints with annular-ringed shank nails for Cross-Laminated Timber structures, Construction and Building Materials, 122 (2016), pp. 446-457, https://doi.org/10.1016/j.conbuildmat.2016.06.072

[100] Kraler, A., Kögl, J., Maderebner, R.: Sherpa-clt-connector for cross laminated timber (CLT) elements, Proceedings of 13$^{th}$ World Conference on Timber Engineering (WCTE2014), Quebec, 2014.

[101] Polastri, A., Angeli, A., Gianni, D.R.: A new construction system for clt structures, Proceedings of 13$^{th}$ World Conference on Timber Engineering (WCTE2014), Quebec, 2014.

[102] Ceccotti, A., Sandhaas, C., Okabe, M., Yasamura, M., Minowa, C., Kawai, N.: SOFIE project-3D shaking table test on a seven-storey full-scale cross-laminated timber building, Earthquake Engineering & Structural Dynamics, 42 (2013) 13, pp. 2003-2021.

[103] Flatscher, G., Schickhofer, G.: Shaking-table test of a cross-laminated timber structure, Proceedings of the Institution of Civil Engineers - Structures and Buildings, 168 (2015) 11, pp. 878-888, https://doi.org/10.1680/stbu.13.00086

[104] Follesa, M., Fragiacomo, M., Lauriola, M.P.: A proposal for revision of the current timber part (Section 8) of Eurocode 8 Part 1, 42$^{th}$ CIB-W18 Meeting, Alghero, 2011.

[105] Dujič, B., Klobčar, S. Zarnić, R.: Influence of openings on shear capacity of wooden walls, Proceedings of 40$^{th}$ CIB-W18 Meeting, Bled, 2007.

[106] Kawai, N., Tsuchimoto, T., Tsuda, C., Murakami, S., Miura, S., Isoda, H., Miyake, T.: Lateral loading tests on CLT shear walls by assembly of narrow panels and by a large panel with an opening, Proceedings of 13$^{th}$ World Conference on Timber Engineering (WCTE2014), Quebec, 2014.

[107] Bejtka, I.: Cross (CLT) and Diagonal (DLT) Laminated Timber as Innovative Material for Beam Elements, Research report, KIT Scientific Publication, Karlsruhe, Germany, 2011.