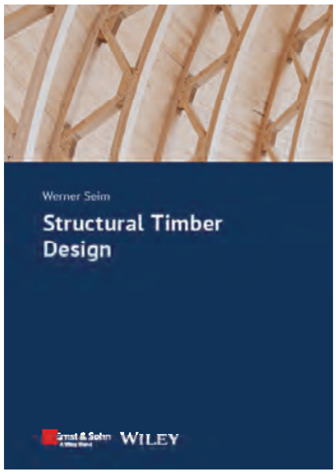
Ernst & Sohn
A Wiley Brand

Werner Seim

Structural Timber Design

- **For experienced engineers and for beginners alike**
- **Also suitable as a textbook in the Master's programme**
- **Offers background knowledge instead of pure application of standards**

This book provides knowledge required for the design, construction and dimensioning of timber structures for typical buildings. For a basic understanding, the essential phenomena are explained and only then the normative regulations are considered.



2024 · 416 pages · 60 figures · 108 tables

Softcover
ISBN 978-3-433-03404-0 **€ 79***

eBundle (Print + ePDF)
ISBN 978-3-433-03403-3 **€ 129***

ORDER
+49 (0)30 470 31–236
marketing@ernst-und-sohn.de
www.ernst-und-sohn.de/en/3404

* All book prices inclusive VAT.

Werner Seim

Structural Timber Design

Ernst & Sohn
A Wiley Brand
WILEY

Author:
Prof. Dr.-Ing. Werner Seim
Fachgebiet Bauwerkserhaltung und Holzbau
Institut für Konstruktiven Ingenieurbau
Universität Kassel
Kurt-Wolters-Straße 3
34125 Kassel, Germany

Cover: Airship hangar in Mülheim, Germany, as a timber construction with impressive dimensions (42 × 26 × 92 metres).

Image: Ripkens Wiesenkämper Ingenieure / © Virtua ethic

Library of Congress Card No.: applied for

British Library Cataloguing-in-Publication Data
A catalogue record for this book is available from the British Library.

Bibliographic information published by the Deutsche Nationalbibliothek The Deutsche Nationalbibliothek lists this publication in the Deutsche Nationalbibliografie; detailed bibliographic data are available on the Internet at <http://dnb.d-nb.de>.

Print ISBN: 978-3-433-03404-0
ePDF ISBN: 978-3-433-61158-6
ePub ISBN: 978-3-433-61157-9
oBook ISBN: 978-3-433-61159-3

Typesetting: Straive, Chennai, India

Cover: Petra Franke, Ernst & Sohn GmbH, Berlin, Germany

Printing and binding:

Preface

Timber construction is actually one of the most innovative areas of the building industry. This applies equally to developments in materials, joining and manufacturing technologies, as well as construction site logistics. The speed with which new products are introduced into practical applications is almost breathtaking, especially when compared to the other construction materials in the building industry. Consequently, timber construction is continuously increasing its market share in commercial buildings and hall structures, and even in multi-storey constructions for residential and office buildings. Hardly a month goes by without a new height record being reported, even from countries that have not yet been counted among the classic timber construction nations.

This book aims to provide essential knowledge and skills required for the design, detailing and construction of timber structures for typical building structures. Special emphasis is placed on the specific features of timber and wood-based materials compared to other construction materials. This concerns the numerous advantages, such as the comparatively low weight and the good workability of this high-performance material, and the large variety of assembling technologies. However, it also addresses the challenges resulting from the material anisotropy and susceptibility to natural pests. Each chapter begins by explaining the essential phenomena, which are then brought into connection with regulations mainly taken from the different parts of EN 1995. This approach aims to support the basic understanding of the interrelations and dependencies in timber engineering, which forms the fundamental basis of creative engineering.

The individual chapters of the book are structured independently in terms of content. One does not have to work through the book sequentially from beginning to the end, but can start with the topic which seems to be the most interesting one.

The content of the book largely corresponds to the content of the 'Timber Engineering' courses offered in the Bachelor's and Master's programmes in Civil Engineering at the University of Kassel, and is based on the lecture notes that were compiled there over the years. Carsten Pörtner, Martin Schäfers, Heiko Koch, Lars Eisenhut, Tobias Vogt, Johannes Hummel, Michael Schick, Timo Claus, Sascha Schwendner, Jens Frohnmüller and Giuseppe D'Arenzo have contributed significantly to those classes. Annalena Funke, as student assistant, has taken great care to ensure a good and uniform graphic presentation. I would like to thank them all very much for this.

My special thanks go to Johannes Hummel, who supervised the editing of the lecture notes and co-authored the German version of several chapters of this book.

Kassel, December 2023 *Werner Seim*

Contents

7.2 Cross-laminated Timber (CLT)

7.2.1 Production, Load-bearing Characteristics and Strength

Cross-laminated timber (CLT) is a product that is particularly suitable for plane load-bearing elements, such as for slabs and wall panels. Figure 7.13 shows typical applications of CLT for slabs, load-bearing and bracing walls and deep beams. The use of CLT is only permitted in service classes 1 and 2. The durability of the bonding has been verified for the expected moisture content in these service classes.

Panels made of CLT are used, for example, for slabs or as load-bearing elements for flat roofs or flat pitched roofs (see Figure 7.13) and are mainly uniaxially spanned due to the joints that result from the elements being arranged next to each other. The outermost layers define the primary direction (see Figure 7.14). However, the transverse layers can also transfer loads in the secondary direction. The biaxial load-bearing effect allows point supports and offers advantages when transferring concentrated loads.

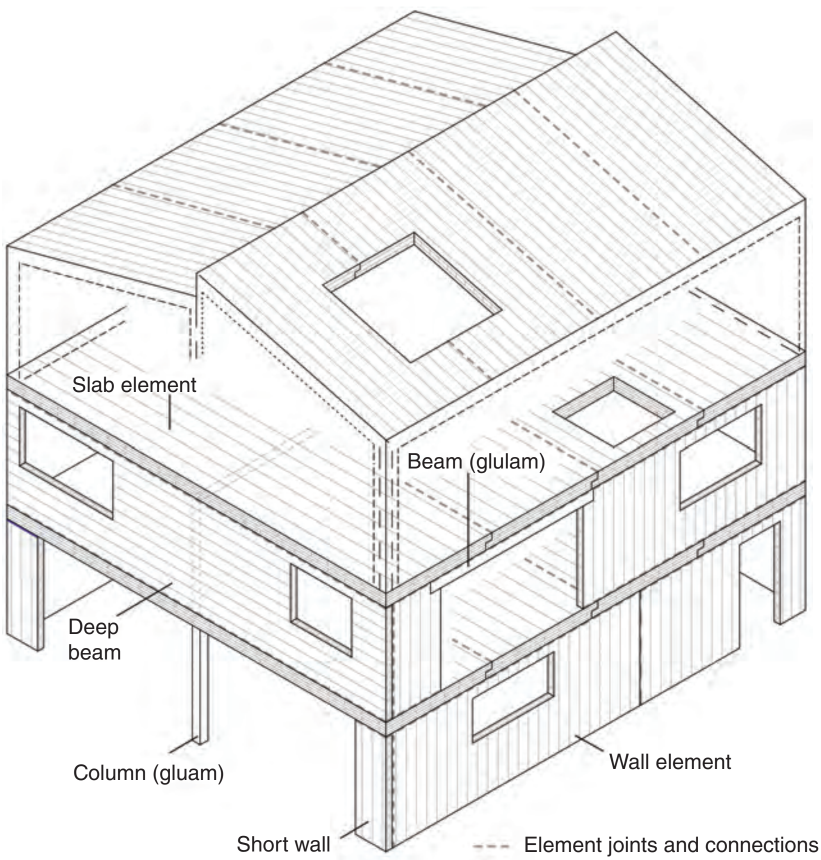


Figure 7.13 Building structure with CLT.

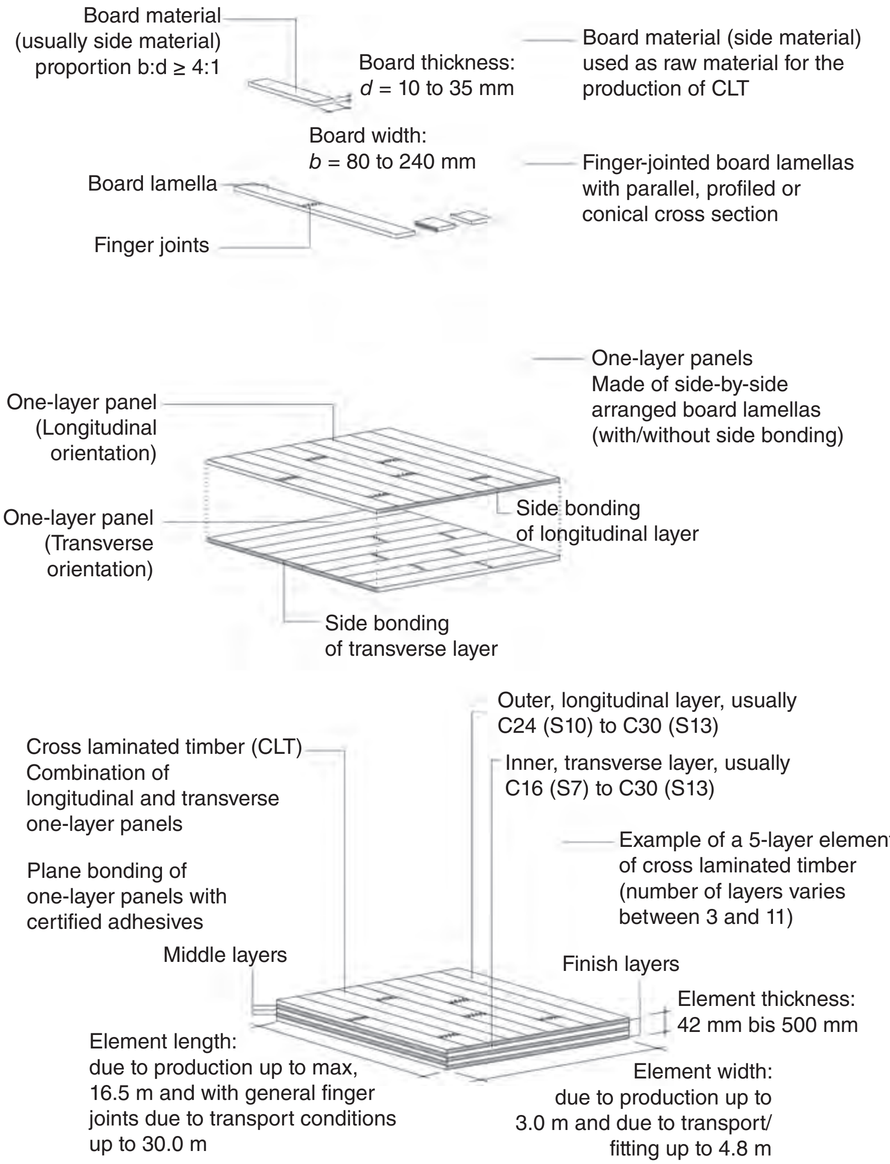


Figure 7.14 Structure of CLT – from single-board lamella to plane elements.

CLT consists of a minimum of three layers. The basic elements are boards, which can also be cut from the edge zone of the trunk (side material). The side material achieves material properties that are in the range of strength classes C24 (S10) and higher. Preferably, board lamellae with strength class C24 are used, although boards with strength classes C16 and C18 are also sometimes taken for the cross layers. The board lamellae are mainly made of soft woods like spruce and fir.

First, a so-called endless lamella is produced from the individual boards. For this purpose, as in the production of glulam, the individual boards are joined by finger joints after single sections with larger knots have been cut out. The dimensions of the board lamella usually range from 80 to 240 mm in width and 10 to 40 mm in thickness. The board lamellae are planed (the edges can be profiled) and sawn to the required length (see Figure 7.14). For the production of panels, the board lamellae are arranged next to each other in such a way that the finger joints are offset from each other by a minimum of 1/3 of the board width. If there are higher demands about air tightness, sound insulation or appearance, the side edges of the board lamellae can be glued to each other (edge gluing). However, this is not offered by all manufacturers.

The individual board layers are stacked in alternating longitudinal and transverse orientation, with the number of layers varying between 3 and 11. The individual layers can have different thicknesses depending on the structural requirements. An adhesive is applied between the individual board layers. PU adhesives, melamine resins and resorcinol resins are used. The board lamellae have a moisture content of about 10% when glued.

A pre-defined contact pressure is required to ensure plararity and adhesive bonding. For this purpose, the layers are 'stacked' and the adhesive is applied in a so-called press bed (see Figure 7.15). There, the surface pressure of all layers is applied with a contact pressure in the range of 0.6–0.8 N/mm^2. The press bed is heated to shorten the time the adhesive needs to cure.

The pressing is followed by the finishing and the joinery. The elements are usually manufactured in the dimensions requested by the customer. The dimensions are limited by the size of the pressing device as well as by boundary conditions during transportation and assembly. CLT elements can be up to 3.0 m wide and up to 16.0 m long. Some manufacturers can also produce dimensions of up to 4.8 m × 30 m (width × length). For such long CLT elements, two shorter elements may have to be connected to each other using large finger joints.

For the required visual quality, the surfaces are either planed again or at least sanded to remove adhesive residues.

(a) (b)

Figure 7.15 Production of CLT elements: (a) adhesive application; (b) addition of panels to be transferred to the press bed. Source: Poppensieker & Derix, Westerkappel.

(a) (b)

Figure 7.16 CLT wall elements (a) on CNC trimming line; (b) with cut-outs for electrical installations; Source: Poppensieker & Derix, Westerkappel.

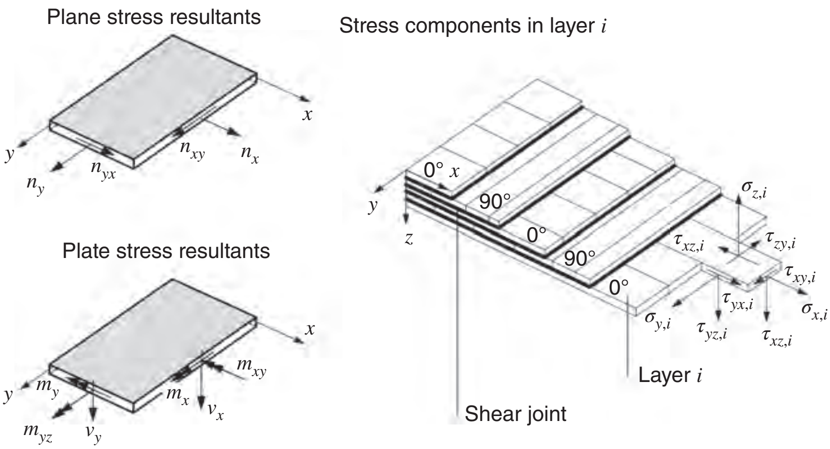


Figure 7.17 Definition of section forces and stresses for CLT slabs and panels.

During the trimming line procedure, window and door openings, ceiling openings and, if necessary, cut-outs, for example, for connections or installation lines, are made (see Figure 7.16).

Due to the layered structure of CLT, the stresses and deformations cannot be determined as with a monolithic cross section. The orthogonal structure of each layer determines the magnitude and distribution of the stresses throughout the height of the cross section. In the typical regular structures, in which longitudinal and transverse layers alternate, only every second layer participates in the transfer of bending moments and normal forces. In addition, the rolling shear stress of the respective intermediate layer is of particular importance for both plates and panels.

In Figure 7.17, plate and panel internal forces are given with reference to an x-y-z coordinate system as well as the associated stresses for layer i. When defining the bending moments, it should be noted that the index corresponds to the associated bending stress. Thus, a bending moment m_x causes bending stresses in the direction of the x-axis, but 'rotates' around the y-axis.

The material properties of CLT elements are currently still regulated in technical approvals. For this reason, a range of characteristic values is given in Table 7.1,

Table 7.1 Material values for CLT.

Strength (N/mm²)		Modulus of Elasticity (N/mm²)	
$f_{m,k}$	**24.0**	$E_{0,mean}$	11.000–12.000
$f_{t,0,k}$	**14.0**–16.5	$E_{90,mean}$	**370**
$f_{t,90,k}$	0.12–**0.4**–0.5	G_{mean}	600–**690**–720
$f_{c,0,k}$	**21.0**–24.0	$G_{r,mean}$	**50**–69
$f_{c,90,k}$	**2.5**–2.7	$E_{0.05} = 5/6 \cdot E_{0,mean}$ and $G_{05} = 5/6 \cdot G_{mean}$	
$f_{v,90,k}$ a)	**0.8**–1.5	Density (kg/m³)	
$f_{v,k}$ b),c)	1.6–3.5	ρ_k	350–**380**
$f_{v,tor,k}$ b)	**2.5**	ρ_{mean}	**420**–450

a) Plates loaded perpendicular to the plane.
b) In-plane loaded panels.
c) In some technical documentations it is referred to values for fictive shear strength.

which can be found in the various approvals based on a strength of C24 of the lamellae of the outermost layer. These values can be considered strength if the stresses acting on the composite cross section are determined using the calculation methods explained in the following sections. For individual products, design values of the load-bearing capacities and stiffnesses are also given as tabulated values in the technical documentation.

As modification coefficients k_{mod} for the strengths and k_{def} for the deformations, the values specified for glulam can be used (see Section 2.1.2).

7.2.2 Plates

7.2.2.1 Bending and Shear Stiffness

The procedure for determining the stiffness values in order to carry out the calculations of the stresses is shown exemplarily for the x-direction. The x-direction follows the fibre direction of the outer layers and thus becomes the main load-bearing direction. For the y-direction, the stiffness values can be determined in the same way. The following considerations refer to a panel strip of one meter width.

The individual lamellae of a cross section of CLT, when subject to bending stress, are flexibly connected by transverse layers. This leads to higher bending edge stresses $\sigma_{x,max}$ compared to the rigid bond, as illustrated in Figure 7.18. Due to the lack of edge bonding or because of unavoidable shrinkage cracks parallel to the grain, the transverse layers typically do not participate in load transfer in the event of bending stress in the x-direction.

The influence of the shear deformation of the transverse layers on the stresses of the longitudinally arranged lamellae depends not only on their thickness and the rolling shear modulus but also on the loading and the static system. Under certain

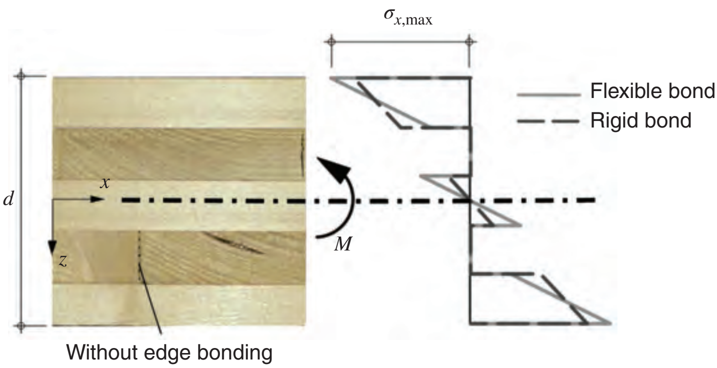


Figure 7.18 Bending stresses for rigid and flexible bond; section with five layers without bonding of the side faces, according to Mestek (2011).

conditions, the influence is so small that the determination of the stresses is sufficiently accurate for the assumption of rigid bond. In this context, the bending slenderness of the element plays a decisive role. The bending slenderness is defined as the ratio of the span length l_i of the ideal single-span beam (see Figure 6.21) to the thickness d of the component.

Studies by Guggenberger and Moosbrugger (2006) and Mestek (2011) have shown that for single-span systems under uniform load with a bending slenderness $l_i/d \geq 20$, the assumption of a rigid bond provides sufficiently accurate results. The deviation in the bending edge stress is less than 2% from the correct solution with a flexible bond. Consequently, the stiffness contribution of the intermediate layer is therefore neglected. For a more precise consideration, one can refer to the explanations on the composite beams in Sections 11.4 and 6.3.

The bending stiffness $(EI)_x$ of a panel strip with width 1 is composed of the stiffnesses of the single lamella and the Steiner components.

$$(EI)_x = \sum_{i=1}^{n} \left(E_{x,i} \cdot d_i^3/12\right) + \sum_{i=1}^{n} \left(E_{x,i} \cdot d_i \cdot z_{s,i}^2\right) \tag{7.3}$$

The geometric relationships are shown in Figure 7.19. In most cases, the cross sections are symmetrical. The transverse layers are neglected when determining the bending stiffness and the stresses.

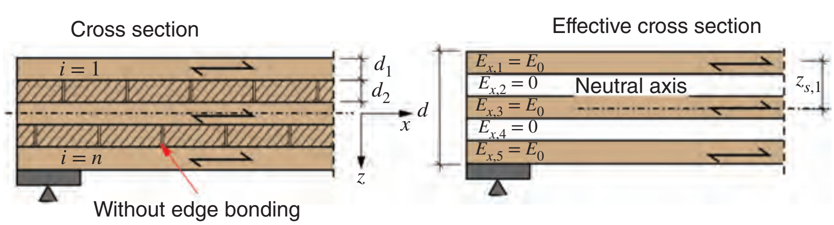


Figure 7.19 Geometric relationships and transition to the effective cross section.

If the cross section consists of layers with different MOIs, a reference value E_0 can be chosen, and an effective area moment of inertia can be specified as

$$I_{\mathrm{ef,x}} = \frac{(EI)_{\mathrm{x}}}{E_0} \tag{7.4}$$

If the MOI is the same for all layers, then the following applies for the main load-bearing direction.

$$I_{\mathrm{ef,x}} = \sum d_i^3/12 + \sum \left(d_i \cdot z_{\mathrm{s},i}^2\right) \quad i = 1, 3, 5, \ldots \tag{7.5}$$

This equation also applies to the transverse direction if the values 2, 4, etc. are used for i.

$$I_{\mathrm{ef,y}} = \sum d_i^3/12 + \sum \left(d_i \cdot z_{\mathrm{s},i,}^2\right) \quad i = 2, 4, \ldots \tag{7.6}$$

Since the individual board layers are glued together over their entire surface, it can be assumed that shear deformation between the layers arranged in one direction occurs due to the rolling shear stress of the respective transverse layer.

There are different approaches to take this relationship into account. Mestek (2011) defines an equivalent shear stiffness based on the shear analogy method. The relationship between shear deformation and equivalent shear stiffness $(GA)_{\mathrm{xz}}$ is illustrated in Figure 7.20.

The equivalent shear stiffness can be calculated using Eq. (7.7) and results from the equalisation of the total deformation u from shear at the layered cross section and the shear deformation of the homogeneous equivalent cross section.

$$(GA)_{\mathrm{ef,xz}} = a^2 \cdot \left[\frac{d_1}{2 \cdot G_{\mathrm{xz},1}} + \sum_{i=2}^{n-1} \frac{d_i}{G_{\mathrm{xz},i}} + \frac{d_n}{2 \cdot G_{\mathrm{xz},n}}\right]^{-1} \tag{7.7}$$

In this equation, it should be noted that the shear modulus (for $i = 1, 3, 5, \ldots$) and the rolling shear modulus (for $i = 2, 4, \ldots$) must be used alternately for G_{xz}.

For commonly used cross sections, this approach yields values that are about 10% of the shear stiffness of a monolithic timber cross section. The shear analogy method assumes a constant shear flow over the cross section height and therefore provides comparatively low values for the equivalent shear strength. Wallner-Novak et al. (2013) consider a shear-soft Timoshenko beam and determine reduction factors

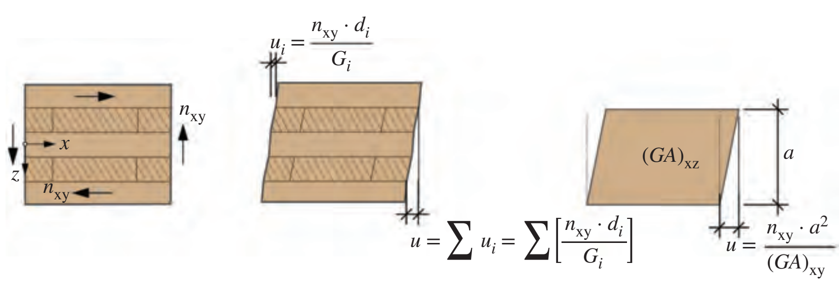


Figure 7.20 Shear deformations of the layers and calculation of fictive shear stiffness, according to Mestek (2011).

that are approximately between 0.2 and 0.3, depending on the number of layers. This results in a conservative approach for the shear stiffnesses as follows:

$$(GA)_{\text{ef,xz}} = 0.2 \cdot G \cdot \sum A_i \quad i = 1, 3, 5, \dots \tag{7.8}$$

$$(GA)_{\text{ef,yz}} = 0.2 \cdot G \cdot \sum A_i \quad i = 2, 4, \dots \tag{7.9}$$

Due to the layered construction, also the torsional stiffness is reduced. If no precise knowledge is available, then the torsional stiffness should be neglected:

$$(EI)_{\text{xy}} = 0 \quad \text{and} \quad (EI)_{\text{yx}} = 0. \tag{7.10}$$

7.2.2.2 Uniaxial Load Bearing

The beam theory is largely sufficient to determine the internal forces of uniaxially spanned CLT panels under uniform load. For systems with bending slendernesses <20, the stresses for the flexible connected layers should be calculated with coupled beams or with an FE model. For this purpose, the procedure explained in Section 7.3.1 can be used.

The bending stress σ_{x} for layer i is calculated as follows:

$$\sigma_{\text{m,x},i} = \frac{m_{\text{x}} \cdot E_{\text{x},i}}{(EI)_{\text{x}}} \cdot z \tag{7.11}$$

With uniform modulus of elasticity, Eq. (7.11) simplifies to:

$$\sigma_{\text{m,x}} = \frac{m_{\text{x}}}{I_{\text{ef,x}}} \cdot z \tag{7.12}$$

with the effective area moment of inertia $I_{\text{ef,x}}$ according to Eq. (7.5).

To determine the shear stress distribution, the static moments S_{x} at the transition from lamella i to $i + 1$ are required. These result from the area of the individual cross sections and the corresponding distance $z_{\text{s},j}$.

$$(ES)_{\text{x},i/i+1} = \sum_{j=i+1}^{n} E_{\text{x},j} \cdot d_{\text{x},j} \cdot z_{\text{s},j} \tag{7.13}$$

If $E_{\text{x}} = 0$ is assumed for the transverse layers and with a uniform modulus of elasticity in the x-direction, the equation can also be simplified here to

$$S_{\text{x},i/i+1} = \sum_{j=i+1}^{n} d_{\text{x},j} \cdot z_{\text{s},j} \tag{7.14}$$

The shear stress at the transition between layer i and $i + 1$ is then determined for the shear force v_{x} to be

$$\tau_{\text{xz},i/i+1} = \frac{S_{\text{x},i/i+1}}{I_{\text{ef,x}}} \cdot v_{\text{x}} \tag{7.15}$$

The course of the bending and shear stresses is shown in Figure 7.21 for the longitudinal and transverse directions. Note that the shear stresses in the lamella running transversely to the load-bearing direction act as rolling shear stresses (see Figure 7.22), which is a characteristic of CLT construction.

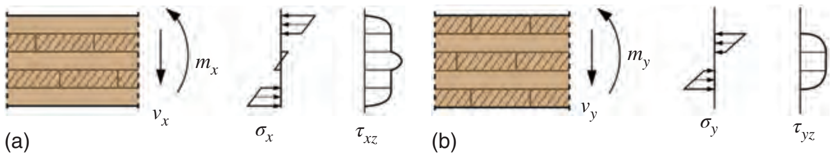


Figure 7.21 Bending and shear stresses for CLT plates: (a) main direction; (b) transverse direction.

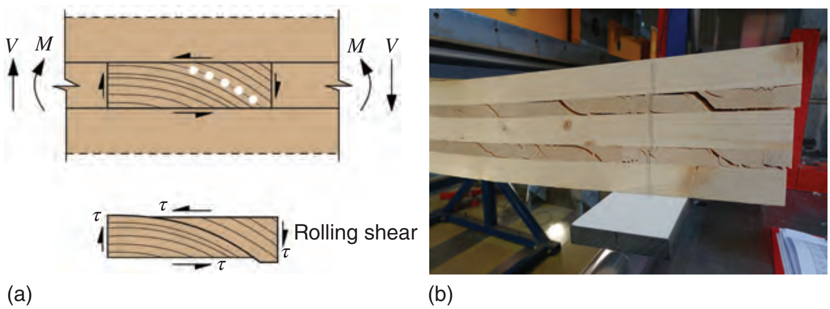


Figure 7.22 Shear-stressed CLT plates: (a) shear stresses of the transverse layer; (b) rolling shear failure of the transverse layers. Source: Institut für Holzbau und Holztechnologie, TU Graz.

When verifying the bending stresses, it may be taken into account that the load in CLT is borne simultaneously by several parallel board lamellae, which are coupled with each other via the transverse layer. Due to statistical effects, the bending strength can be increased by a system coefficient k_1.

$$\frac{\sigma_{\mathrm{m,d}}}{k_1 \cdot f_{\mathrm{m,d}}} \leq 1 \tag{7.16}$$

with

$$k_1 = \min \begin{cases} 1 + n \cdot 0.025 \\ 1.1 \end{cases} \tag{7.17}$$

The parameter n stands for the number of adjacent lamellae that are stressed. The number of adjacent lamellae is determined for the spread width of the corresponding loading and is limited to $n = 4$.

In addition to the usual shear stress verification

$$\frac{\tau_{\mathrm{v,d}}}{f_{\mathrm{v,d}}} \leq 1 \tag{7.18}$$

the verification against rolling shear stress must also be carried out. The design value of the maximum shear stress in the lamella transverse to the considered load-bearing direction is to be used for $\tau_{\mathrm{v,90,d}}$:

$$\frac{\tau_{\mathrm{v,90,d}}}{f_{\mathrm{v,90,d}}} \leq 1 \tag{7.19}$$

Information on characteristic values of the rolling shear strength can be found in Table 6.2.

7.2.2.3 Biaxial Load Bearing

If CLT elements are to be used for biaxial load transfer, the orthotropic load-bearing behaviour must be taken into account in the calculation of the internal forces and in the verifications in the serviceability limit state.

CLT is constructed orthogonally in layers. This means that a biaxial load transfer can occur in the case of a bending load, and bending and shear stresses then arise both in the direction of the outer layers (primary load-bearing direction) and in the transverse direction (secondary load-bearing direction). Thus, bending stresses can be directed around openings and a transverse distribution under single loads is made possible. However, biaxial load transfer is in most cases limited to local areas due to the joints between the individual elements (see Figure 7.13). The internal forces can be determined for an orthogonal plate using a finite element calculation, taking into account the longitudinal and transverse stiffness (x- and y-directions) for bending and shear. How the corresponding stiffnesses are determined has already been explained at the beginning of this section. In any case, the position and design of the joints must be taken into account in the calculation model.

For slenderness $l_i/d \geq 20$, a calculation with an FE programme based on plate theory can be carried out if the orthotropy is taken into account when defining the stiffnesses (Figure 7.23). Cross-sections with $l_i/d < 20$ are to be calculated as layered coupled cross sections considering the flexible shear connection. Additional information is provided in Section 7.3.1. Stress verifications are carried out for both x- and y-directions according to Eq. (7.16).

7.2.2.4 Single Loads

For slabs with point supports or single loads, it is advisable to calculate the internal forces with an FE programme. Special attention is then paid to the introduction of concentrated forces acting perpendicular to the slab, whether as concentrated load or as reaction force at the support. Figure 7.24 shows examples of situations where

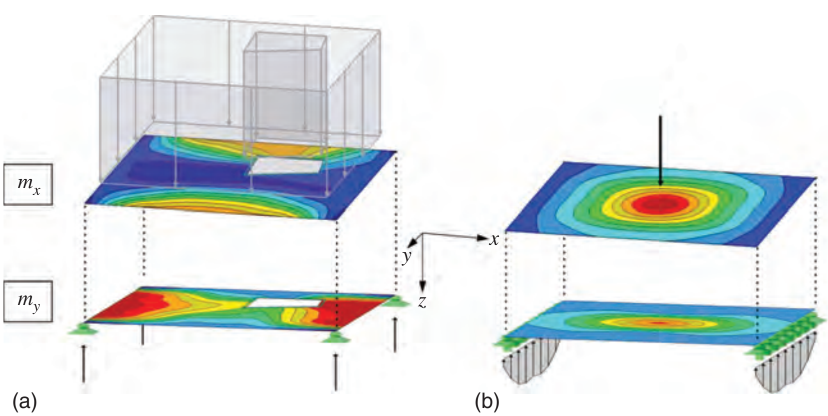


Figure 7.23 Section forces (bending moments m_x, m_y) and reaction forces of a plate (a) with distributed load, point supports and opening; (b) with linear support and single load at midspan.

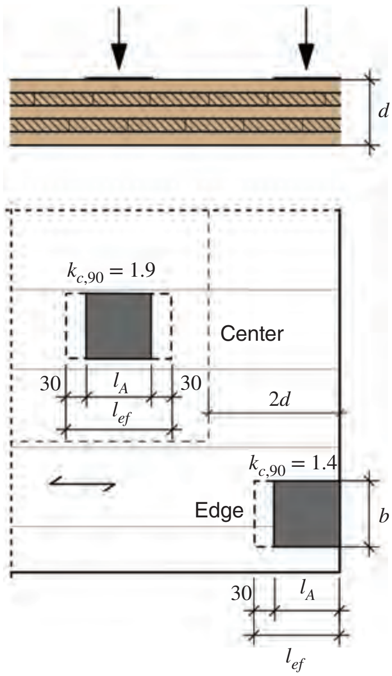


Figure 7.24 Areas with concentrated loads – single load or point support, according to Wallner-Novak et al. (2013).

Table 7.2 Load arrangement factor $k_{c,90}$.

Position	Center	Edge	Corner
$k_{c,90}$	1.9	1.4	

concentrated forces are introduced. In addition to the verification of the transverse compression stress, the high shear stress – in analogy to verification for reinforced concrete plates the punching shear – plays a decisive role.

The verification of compression perpendicular to the grain is carried out as for beam-type components (see Section 3.2). The spreading of the load to determine the effective area is only taken into account parallel to the grain direction of the outermost layers. The load arrangement factors were adjusted and can be found in Table 7.2.

Mestek (2011) developed a three-step calculation method for the verification of shear forces in the area of concentrated loads. In the first two steps, proportional shear forces and effective widths are determined for the main and secondary load-bearing directions, depending on the position – centre, edge or corner – of the load application area (Figure 7.25). Two coefficients are then introduced into the subsequent calculation of the rolling shear stresses. The first coefficient, k_R, takes into account the more uniform stress distribution over the cross section height with increasing number of layers, and the second coefficient, k_A, accounts for the stress peaks in corner and edge areas.

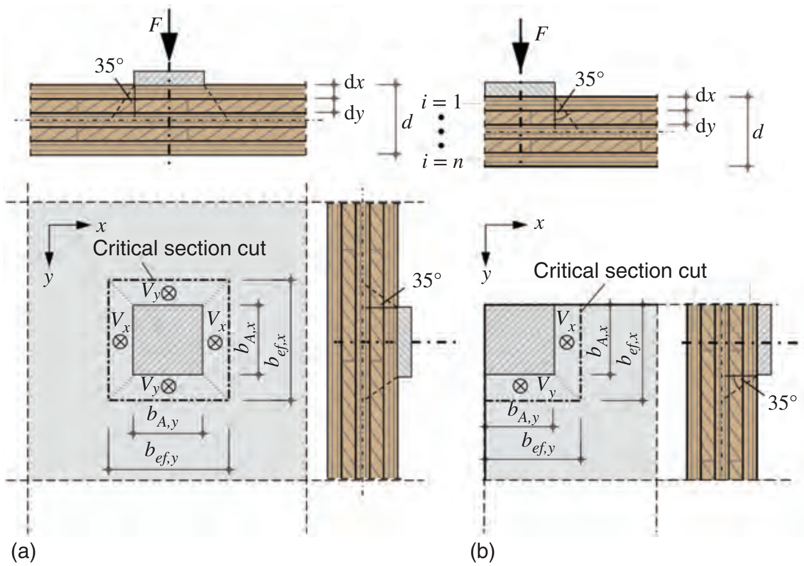


Figure 7.25 Load introduction, critical section cut and effective width: (a) central position; (b) corner or edge position.

The following applies to central position of the load application:

$$\tau_{\mathrm{v,90,xz}} = \frac{V_{\mathrm{x}}/b_{\mathrm{ef,x}}}{k_{\mathrm{R,x}} \cdot (d_{\mathrm{x}} + d_{\mathrm{y}})} \tag{7.20}$$

$$\tau_{\mathrm{v,90,yz}} = \frac{V_{\mathrm{y}}/b_{\mathrm{ef,y}}}{k_{\mathrm{R,y}} \cdot (d_{\mathrm{x}} + d_{\mathrm{y}})} \tag{7.21}$$

with shares of the shear force and effective width

$$V_{\mathrm{x}} \approx 0.33 \cdot n^{-0.1} \cdot F \tag{7.22}$$

$$V_{\mathrm{y}} \approx 0.5 \cdot F - V_{\mathrm{x}} \tag{7.23}$$

$$b_{\mathrm{ef,x}} = b_{\mathrm{A,x}} + d \cdot \tan(35^\circ) \tag{7.24}$$

$$b_{\mathrm{ef,y}} = b_{\mathrm{ef,x}} \tag{7.25}$$

For loading positions at the corner, applies

$$\tau_{\mathrm{v,90,xz}} = \frac{V_{\mathrm{x}}/b_{\mathrm{ef,x}}}{k_{\mathrm{R,x}} \cdot (d_{\mathrm{x}} + d_{\mathrm{y}})} \cdot k_{\mathrm{A}} \tag{7.26}$$

$$\tau_{\mathrm{v,90,yz}} = \frac{V_{\mathrm{y}}/b_{\mathrm{ef,y}}}{k_{\mathrm{R,y}} \cdot (d_{\mathrm{x}} + d_{\mathrm{y}})} \cdot k_{\mathrm{A}} \tag{7.27}$$

with shares of the shear force and effective width

$$V_{\mathrm{x}} \approx 0.67 \cdot n^{-0.1} \cdot F \tag{7.28}$$

$$V_{\mathrm{y}} \approx F - V_{\mathrm{x}} \tag{7.29}$$

Table 7.3 Factors k_R and k_A according to Mestek (2011).

n	**5**	**7**	**9**	**11**
$k_{R,x}$ [−]	2.00	2.50	3.33	3.89
$k_{R,y}$ [−]	1.00	2.00	2.50	3.33
$b_{A,x}/d$ resp. $b_{A,y}/d$	≤1.0	≤1.5	≤2.0	
k_A [−]	1.35	1.50	1.65	

$$b_{ef,x} = b_{A,x} + d/2 \cdot \tan(35°) \tag{7.30}$$

$$b_{ef,y} = b_{ef,x} \tag{7.31}$$

The corresponding coefficients are given in Table 7.3.

The method is applicable for CLT elements with square loaded areas that have a symmetrical cross section with a minimum of five and a maximum of 11 layers of equal thickness ($d_x = d_y$).

For a load application parallel to the edge, shear force, effective length and rolling shear stress can be assumed for the load transfer as for the corner area. For the load transfer perpendicular to the edge, the transverse force component is obtained from the equilibrium condition, and the contributing width and rolling shear stress can be determined here as for an introduction in the centre.

These considerations are based on the critical circular section with a spreading angle of 35°. The check of the shear stresses is carried out according to Eq. (7.19).

If the design conditions in the load application area are not fulfilled, the contact area can be increased. Another possibility is to reinforce the critical area by means of inclined fully threaded screws. Calculation methods for this can be found in Mestek (2011), among others.

7.2.2.5 Deflections

For the dimensioning of CLT slab panels, the deflections are also particularly relevant. In addition to pure bending deformation, CLT panels also experience shear deformation, which is mainly due to the flexible shear connection of the transverse layers (see Figure 7.20).

For the single-span beam under uniform loading, the deflection can be calculated from the sum of the bending and shear contributions:

$$w = w_B + w_S = \frac{5 \cdot q \cdot l^4}{384 \cdot (EI)_x} + \frac{q \cdot l^2}{8 \cdot (GA)_{xz}} \tag{7.32}$$

However, the share of shear deformation is comparatively low for slender load-bearing elements.

The calculation of natural frequencies for CLT elements is dealt with in Section 8.2. For more complex systems, such as point-supported CLT slab panels, the deflections and natural frequencies can be determined using FE calculations. Information on how to take the orthotropic structure into account in such calculations can be found in Section 7.3.1

Fact Sheet 7.2
CLT slab element – distributed load and linear support

1. **Calculate action combinations and section forces** (see Fact sheet 2.1)
2. **Calculate bending stresses** – consider only the lamella oriented in the stressed direction,
   – if $l_i/d \geq 20$: assume rigid bond
   – if $l_i/d < 20$: consider elastic bond, e.g. with γ-method.
3. **Check design consideration for bending**
   take strength from product declaration,
   increase strength with system coefficient k_l
4. **Calculate shear stresses**
5. **Check design consideration for rolling shear stresses**
6. **Check requirements for SLS**
   calculate stiffness depending on slenderness l_i/d, consider elastic bond if necessary (see step 2)

7.2.3 Wall Panels

CLT panels are also well suited for load-bearing and bracing walls. In this case, the elements are mainly in-plane loaded by vertical loads (e.g. from the slabs) and by horizontal loads (e.g. from wind or earthquakes). The vertical action results in a risk of buckling, and the wall experiences shear stress from the horizontal in-plane action. When used as exterior walls, wall elements must also take wind loads that act perpendicular to the surface.

7.2.3.1 In-plane Stiffness

If CLT elements are in-plane loaded in the normal direction, information on the corresponding elongation stiffness $(\mathrm{EA})_\mathrm{x}$ is required:

$$(EA)_\mathrm{x} = \sum_{i=1}^{n} (E_{\mathrm{x},i} \cdot d_i) \quad i = 1, 3, 5, \ldots \tag{7.33}$$

As with the bending stiffness, the lamellae perpendicular to the load-bearing direction can also be neglected here. The elongation stiffness $(EA)_\mathrm{y}$ can be determined analogously.

The shear stiffness $(GA)_\mathrm{xy}$ can be determined according to Moosbrugger et al. (2006) with the introduction of an effective shear modulus $G_\mathrm{ef,xy}$:

$$G_\mathrm{ef,xy} = \frac{G_\mathrm{mean}}{1 + 6 \cdot \left[0.32 \cdot \left(\frac{d_\mathrm{m}}{b_\mathrm{m}}\right)^{-0.77}\right] \cdot \left(\frac{d_\mathrm{m}}{b_\mathrm{m}}\right)^2} \tag{7.34}$$