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TIMBER ENGINEERING - VSM196

LECTURE 14 –
CROSS LAMINATED TIMBER –
MATERIAL AND STRUCTURES

SPRING 2020

Source: Stora Enso

Topic

- Cross laminated timber
    - Material
    - Structures

- [DoTS: Chapter 2]
- https://www.swedishwood.com/publications/list_of_swedish_woods_publications/the-clt-handbook/

Content

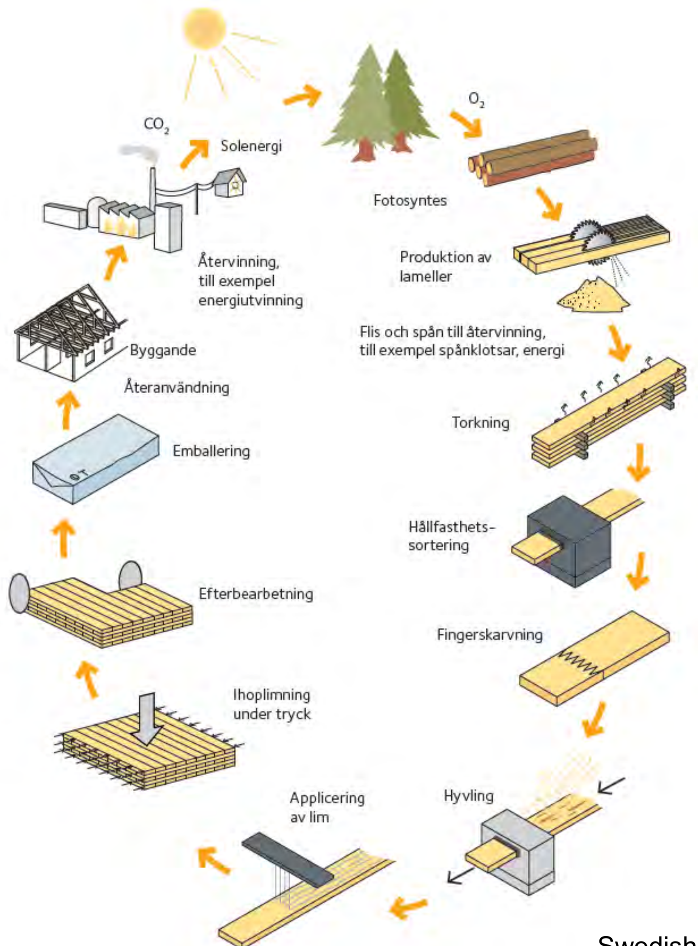
- Material properties
- Design of CLT elements and connections
- Examples and Structures

Intended Learning Outcomes of this lecture

- You understand the production and properties of CLT
- You can determine the relevant stresses in a CLT element
- You know different possibilities for connection of CLT elements
- You will be able to design a simple structure made of CLT

Material Production

Production

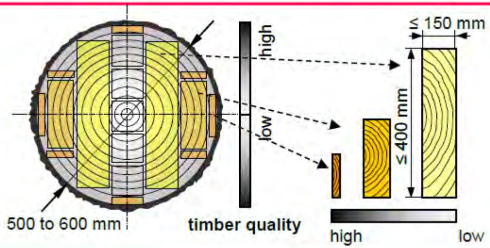


Swedish Wood

Production

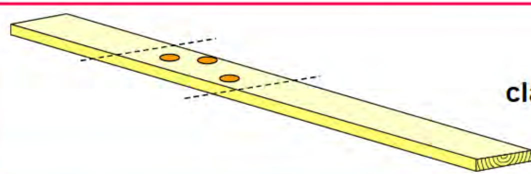
STEPs | **intermediate products | steps in production**

STEP I
log



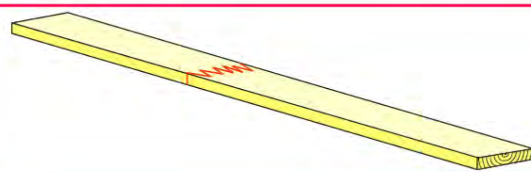
breakdown

STEP II
board



classification / grading
trimming

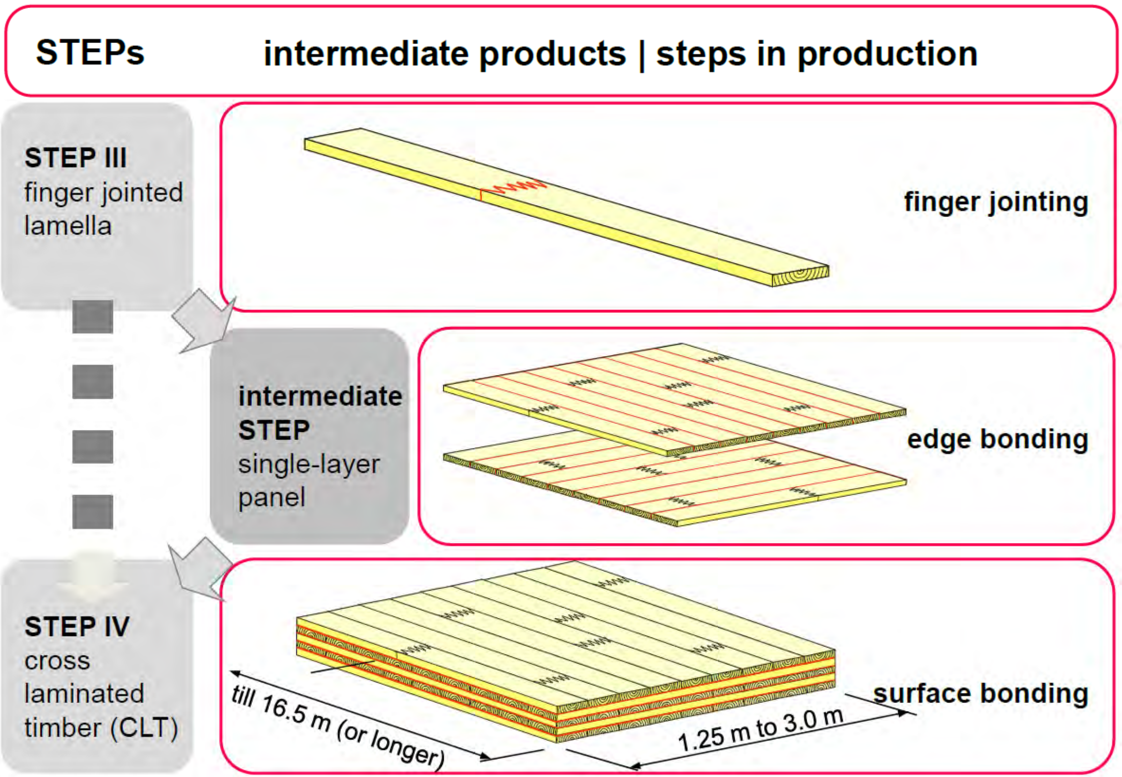
STEP III
finger jointed
lamella



finger jointing

Courtesy of R. Brandner & G. Schickhofer

Production

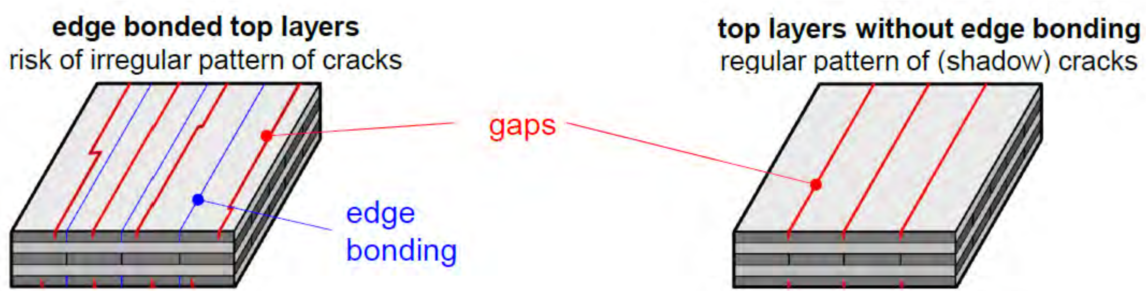


Courtesy of R. Brandner & G. Schickhofer

Different production processes

- CLT from single-layer panels
- Pros:
  - Gaps minimised
  - Lower requirements
    - $w_P/t_P \geq 4$ even when $w_B/t_B < 4$
    - Surface bonding pressure
  - Building physics, joining technigue, appearance
- Cons:
  - Swelling and shrinkage:
  - Irregular pattner of crack (appearance!)
    - Reduced properties in building physics
    - Relativization of $w_B/t_B < 4$

  ⇨ smaller gaps with thinner top layers

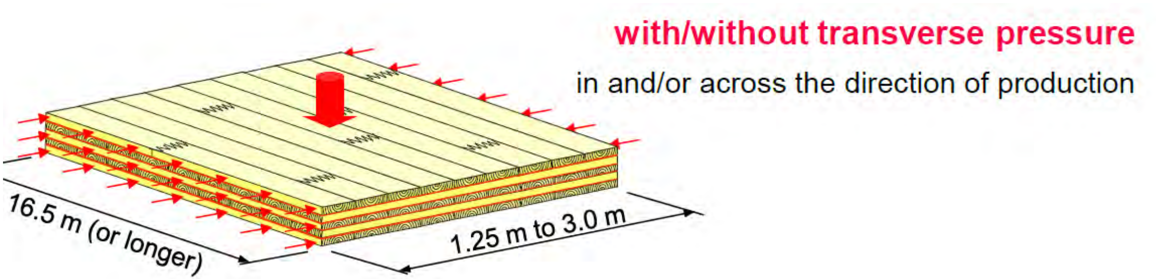


Courtesy of R. Brandner & G. Schickhofer

Production

Possibilities for surface bonding

- Continuously by press facilities
  - Hydraulic (pneumatic) press (0,10-1,00 N/mm2)
  - Vacuum press (0,05-0,10 N/mm2)
- Discontinuously by pin-shaped fasteners
  - Pressing with screws, nails or brackets (0,01-0,20 N/mm2)

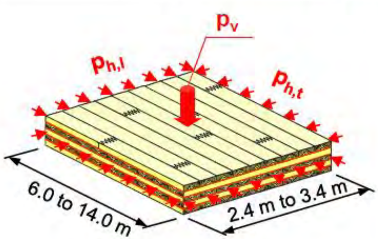


Courtesy of R. Brandner & G. Schickhofer

Production – hydraulic press

Schickhofer G (2012) Presentation, Edinburgh, Scotland, 30th October 2012; adapted

		MINDA "CLT press" (G)	**Kallesoe** "CLT press" (DK)
CLT dimensions		l = (**6.0 to 18.0**) m w = (**2.1 to 3.5**) m t = (**70 to 400**) mm	l = (**4.0 to 20.0**) m w = (**2.2 to 3.2**) m t = (**60 to 400**) mm
type of press system		hydraulic, continuous	hydraulic, discontinuous high frequency press
bonding pressure	vertical, $\mathbf{p_v}$	(**0.4 to 0.6** (0.8)) N/mm²	≤ **1.0** N/mm²
	horizontal transverse, $\mathbf{p_{h,t}}$	10 kN/m	available
	horizontal lengthwise, $\mathbf{p_{h,l}}$	45 kN	available



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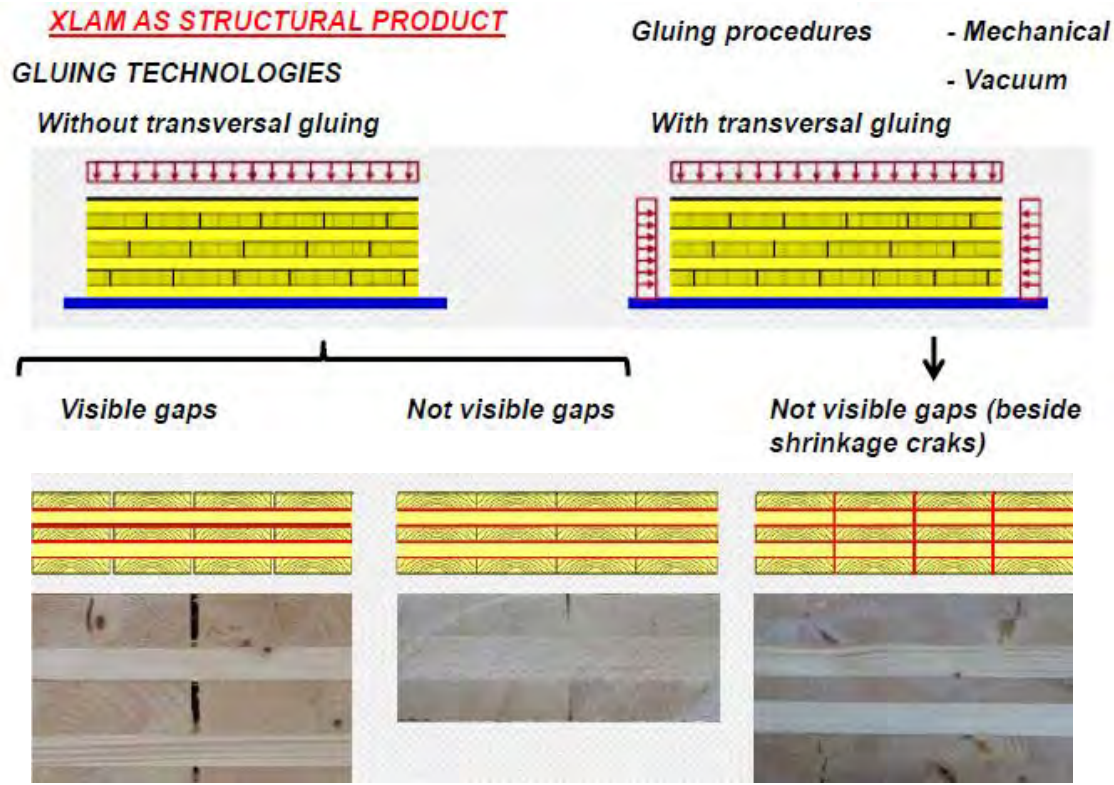
Vacuum press

Production



Courtesy of Roberto Tomasi

Production

- Pros
- Cons

Bracket, nail or screw pressing
Small productions, minor investments, primary manual production

Pros:
- Curved, shaped CLT elements
- On-site bonding

Cons:
- Limited bonding pressure
- Damage of tools by fasteners

Vacuum press equipment
Medium productions, medium investments, semi-mechanical production

Pros:
- Curved, shaped CLT or composite elements (box-beams or rib floors)

Cons:
- Limited bonding pressure
- Stress relieves
- Limited layer thickness and/or species

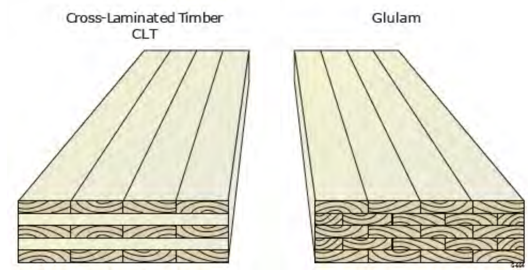
Hydraulic (pneumatic) press equipment
Medium to large productions, high investments, semi-mech. to automated production

Pros:
- Flexibility in bonding pressure
- Specific edge pressure possible
- Flexibility in automation

Cons:
- Restricted to even, straight elements
- Limited possibility to balance local unevenness or thickness deviations

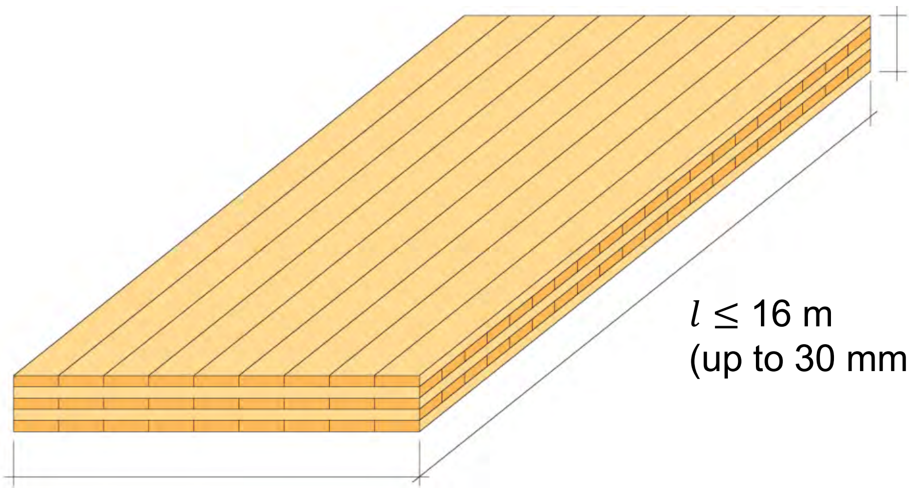
Modern production of CLT, cf. glulam

- Kiln-dry boards to 12% MC (but range 8 to 15% ±2%)
- Strength grading (tensile strength ex. T14),
- Finger jointing lamellas t_B (boards)
  - Thickness t_B = (12 to 45 mm)
  - Width w_B = (40 to 300 mm)
  - $w_B/t_B > 4$, due to rolling shear stresses between the layers



- Four-side planing
- Surface bonding
  - (bond line thickness of the gluline is within 0.1 to 0.3 mm)

Typical dimensions



t = 80 – 300 mm
(up to 60-500mm)

$l \leq$ 16 m
(up to 30 mm)

b = 1,2 - 3,0 m
(up to 4,8 mm)

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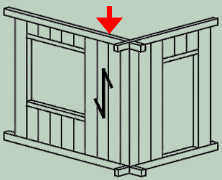
Building with CLT

Development of CLT

Load transfer

Tradition

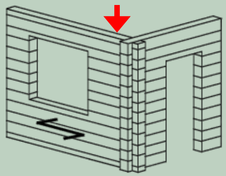
Beam type
(II to grain)



Wall
(e.g. Norway)

Stave church

Beam type
(⊥ to grain)

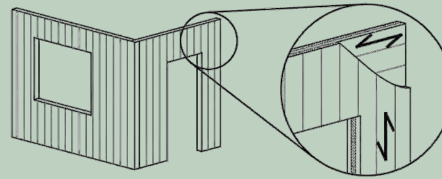


Blockwall
(e.g. Alpine region)

Blockhouse

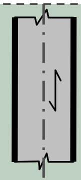
Innovation

Panel type
(Interaction of II and ⊥ to grain)



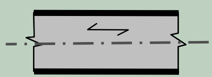
Massiv timber construction in CLT

Single family house



vertical

\+



horizontal

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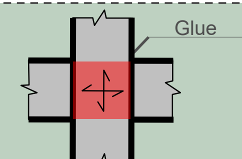

Cross**L**aminated**T**imber **(CLT, X-Lam)**

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Building with CLT


storage (production site)


charging and transport


discharging (building site)

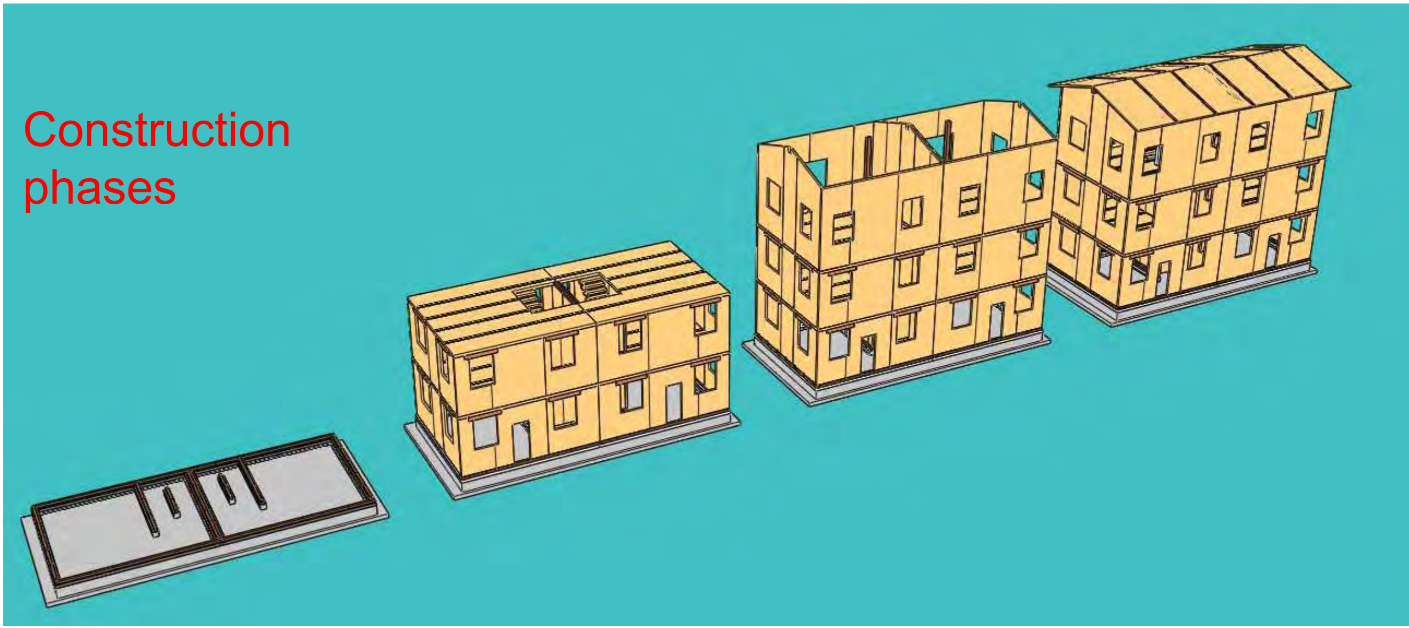

assembling of roof elements


assembling of ceiling elements


assembling of wall elements

Schickhofer G (2012) Presentation, Edinburgh, Scotland, 30th October 2012, adapted

CLT Systems



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CLT Systems

Benefits of building with CLT

- Opens to new dimensions in timber engineering (e.g. monolithic buildings)
  - High degree and accuracy in pre-fabrication
  - Dry and clean construction site
  - Short erection times

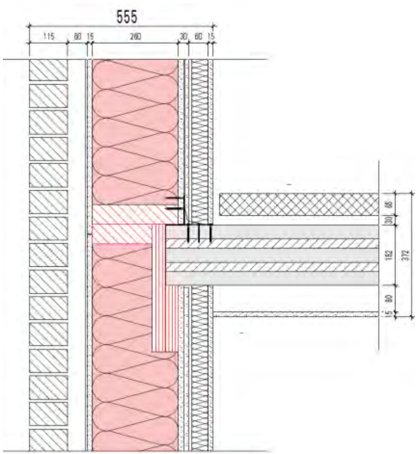
- In comparison to light-weight timber structures
  - Clear separation of load bearing, insulation & installation layers
  - Building physics: air permeability, specific storage capacity (humidity and temperature)
  - Independence of a modular dimension for window/door opening and fastening of furniture

- Substitutes reinforced concrete and brick construction

Comparison

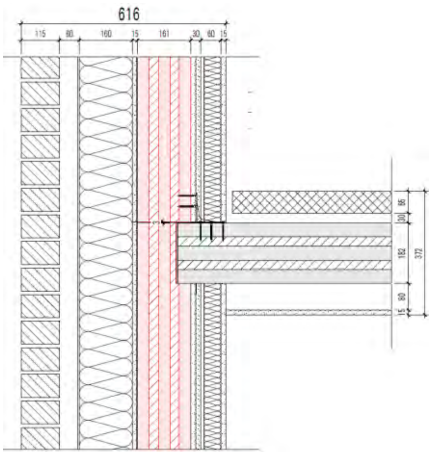
- Example Bridport Place London 2011:
- Comparison: wood consumption

- Light-frame



- 280m^3

- CLT



- 840m^3

Design with CLT

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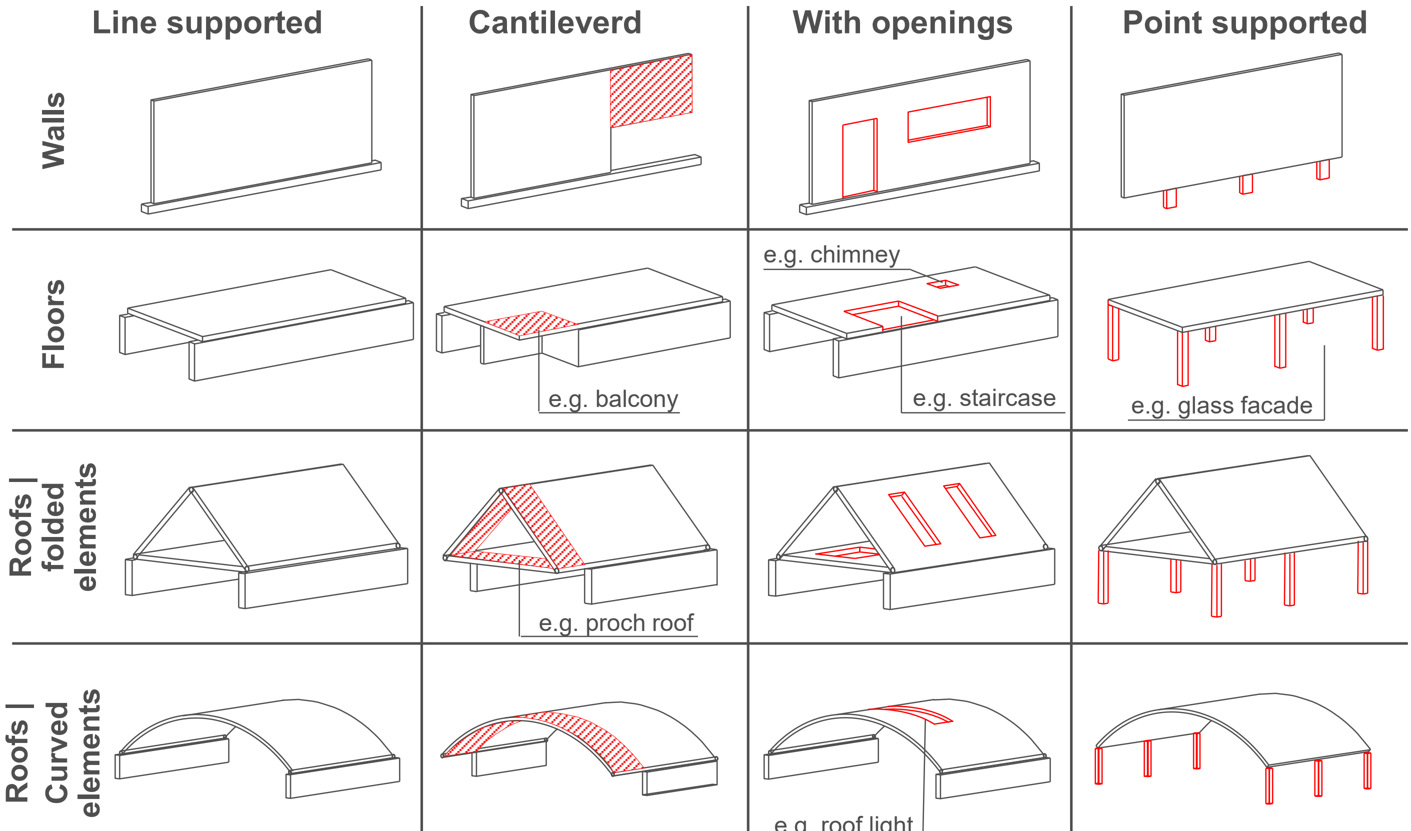
Fields of application, 2D elements



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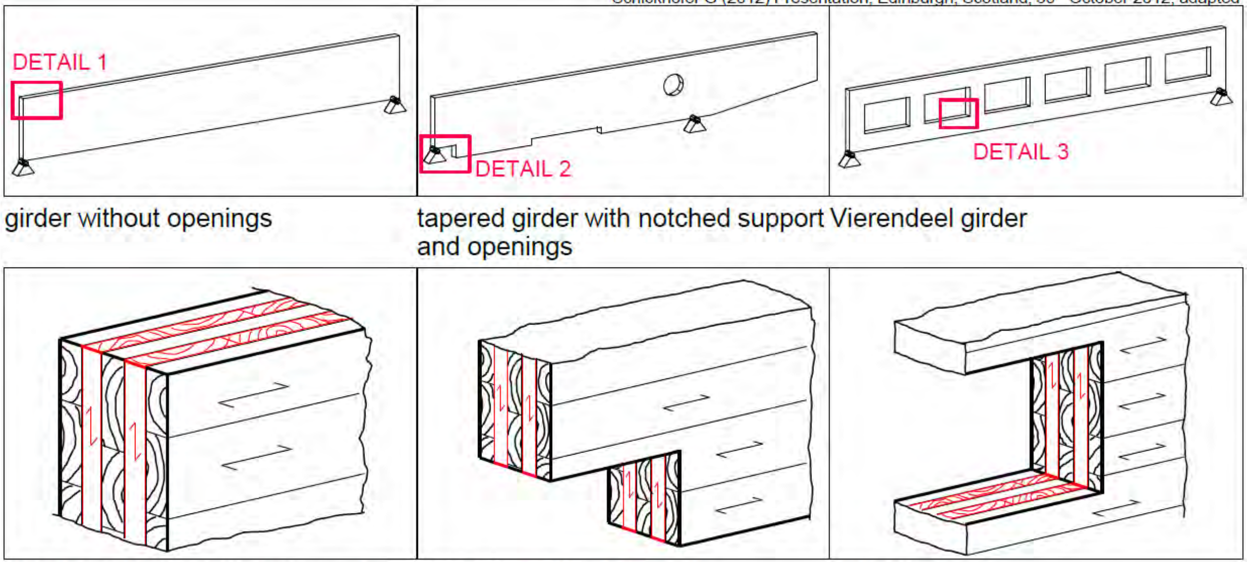
Fields of application, 1D elements

Schickhofer G (2012) Presentation, Edinburgh, Scotland, 30th October 2012; adapted

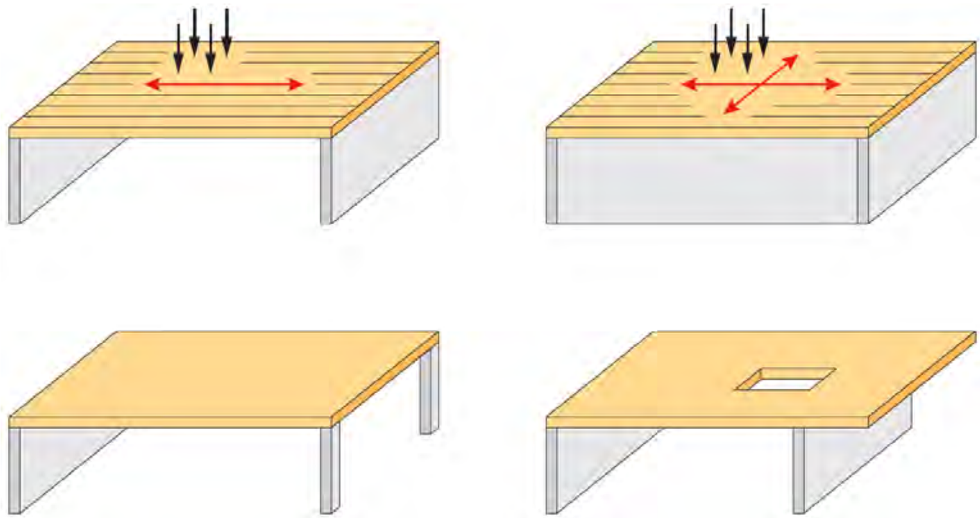


girder without openings | tapered girder with notched support and openings | Vierendeel girder

detail 1: 5-layered CLT-element | detail 2: notched support | detail 3: opening

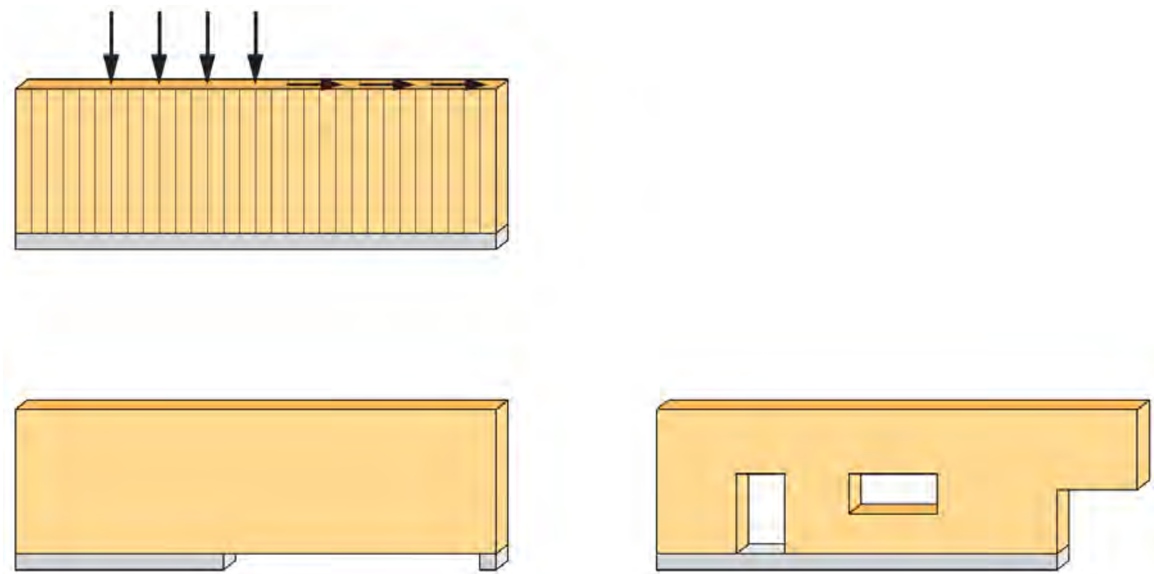
- Cross-layers as reinforcement
- Increases resistance in shear and tension perp. to grain!

Loading situations



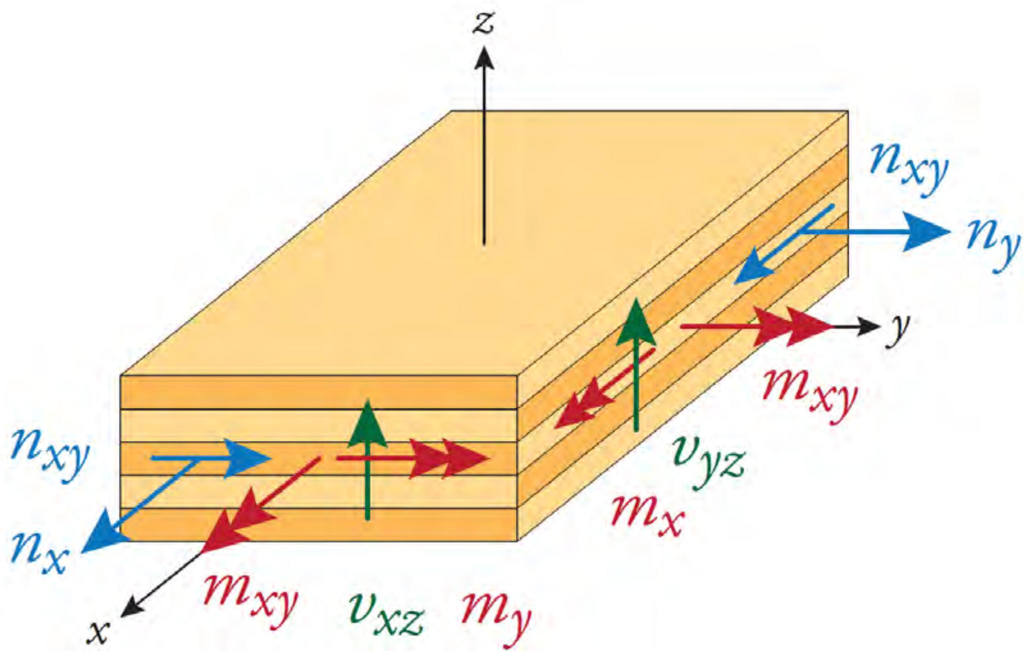
Swedish Wood

Loading situations



Swedish Wood

Loading situations



Swedish Wood

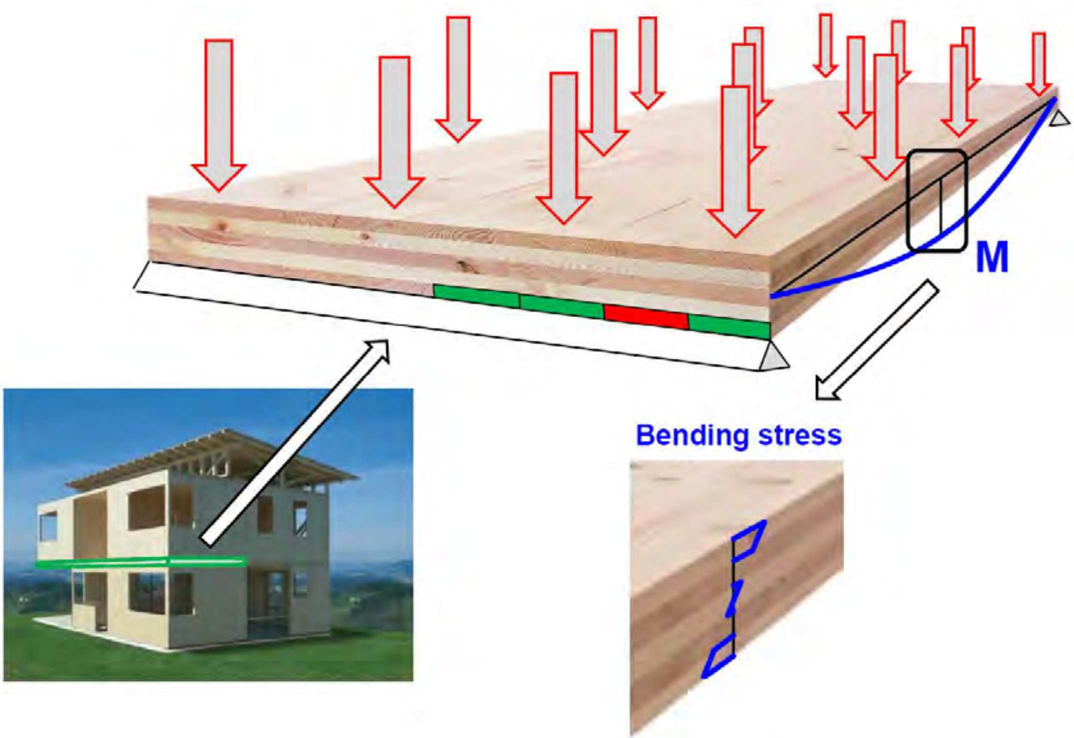
Sample building

Courtesy of T. Ehrhart

Sample building

Courtesy of T. Ehrhart

Bending of the plate



Courtesy of T. Ehrhart

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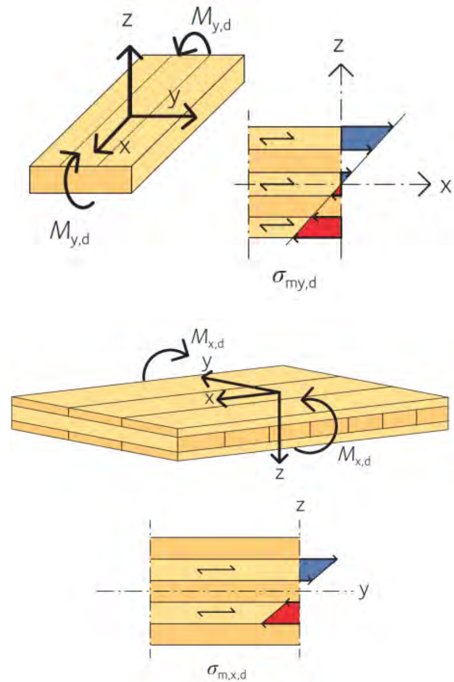
Bending

- Bending stress in plane

$$\sigma_{m,d} = \frac{M_d}{W_{net}} \leq k_{sys} f_{m,d}$$

$$W_{net} = \frac{I_{net}}{h/2}$$

$$I_{net} = \sum \left(\frac{b \cdot t_i^3}{12} + b \cdot t_i \cdot a_i^2 \right)$$



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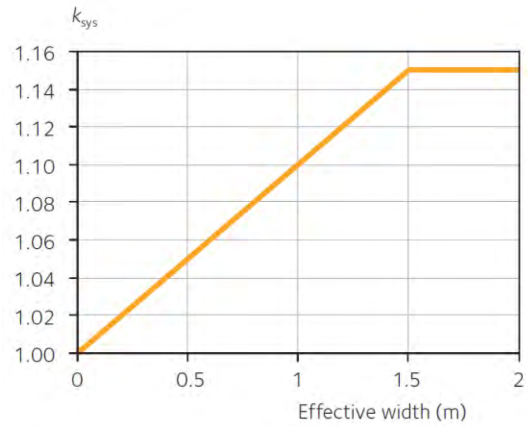
Bending

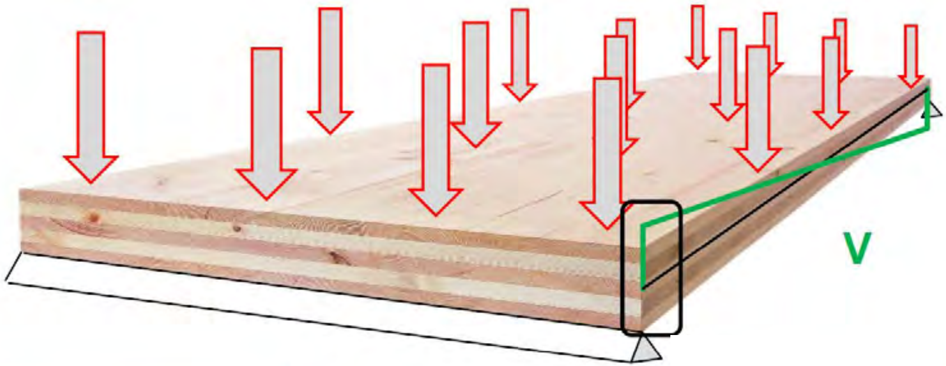
- System factor for CLT

$$k_{sys} = \min\begin{cases} 1{,}15 \\ 1 + 0{,}1b \end{cases}$$

  - Where b is the effective cross-section width in [m]



Shear in the plate



Courtesy of T. Ehrhart

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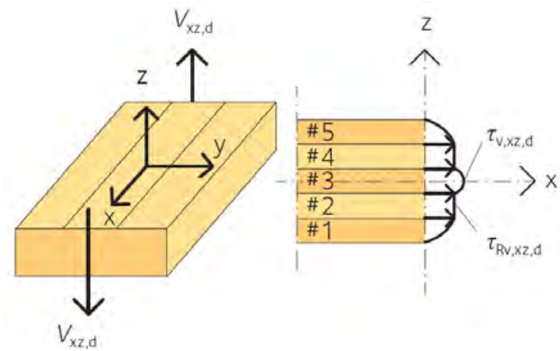
Shear

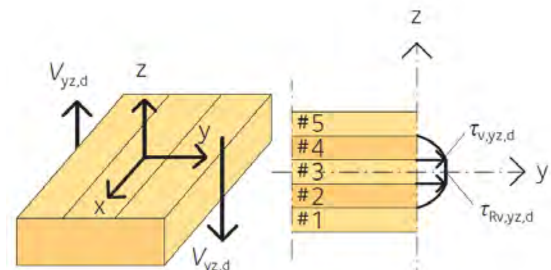
- Shear stresses for bending

$$\tau_d = \frac{V_d \cdot S_{net}}{b \cdot I_{net}} \leq \begin{cases} f_{v,R,d} \\ f_{v,d} \end{cases}$$

$$S_{net} = \sum b \cdot t_i \cdot a_i$$

$$I_{net} = \sum \left(\frac{b \cdot t_i^3}{12} + b \cdot t_i \cdot a_i^2 \right)$$





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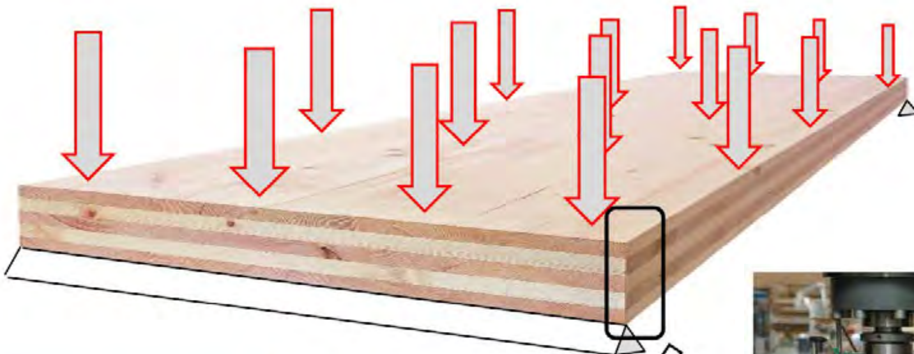
Compression perpendicular to grain



Courtesy of T. Ehrhart

Compression perpendicular to grain

- Compression stresses

$$\sigma_{c,90,d} = \frac{F_{c,90,d}}{A_{ef}} \leq k_{c90} \cdot f_{c,90,d}$$

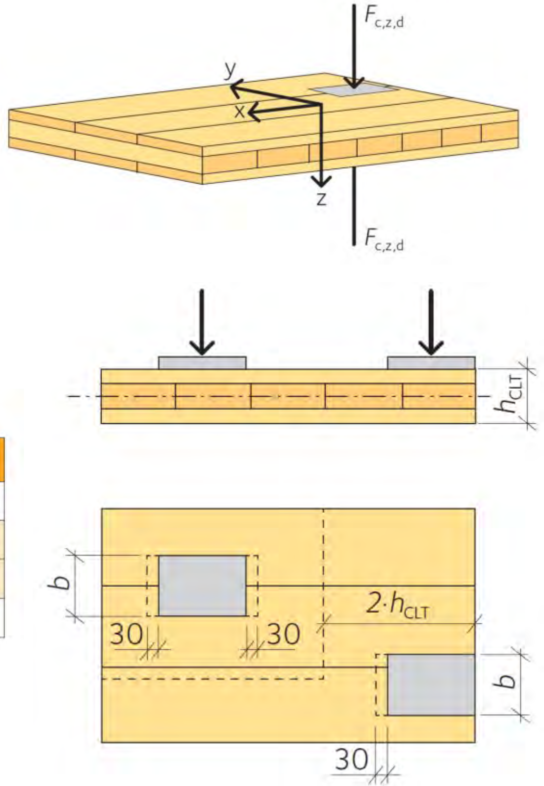


Table 3.16 Contact area A in mm² and b in mm plus value of $k_{c,90}$.

Location	Direction	Contact area, A_{ef}	$k_{c,90}$
Central	–	$A_{ef} = A_{tryck} + (30 + 30)b$	1.9
At edge	Parallel with grain	$A_{ef} = A_{tryck} + (30 + 30)b$	1.0 – 1.5
	Perpendicular to grain	$A_{ef} = A_{tryck} + 30b$	1.5
At corner	–	$A_{ef} = A_{tryck} + 30b$	1.3

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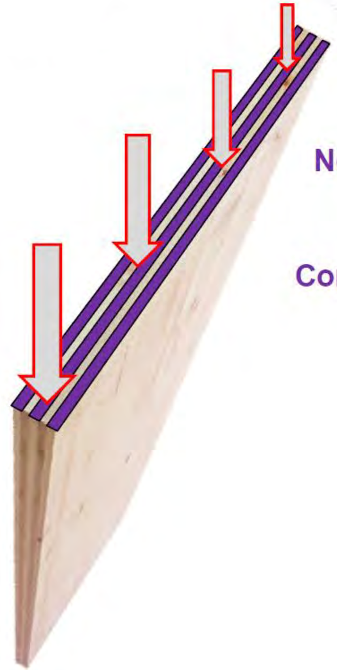
Sample building

Courtesy of T. Ehrhart

Axial loading



Net cross section

Compression 0°

Courtesy of T. Ehrhart

In plane axial loading

- Normal stresses
  - Tension

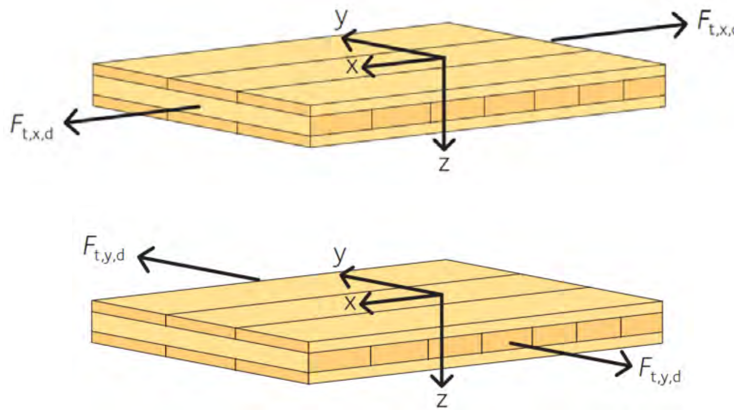
$$\sigma_{t,d} = \frac{N_{t,d}}{A_{net}} \leq k_{sys} \cdot f_{t,d}$$

$$A_{net} = \sum b \cdot t_i$$

  - Compression

$$\sigma_{c,d} = \frac{N_{c,d}}{A_{net}} \leq f_{c,d}$$

    - Consider also k_c



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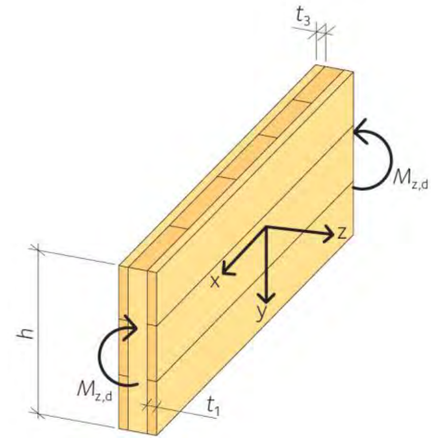
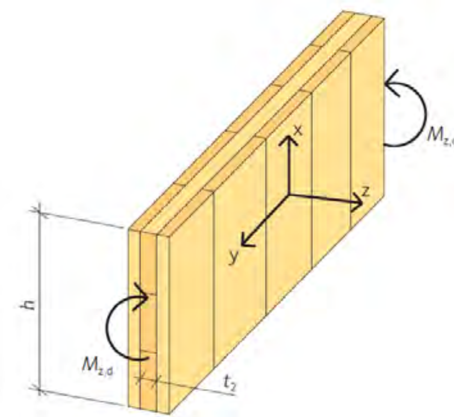
Bending

- Bending edgewise (wall or panel)

$$\sigma_{m,d} = \frac{M_d}{W_{net}} \leq f_{m,d}$$

$$W_{net} = \frac{\sum t_i \cdot h^2}{6}$$





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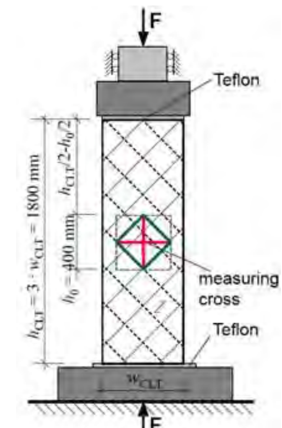
Compression

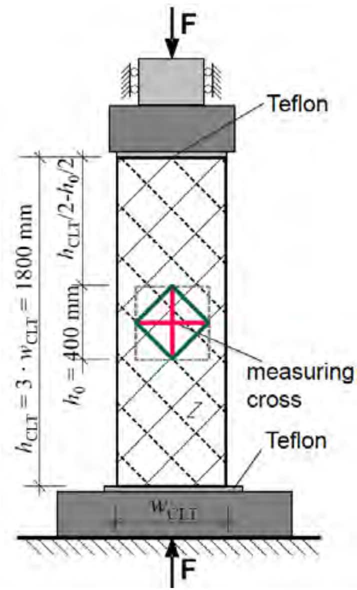
- In plane shear

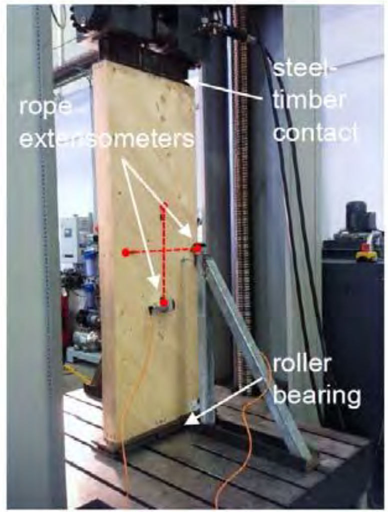
Shear (in-plane)
(Earthquake / Wind)

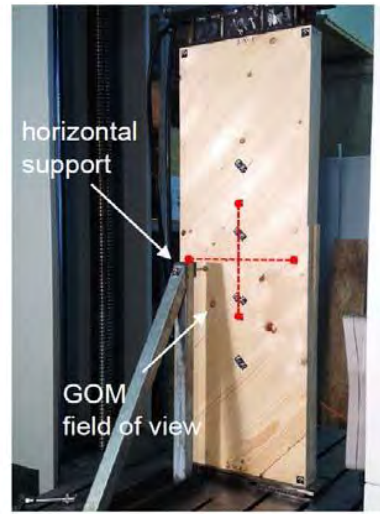


Courtesy of T. Ehrhart

Determination of shear strength in plane







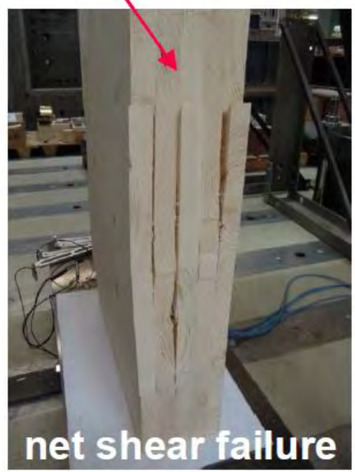
Courtesy of T. Ehrhart

Determination of shear strength in plane

- Results of shear tests depend on
  - Layer thickness, lay-up configuration
  - Number of layers
  - Edge/non-edge bonding and gap width

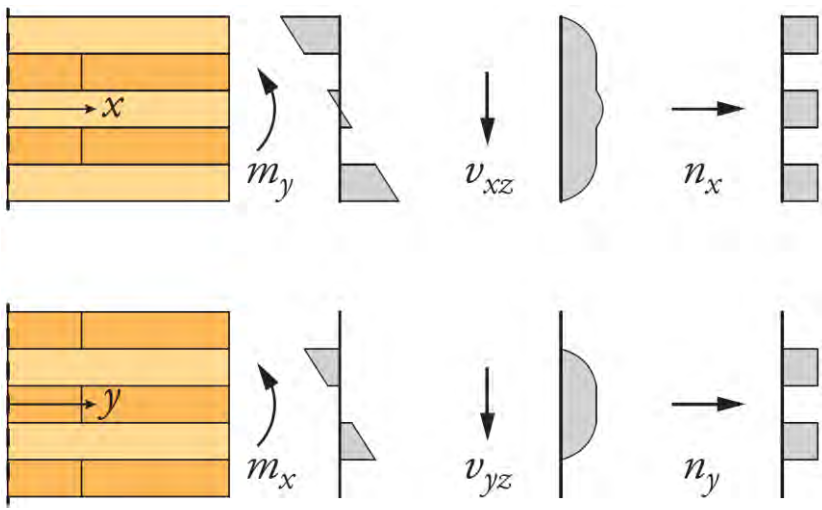
Edge bonded

Non-edge bonded



Courtesy of T. Ehrhart

Summary of stresses in plane



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Strength values of CLT

Table 3.6 Examples of characteristic strength values for CLT panels based on the strength properties of the timber boards. About directions, *see section 3.3.1, page 40.*

Characteristic strength values		CLT panels with only C24 (MPa)	CLT panels with C30 in main direction of load and C14 across main direction of load (MPa)
Bending strength	$f_{m,x,k}$	24	30
	$f_{m,y,k}$	24	14
Tension strength, in plane	$f_{t,0,x,k}$	14.5	19
	$f_{t,0,y,k}$	14.5	7.2
Tension strength, perpendicular to the plane	$f_{t,90,x,k}$	0.4	0.4
	$f_{t,90,y,k}$	0.4	0.4
Compression strength, in plane	$f_{c,0,x,k}$	21	24
	$f_{c,0,y,k}$	21	16
Compression strength, perpendicular to the plane	$f_{c,90,z,k}$	2.5	2.7
Shear strength, longitudinal shear	$f_{v,090,xlay,k}$	4	4
	$f_{v,090,ylay,k}$	4	3
Shear strength, rolling shear	$f_{v,9090,xlay,k}$	1.1 [1)] or 0.7 [2)]	1.1 [1)] or 0.7 [2)]
	$f_{v,9090,ylay,k}$	1.1 [1)] or 0.7 [2)]	1.1 [1)] or 0.7 [2)]

1) Used for CLT panels with edge-glued boards or where the board thickness is less than 45 mm and the width to thickness ratio for the boards is equal to or greater than 4.

2) Used for CLT panels where the boards are not edge-glued and where the width to thickness ratio for the boards is less than 4, or where grooves have been cut into the boards.

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Stiffness values of CLT

Table 3.7 Examples of characteristic stiffness values for CLT panels based on the stiffness properties of the timber boards. About directions, *see section 3.3.1, page 40.*

Characteristic stiffness values		CLT panels with only C24 (MPa)	CLT panels with C30 in main direction of load and C14 across main direction of load (MPa)
Mean value of modulus of elasticity	$E_{0,x,mean}$	11,000	12,000
	$E_{90,x,mean}$	0 [1] or 400 [2]	0 [1] or 400 [2]
	$E_{0,y,mean}$	11,000	7,000
	$E_{90,y,mean}$	0 [1] or 400 [2]	0 [1] or 280 [2]
Fifth percentile value of modulus of elasticity	$E_{0,x,05}$	7,400	8,000
	$E_{0,y,05}$	7,400	4,700
Mean value of modulus of shear	$G_{090,xlay,mean}$	690	750
	$G_{090,ylay,mean}$	690	440
Mean value of modulus of rolling shear	$G_{9090,xlay,mean}$	50	50
	$G_{9090,ylay,mean}$	50	50

[1] Used for CLT panels without edge-glued boards.
[2] May be used for CLT panels with edge-glued boards.

Table 3.8 Density of CLT panels.

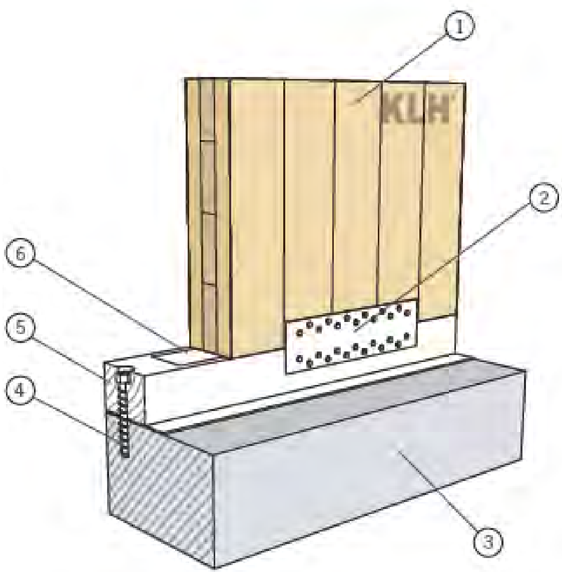
Density		CLT panels with only C24 (kg/m³)	CLT panels with C30 in main direction of load and C14 across main direction of load (kg/m³)
Characteristic value	$\rho_{xlam,k}$	350	approx. 350
Mean value	$\rho_{xlam,mean}$	420	approx. 420

Swedish Wood

Connections in CLT structures

Connections in CLT structures

- typical joint details:
  - Wall-Concrete Connection



1. KLH wall panel according to static requirements
2. E.g. BMF perforated plate for shear connection between KLH wall and sill
3. Concrete component (wall, ceiling, concrete slab)
4. Concrete screws for shear force transmission between sill and concrete
5. Oak or larch sill laid in mortar bed – with the entire surface resting on the base
6. Install joint tape, if necessary

Source: KLH.at

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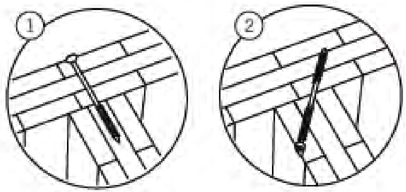
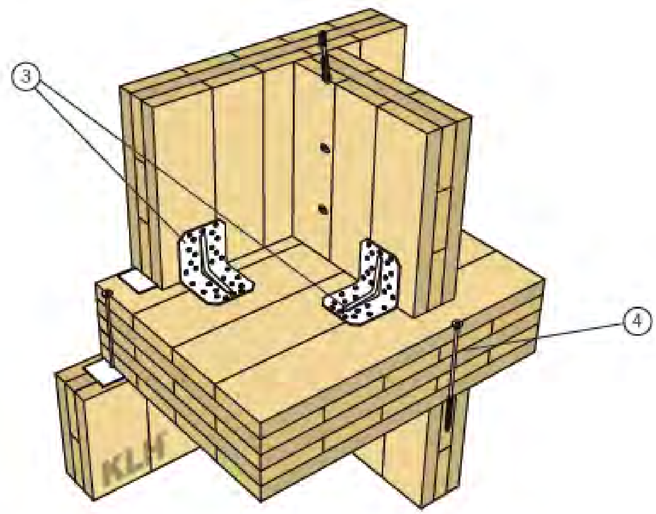
Connections in CLT structures

- typical joint details:
  - Wall-Wall Connection
  - Ceiling-Wall Connection



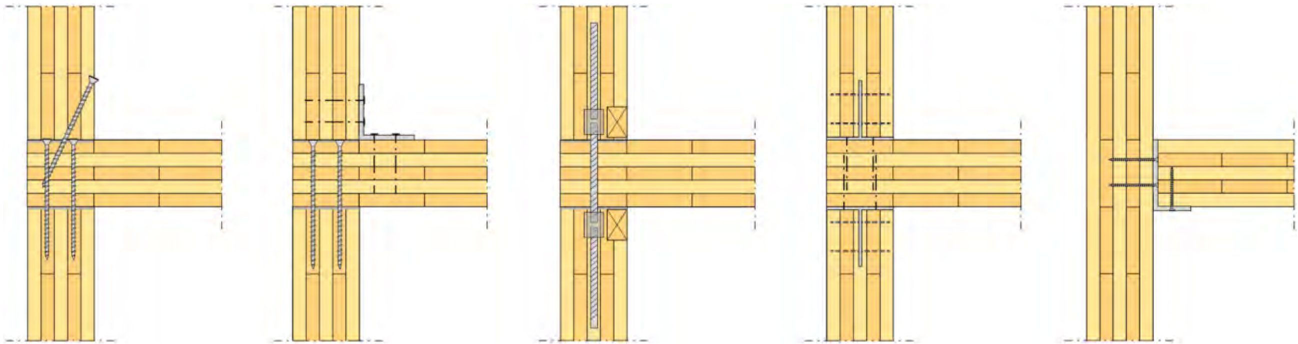
1. Cross wall connection – screw connection from the outside
2. Cross wall connection – screw connection from the inside
3. Shear force transmission along the joint and tension anchorage of walls – e.g. BMF angle bracket – type, distance according to static requirements
4. Screw connection of ceiling with walls according to static requirements



Source: KLH.at

Connections in CLT structures

- typical joint details:
    - Wall-Ceiling-Wall Connection



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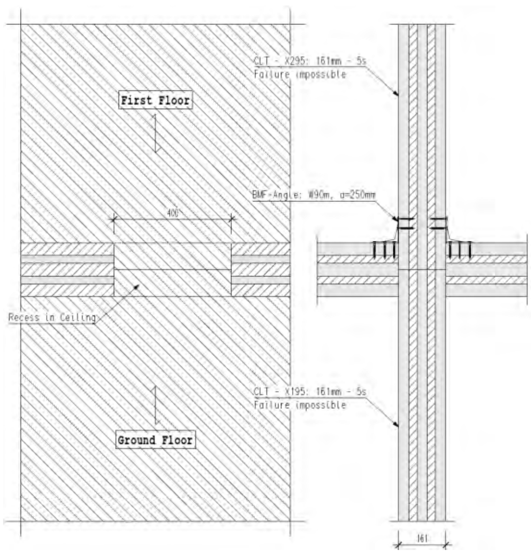
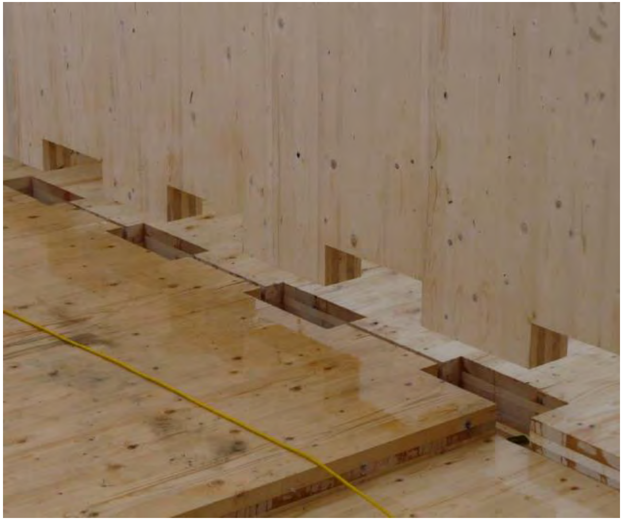
Connections in CLT structures

- Special connection in CLT

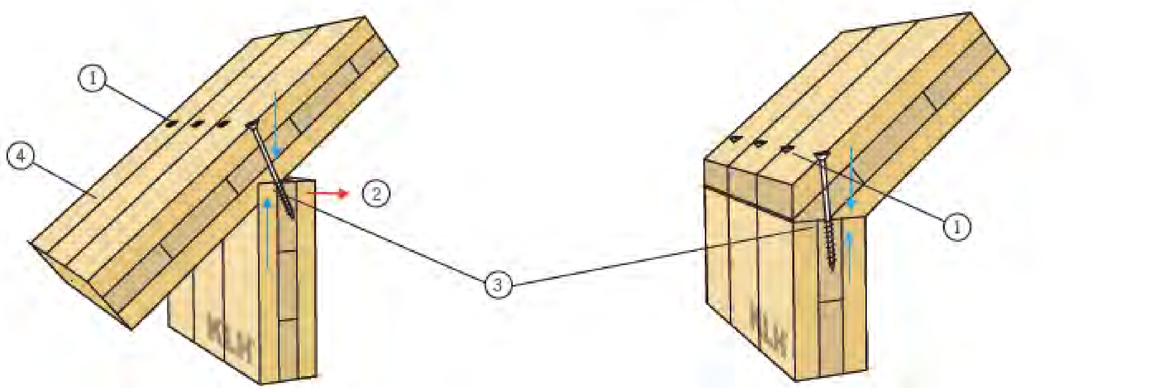




Source: Pirmin Jung

Connections in CLT structures

- typical joint details:
  - eaves design

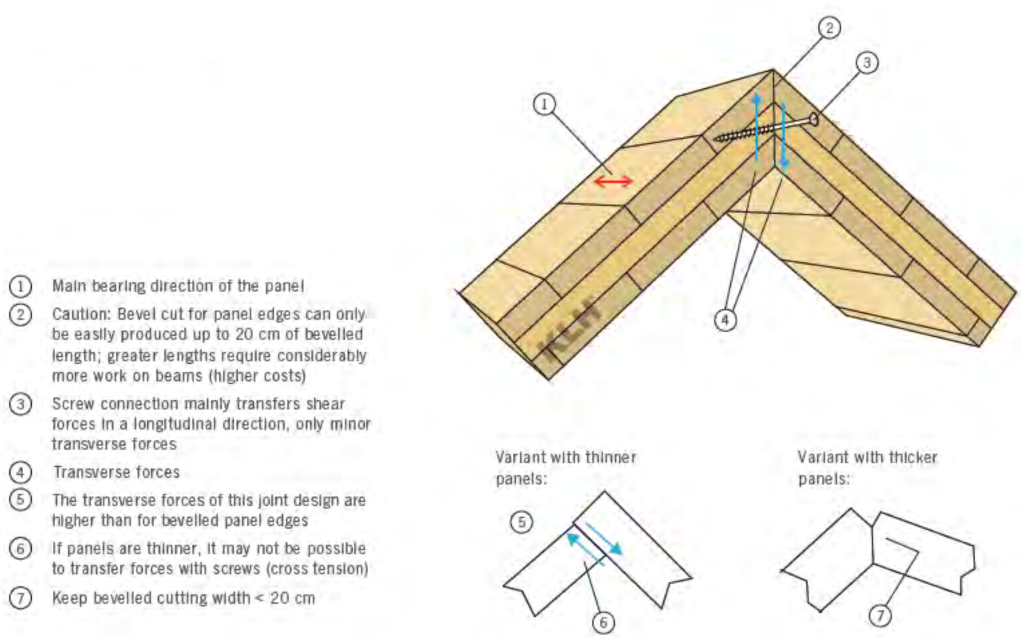


1. Screws absorb shear forces parallel to bearing or wind suction forces
2. Use fully threaded screws for high forces towards the inside
3. The bearing surface must be set at a normal angle in the direction of the main loads
4. If the main bearing direction of the panel is parallel to the bearing, any lateral projections are only possible subject to cross-bearing capacities (middle layers) – static verification required

Source: KLH.at

Connections in CLT structures

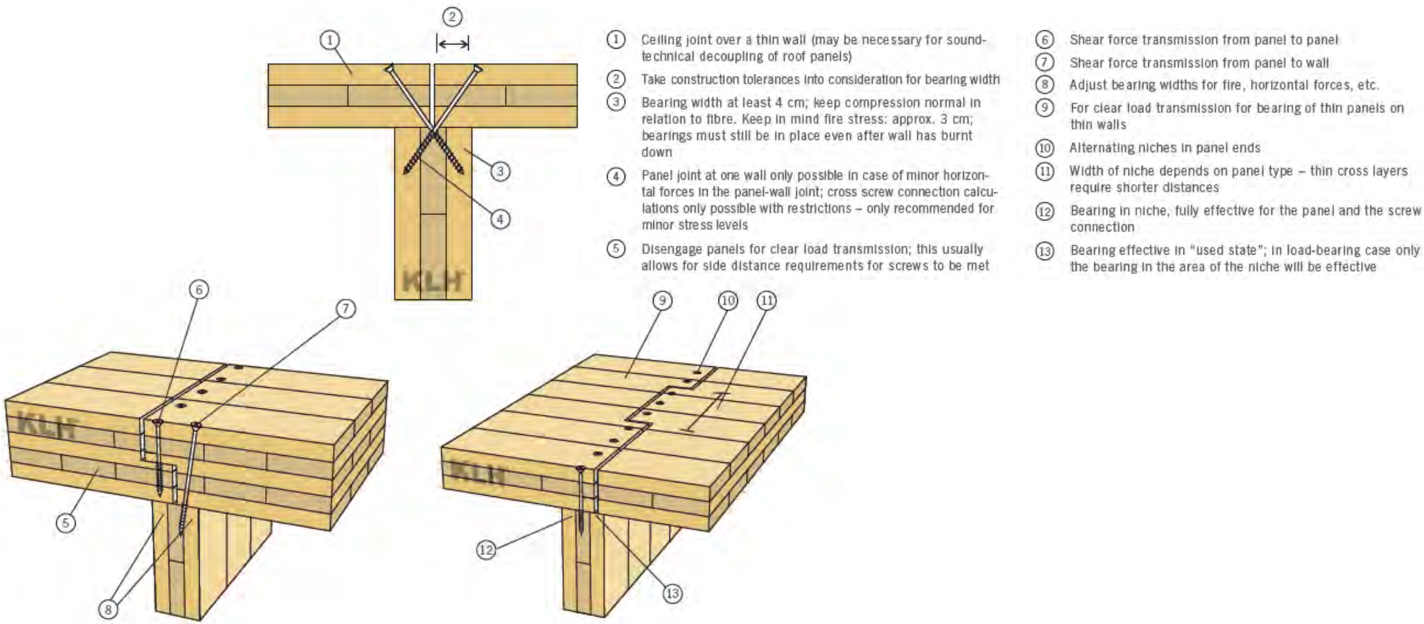
- typical joint details:
    - Roof ridge design



Source: KLH.at

Connections in CLT structures

- typical joint details:
  - Floors

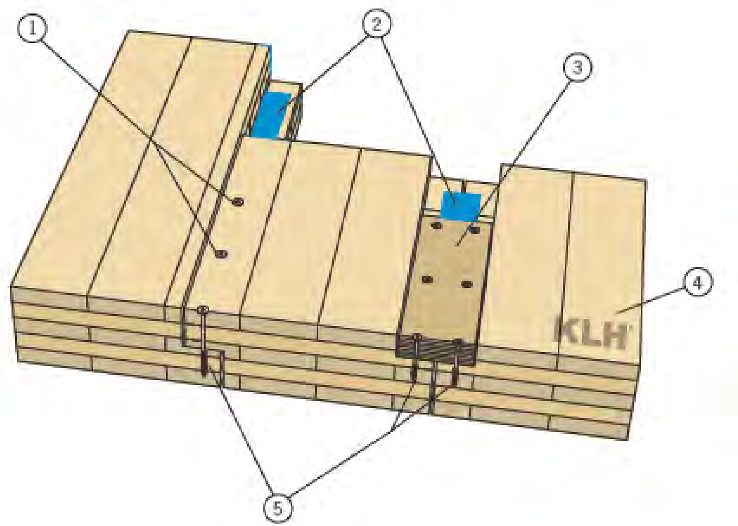


Source: KLH.at

CLT Systems

- typical joint details:
  - hinged connection between floor panels

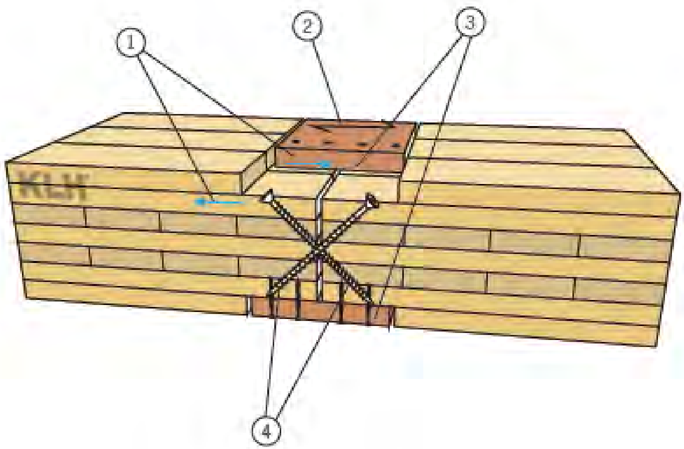
1. Connection for shear transmission in the direction of the joint
2. Install joint tape, if air tightness is required (e.g. fire, smoke)
3. Plywood strip
4. E.g. KLH ceiling panel
5. Type, diameter and distance of screw connection according to static requirements



Source: KLH.at

Connections in CLT structures

- typical joint details:
    - moment rigid connection between floor panels

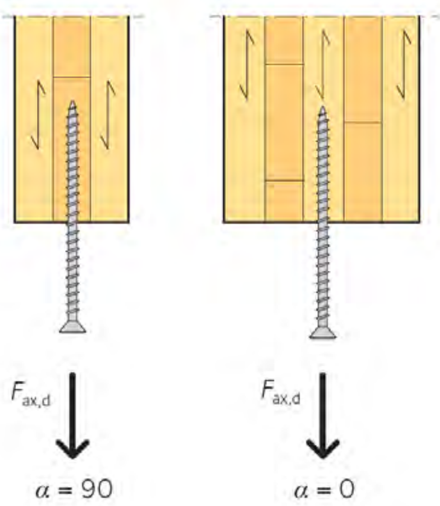


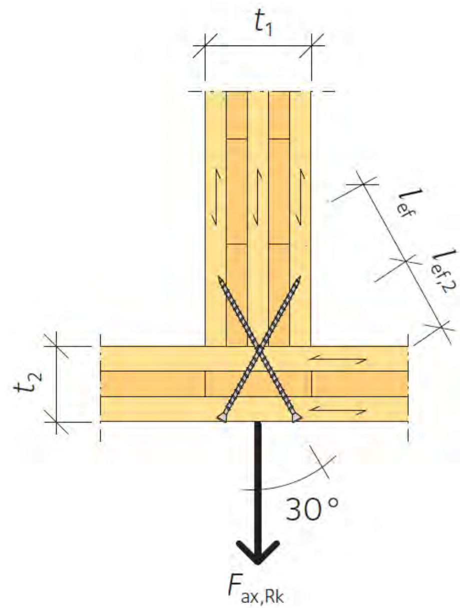
1. Forces transferable by way of the connection
2. Caution: Full 100% transmission force not possible – rather 30 to 50%, depending on panel type. Therefore, its use is only recommended where absolutely necessary. In addition, this design is comparatively expensive, the gluing must be done in a controlled environment (climate, surfaces, etc.).
3. Glue on connection straps (screw-pressure bonding) or only mechanical connection (nails, screws); materials: veneer laminated timber or 3s panels or according to static requirements
4. Transverse force and tensile force transmission with fully threaded screws (screw depiction only symbolic; crossed screws must be set at a certain distance to each other)

Source: KLH.at

Connections in CLT structures

- Consider the different possible directions to the grain!





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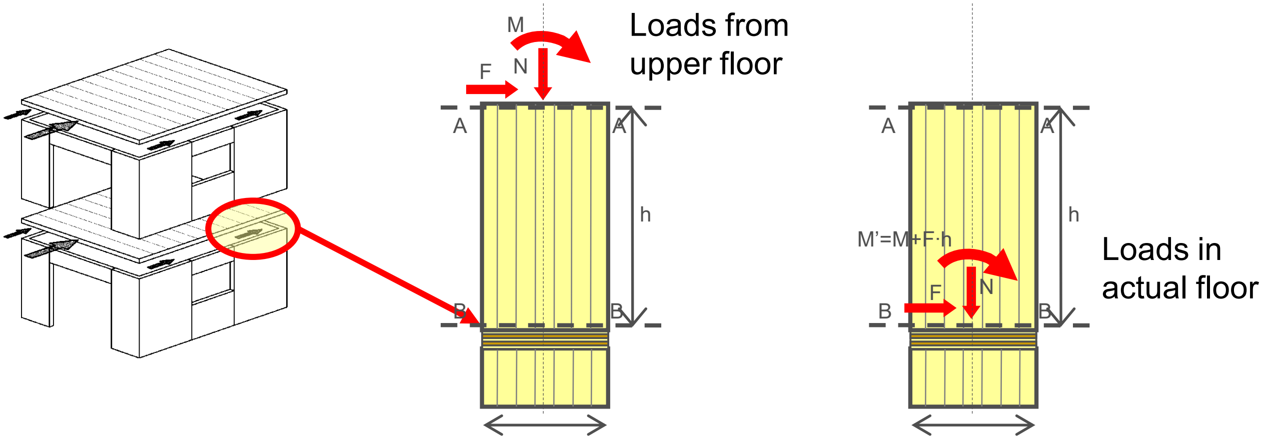
Examples of connections in structures

Connections in structures

- Forces in the wall



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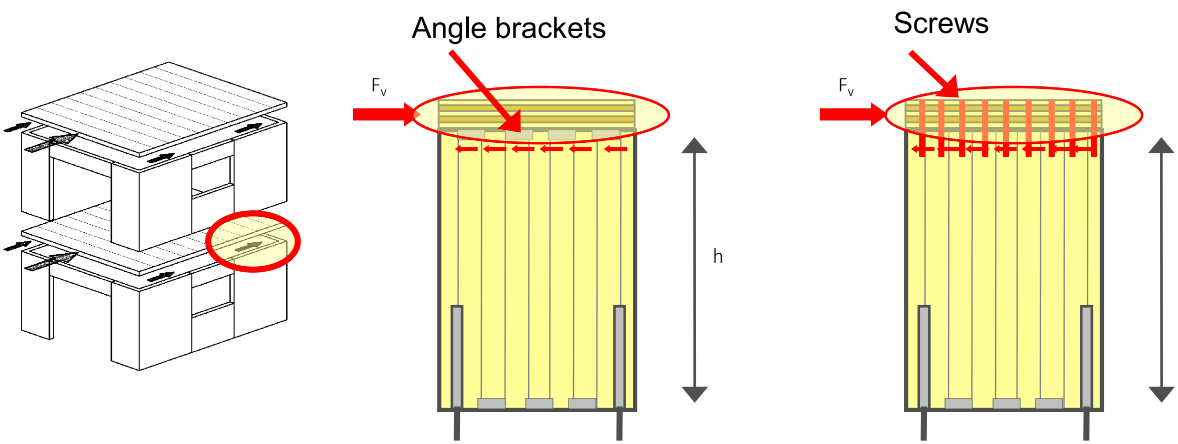
Connections in structures

- Introduction of forces into the wall



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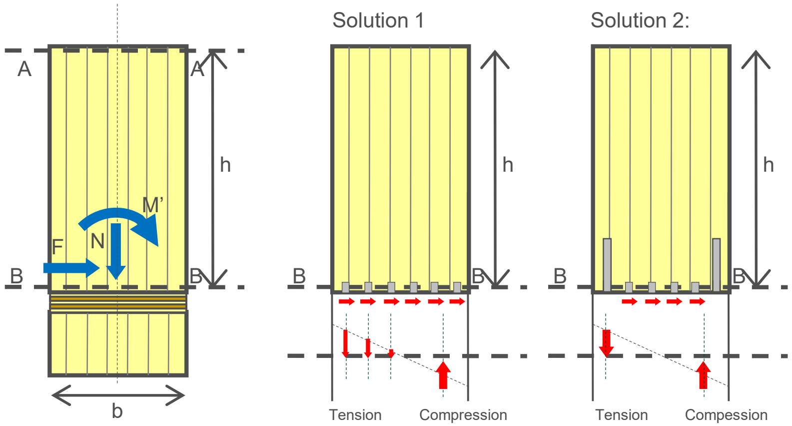
Connections in structures

- Anchorage of forces



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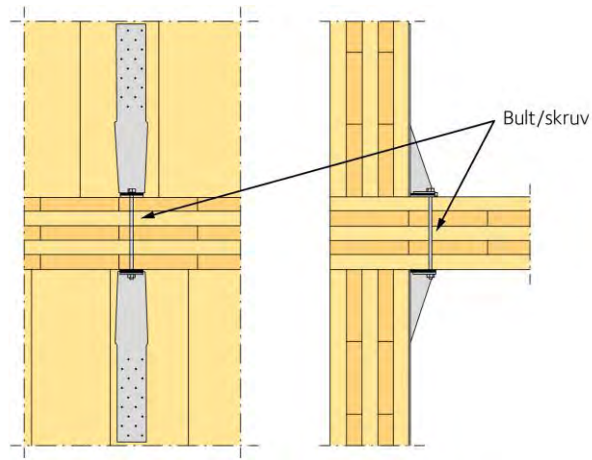
Connections in structures

- Anchorage of forces
  - Examples



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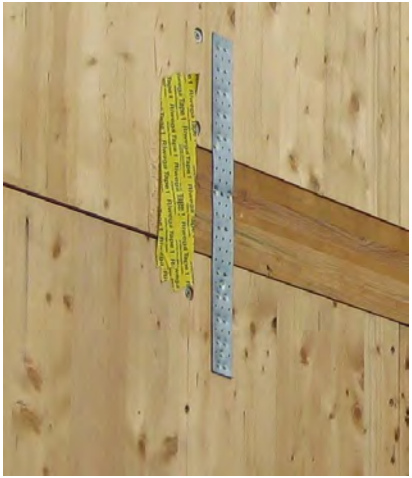
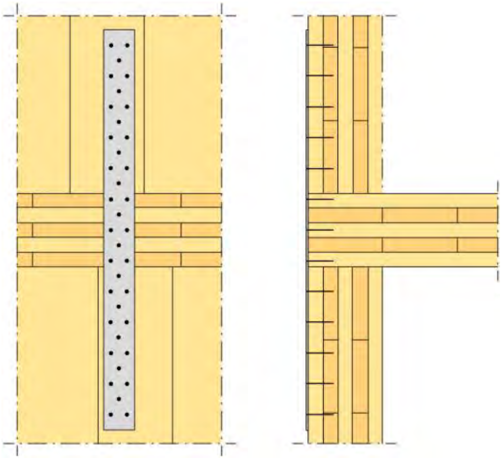
Connections in structures

- Anchorage of forces
  - Examples





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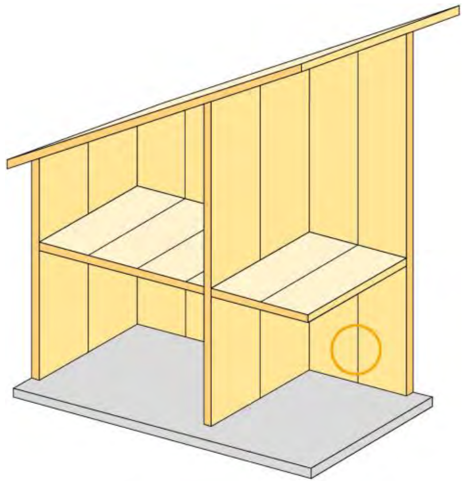
Connections in structures

- Wall-Wall



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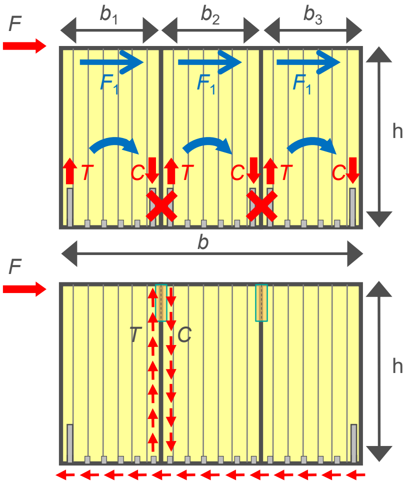
Connections in structures

- Wall-Wall



$T = C = M_i/b_i$

$T = C = F_i \cdot h/b_i$

$v = T/h = F_i \cdot h/b_i/h$

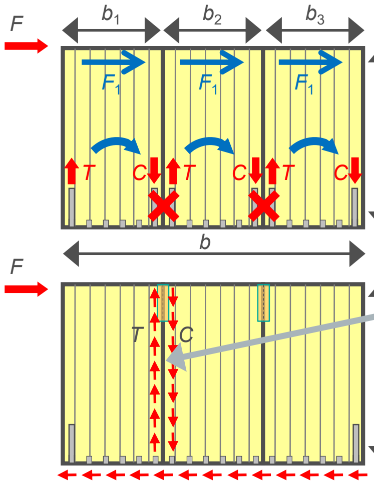
$v = T/h = F_i/b_i$

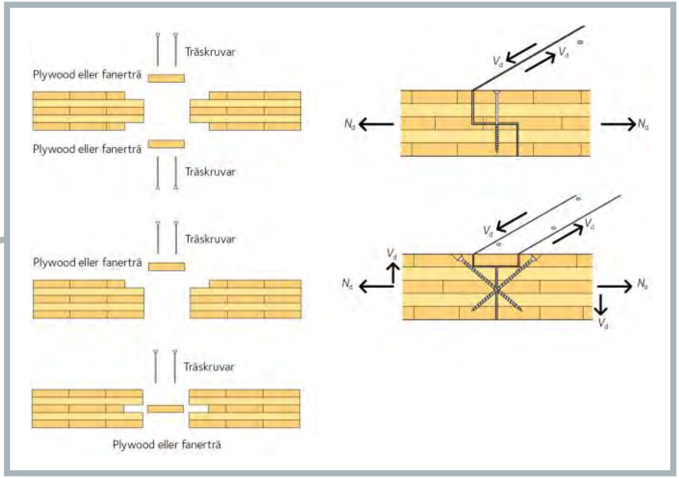
$v = T/h = F/b$

Swedish Wood

Connections in structures

- Wall-Wall





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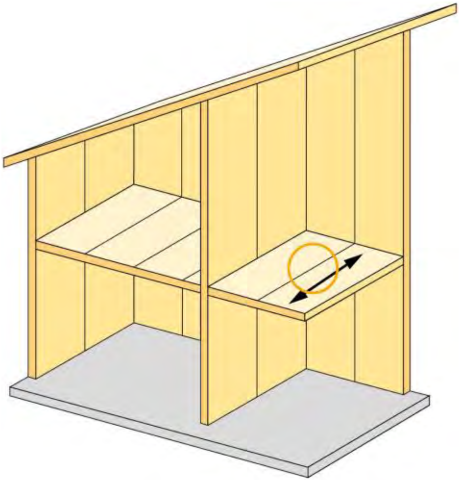
Connections in structures

- Floor-floor



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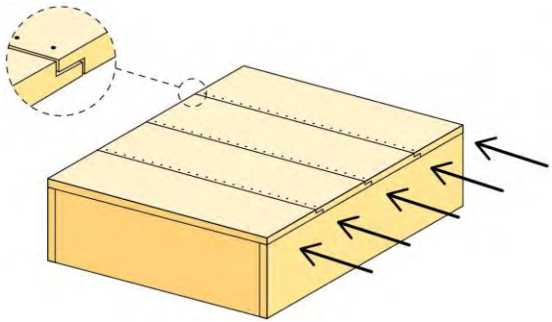
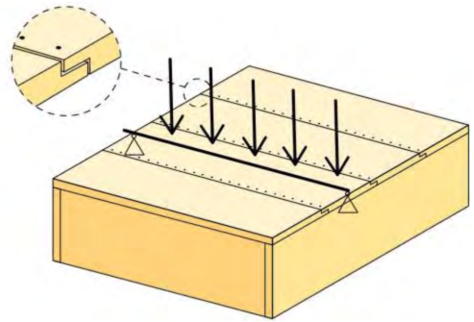
Connections in structures

- Floor-floor





- Diaphragm action
- Prevent unequal deformation

Swedish Wood

Examples of structures

Via Cenni, Milano

http://ircc.azurewebsites.net/new%20page/Workshops/Documents/Austria2013_05Bernascon_workshops.pdf

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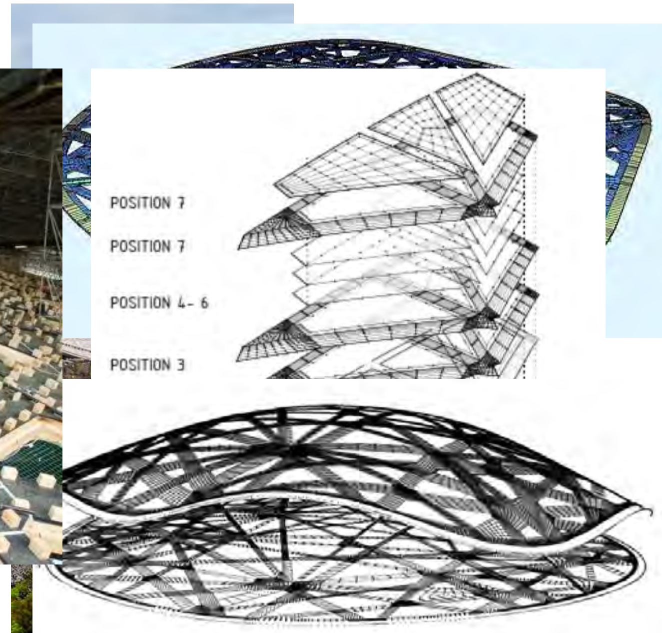
Elephants Park, Zoo, Zurich CH

Elephants Park, Zoo, Zurich CH

- CLT Shell Structure

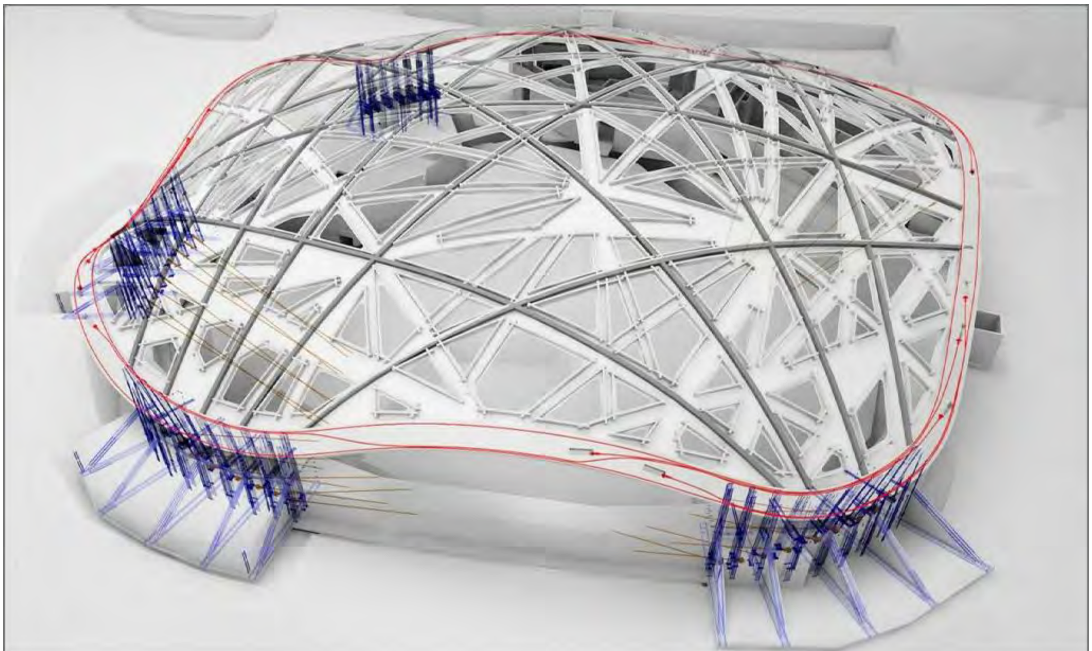


Source: Sofistik, Holzbau Schweiz

Source: Walt+Galmarini AG

Elephants Park, Zoo, Zurich CH

- Model



Source: Walt+Galmarini AG

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- Scaffolding

Source: Walt+Galmarini AG

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- Assembly

Source: Walt+Galmarini AG

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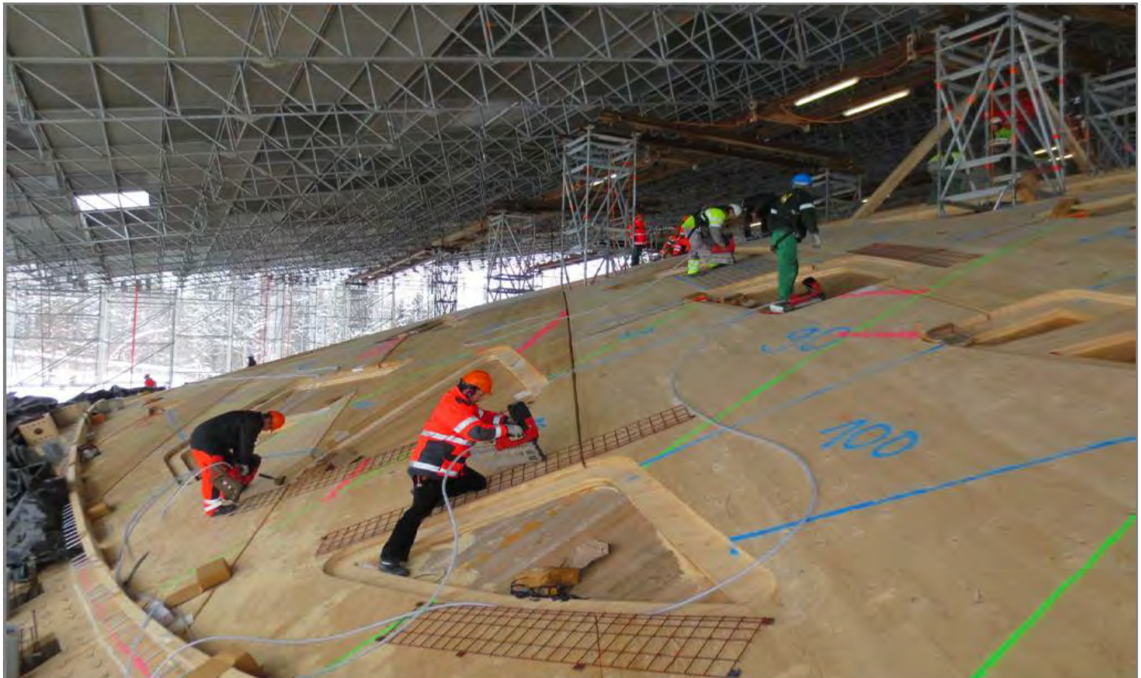
- Assembly



Source: Walt+Galmarini AG

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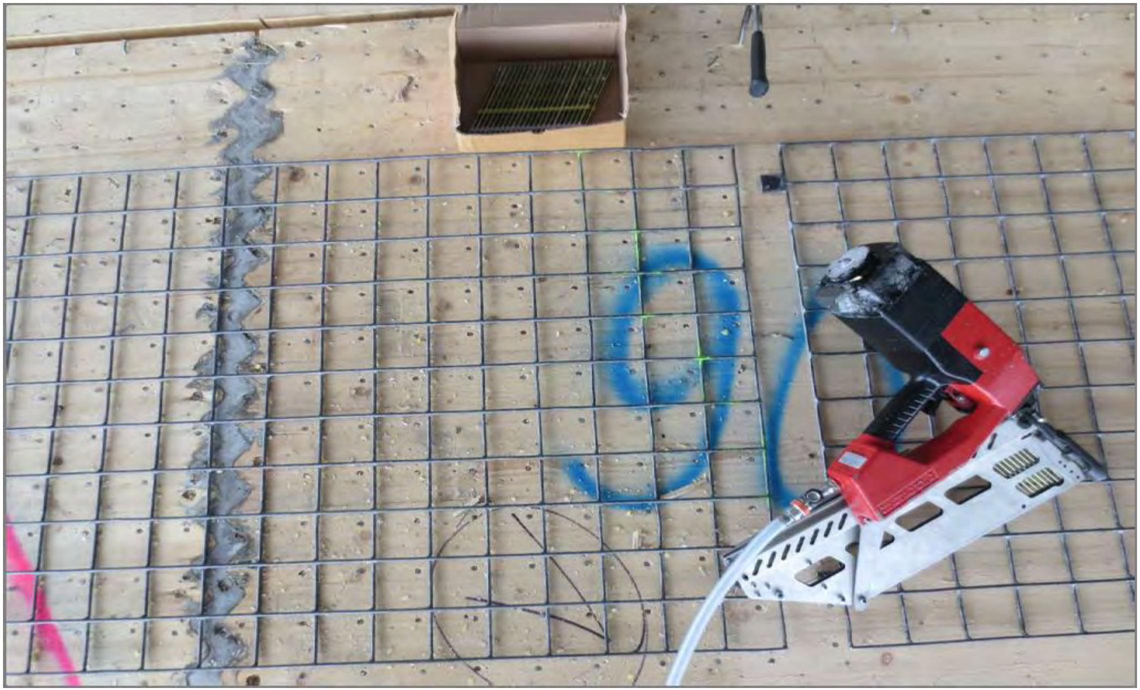
- Connection of layers by nails



Source: Walt+Galmarini AG

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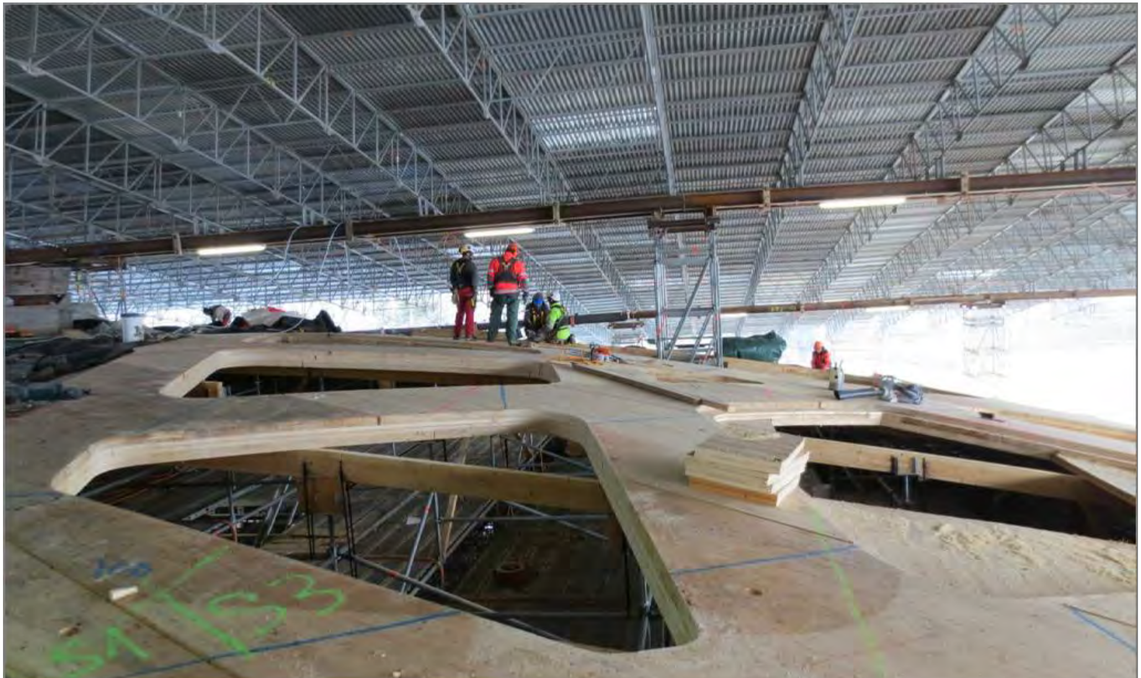
- Cutting of windows



Source: Walt+Galmarini AG

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- Interior view of structure

Source: Walt+Galmarini AG

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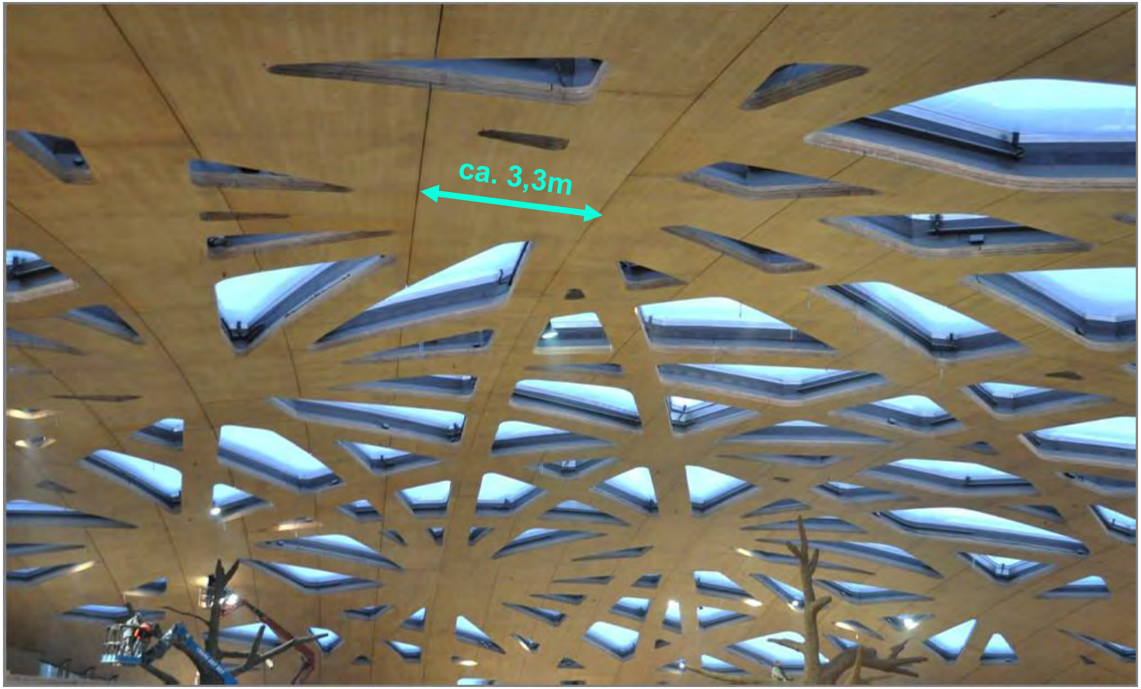

Source: Walt+Galmarini AG

Granat-chapel Penkenjoch, Zillertal, AT

Architect: Mario Botta, Mendrisio, CH

Engineer: Merz Kley Partner, Dornbirn, AT

Source: Merz Kley Partner

Source: Merz Kley Partner

Source: Merz Kley Partner

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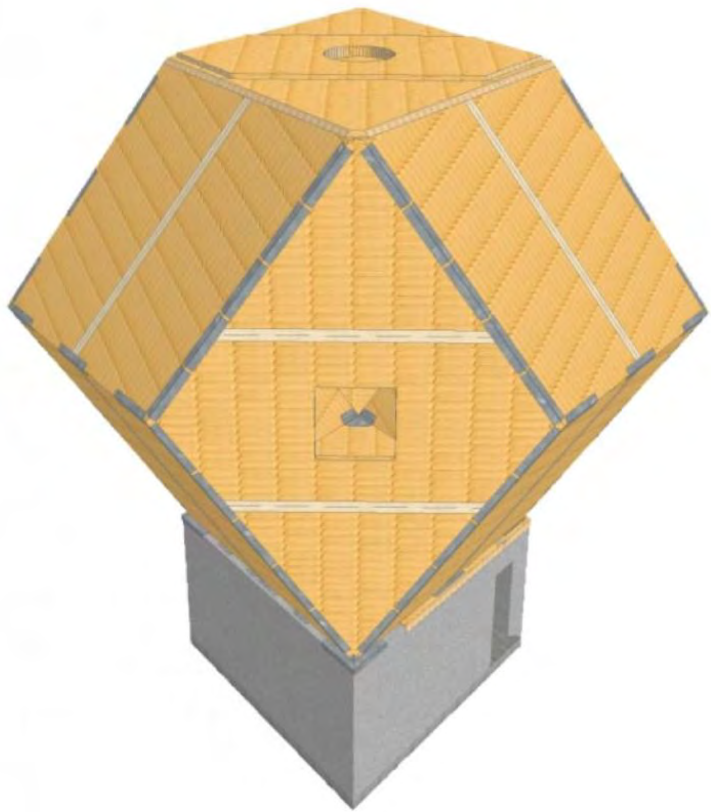

Source: Merz Kley Partner

Source: Merz Kley Partner

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