COST Action FP1004

Final Meeting

15 April – 17 April 2015 – Lisbon, Portugal

Cross Laminated Timber (CLT) – Overview and Development

R Brandner [1], G Flatscher [1], A Ringhofer [1], G Schickhofer [1], A Thiel [2]

[1] Graz University of Technology | [2] holz.bau forschungs gmbh

Content

- Introduction
- Production & Technology
- Characteristic Properties
- Design
- Connections
- Conclusions

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Introduction

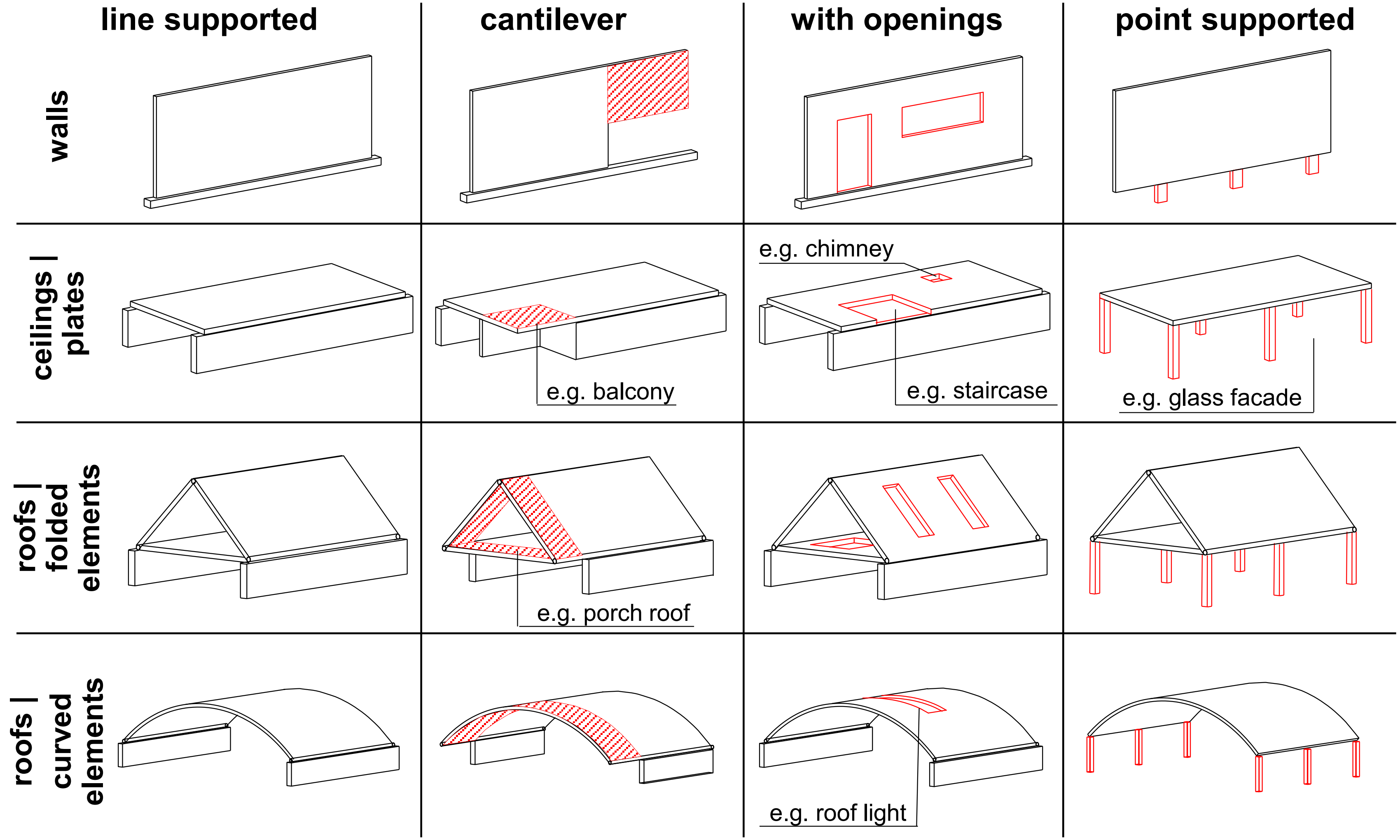
Cross Laminated Timber (CLT) …

- **plate-like engineering timber product**, composed of an uneven number of crosswise layers → locking effect

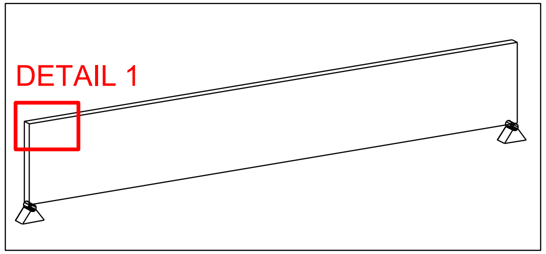
- **opens new dimensions in (timber) engineering** (e.g. monolithic buildings)
  - high degree and accuracy in pre-fabrication
  - dry and clean construction sites
  - short erection times

➔ **SOLID TIMBER CONSTRUCTION TECHNIQUE IN CLT!**

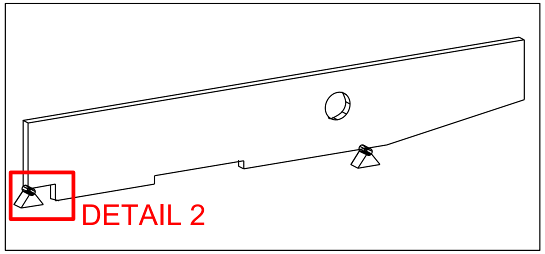
Introduction – CLT as 2D element



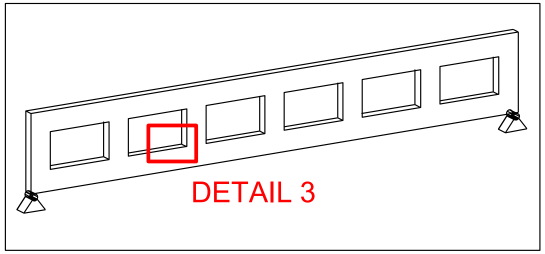
Introduction – CLT as 1D element



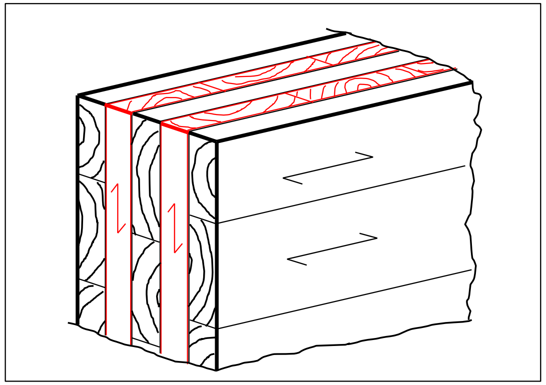
beam
without openings



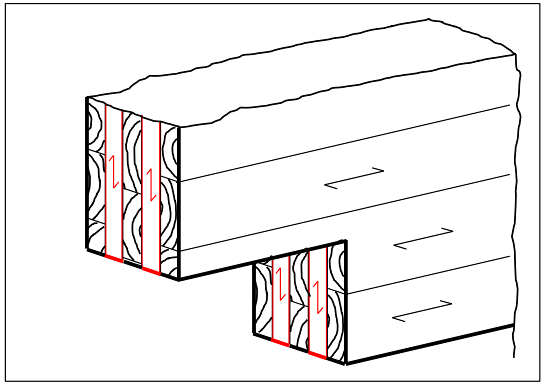
tapered beam | notched support | openings



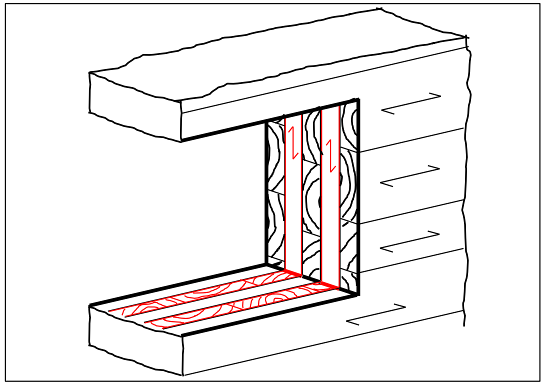
Vierendeel system



detail 1:
5-layered beam element



detail 2:
notched support



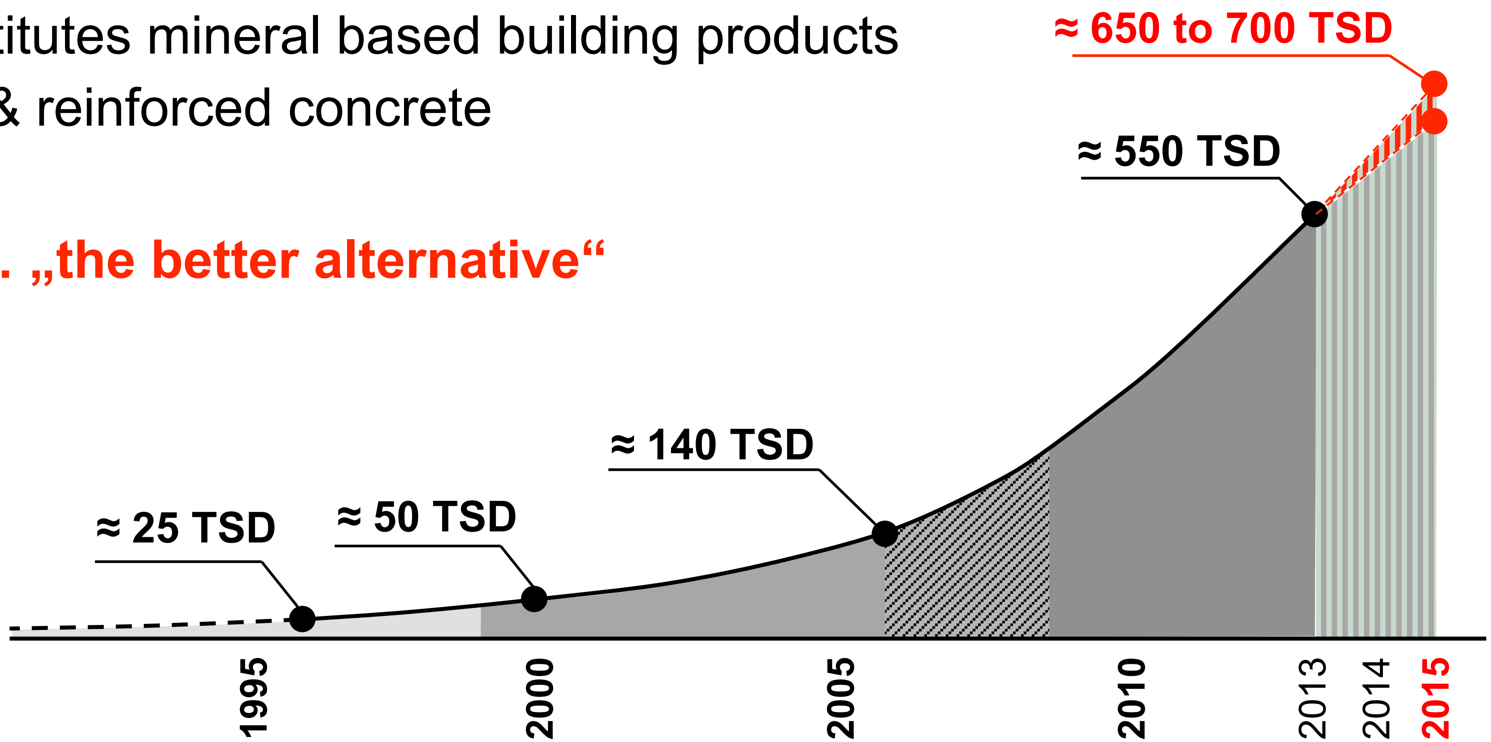
detail 3:
opening

Introduction

Shifting Market Shares → ~~RFC~~ | CLT

- CLT extends, not competes timber engineering
- CLT substitutes mineral based building products masonry & reinforced concrete

➔ CLT, … „the better alternative“



Introduction

Worldwide CLT Activities

- currently > 90 % volume produced in Central Europe
- standards & new production sites in US, CA, JP (‘CLT_roadmap’) expected
- long-time expectation: relevance of CLT comparable to GLT

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Production & Technology – Types of CLT

FLEXIBLE composites

- annular ringed shank nails
- metal brackets, screws, …
- hardwood dowels, screws

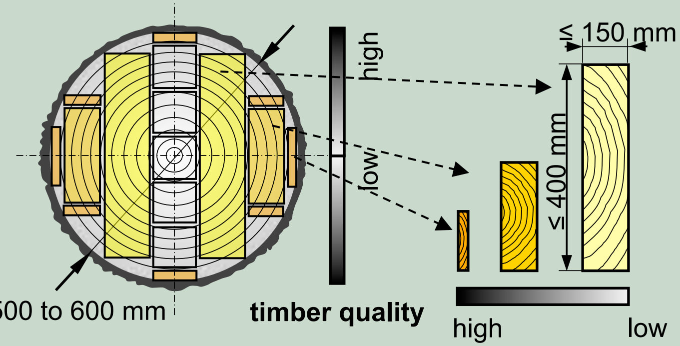
RIGID composites by surface bonding

- hydraulic / pneumatic / vacuum press facilities (→ pressure "global")
- screws, brackets or nails (→ pressure „local")

FOCUS

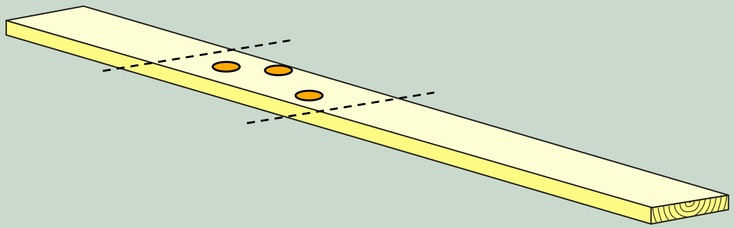
PRODUCTION: overview | STEPs I/II

STEP I
log



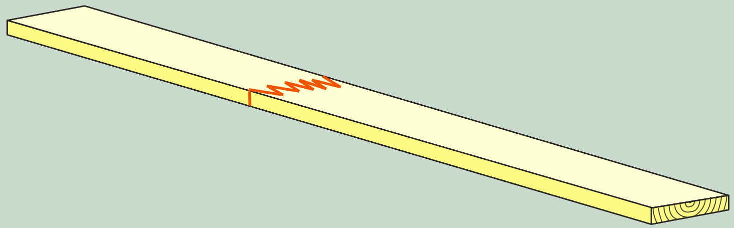
breakdown

STEP II
board



classification / grading
trimming

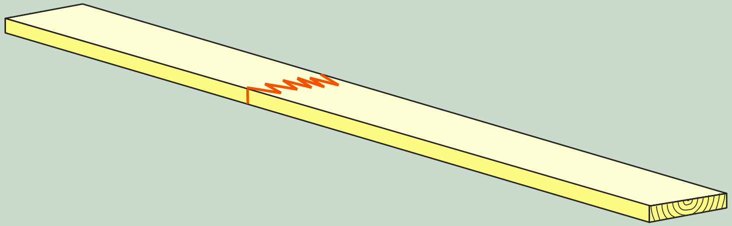
STEP III
finger jointed
lamella



finger jointing

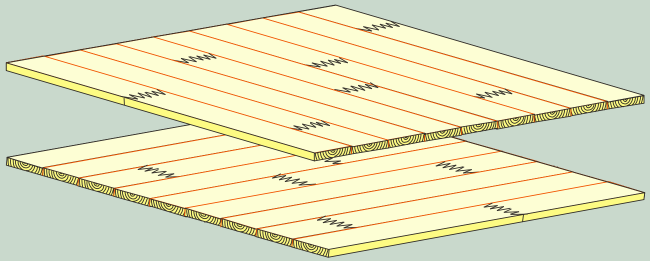
Production & Technology
PRODUCTION: overview | STEPs II/II

STEP III
finger jointed lamella



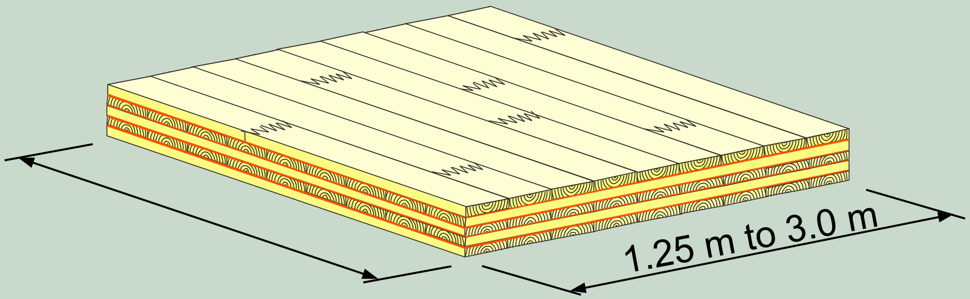
finger jointing

intermediate STEP
single-layer panel



edge bonding

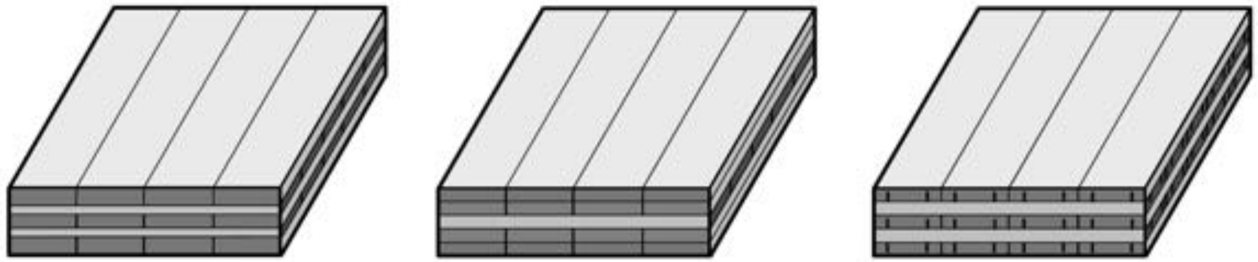
STEP IV
cross laminated timber (CLT)



surface bonding

Production & Technology
PRODUCTION: base material & grading requ.

- **strength grading acc. tensile properties recommended!**
- t_B = 20, 30, 40 mm | $w_{B,ref}$ = 150 mm | w_B / t_B ≥ 4 | u = 12±2 %
- primary softwoods, **hardwoods & combinations can be advantageous!**
- **laminar EWP for single layers possible**



➔ mechanical properties of each layer shall be defined by the lowest strength class of the used base material!

PRODUCTION: gaps within layers

Gaps widths between boards …

- currently **top layers ≤ 2(3) mm**; **core layers ≤ 4(6) mm**
- some approvals allow gaps ≤ 10 mm!

➔ **gaps negatively influence …**

- **building physics** (e.g. fire design, airborne sound, air tightness)
- **joining technique**, i.e. pin-shaped fasteners
- **appearance quality**

➔ **AIM: minimizing gaps!**

➔ **CLT of single layer panels may be (temporarily) advantageous!**

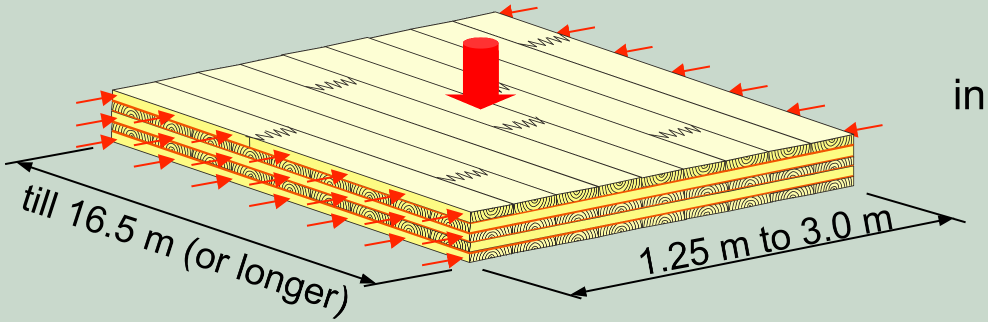
Production & Technology
PRODUCTION: surface bonding

continuously by press facilities

- hydraulic (pneumatic) press (0.10 to 1.00) N/mm²
- vacuum press (0.05 to 0.10) N/mm²

discontinuously by pin-shaped fasteners

- pressing with screws, nails or brackets (0.01 to 0.20) N/mm²

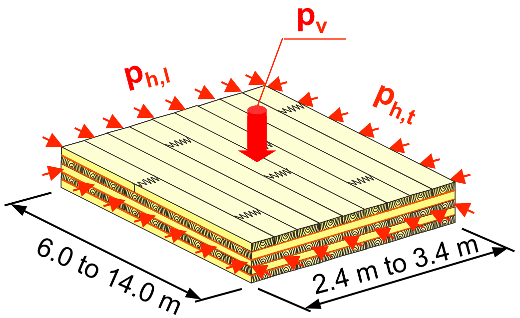


with / without transverse pressure

in and / or across the direction of production

Production & Technology
PRODUCTION: hydraulic press facilities

		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		continuous	discontinuous | high frequ.
bonding pressure	vertical, $\mathbf{p_v}$	(**0.4 to 0.6** (0.8)) N/mm²	≤ **1.0** N/mm²
	horiz. transv., $\mathbf{p_{h,t}}$	10 kN/m	available
	horiz. long., $\mathbf{p_{h,l}}$	45 kN	available



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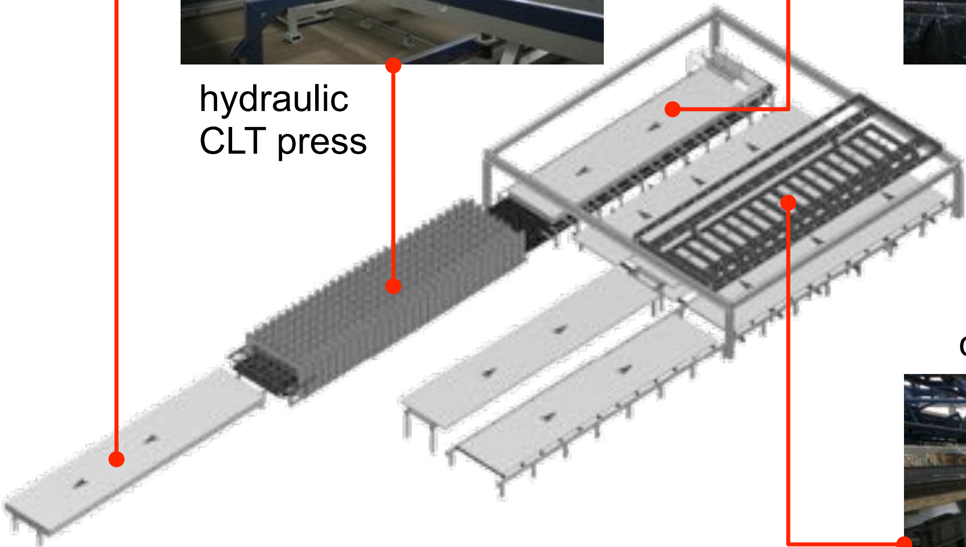
© Kallesoe Maschinery A/S

Production & Technology
PRODUCTION: automatic production line (MINDA)

CLT element ready for
cutting and joining

hydraulic
CLT press

adhesive application
next layer stand-by



cross layers
composing & compressing

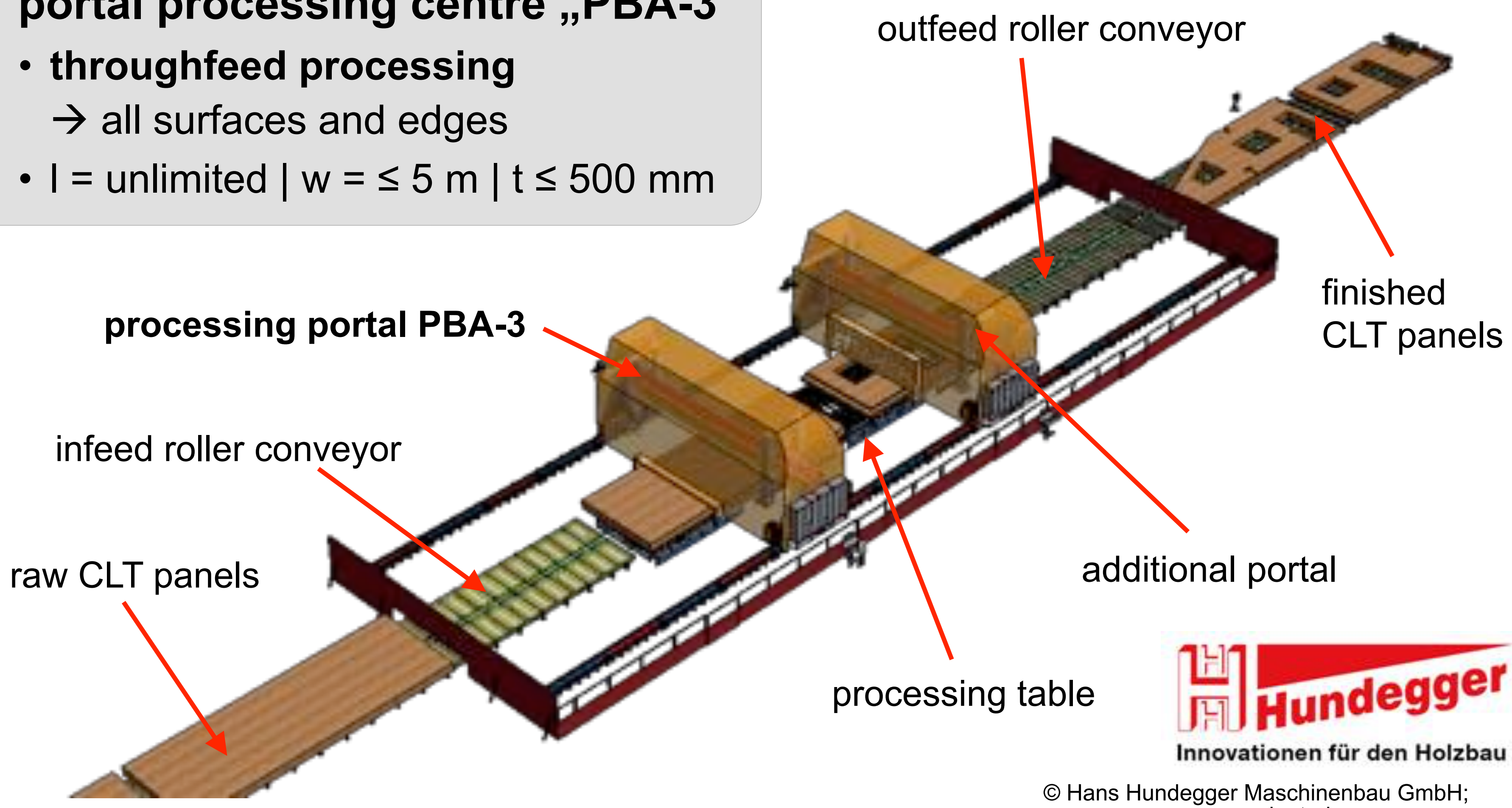
MINDA INDUSTRIEANLAGEN

- CLT of single lamellas
- ≤ 14 press cycles / shift; 1K-PUR (Purbond)
- ≈ 20 TSD m³ / shift / year

CUSTOMIZING: CNC cutting | joining | milling

portal processing centre „PBA-3“

- **throughfeed processing**
  → all surfaces and edges
- l = unlimited | w = ≤ 5 m | t ≤ 500 mm



Production & Technology
Transport & Assembling

storage (production site)

charging and transport

discharging (building site)

assembling of roof elements

assembling of ceiling elements

assembling of wall elements

Content

- Introduction
- Production & Technology
- **Characteristic Properties**
- Design
- Connections
- Conclusions

Characteristic Properties

Proposed Strength Values

base material	T14	
CV [ft,0,l]	25 % ± 5 %	35 % ± 5 %
	CLT strength class	
property	**CL 24h**	**CL 28h**
$f_{m,CLT,k}$	24	28
$f_{t,0,CLT,net,k}$	16	18
$f_{t,90,CLT,k}$	0.5	
$f_{c,0,CLT,net,k}$	24	28
$f_{c,90,CLT,k}$	3.0	
$f_{v,CLT,IP,k}$	5.5	
$f_{T,node,k}$	2.5	
$f_{v,CLT,OP,k}$	3.5	
$f_{r,CLT,k} – w_B/t_B \geq 4{:}1$	1.25	
$f_{r,CLT,k} – w_B/t_B < 4{:}1$	0.70	

... research work is needed

Characteristic Properties

Proposed Stiffness Values

base material	T14	
CV [ft,0,l]	25 % ± 5 %	35 % ± 5 %
	CLT strength class	
property	**CL 24h**	**CL 28h**
$E_{0,CLT,mean}$	11,000	
$E_{0,CLT,05}$	9,167	
$E_{90,CLT,mean}$	300	
$E_{90,CLT,05}$	250	
$E_{c,90,CLT,mean}$	400	
$E_{c,90,CLT,05}$	330	
$G_{CLT,mean}$	650	
$G_{CLT,05}$	540	
$G_{r,CLT,mean}$	100	
$G_{r,CLT,05}$	83	

Characteristic Properties

Selected Topics | Latest Findings

base material	T14	
CV [ft,0,l]	25 % ± 5 %	35 % ± 5 %
	CLT strength class	
property	**CL 24h**	**CL 28h**
$f_{m,CLT,k}$	24	28
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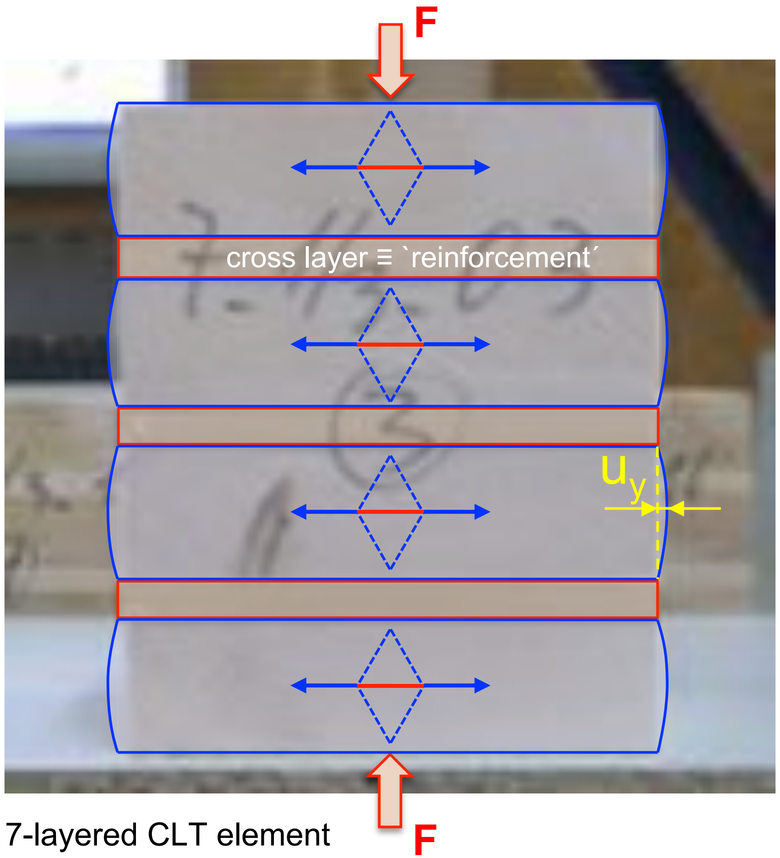
$f_{c,90,CLT,k}$	3.0	
$f_{v,CLT,IP,k}$	5.5	
$f_{T,node,k}$	2.5	
$f_{v,CLT,OP,k}$	3.5	
$f_{r,CLT,k\,-}\ b/t \geq 4{:}1$	1.25	
$f_{r,CLT,k\,-}\ b/t < 4{:}1$	0.70	

... research work is needed

Characteristic Properties

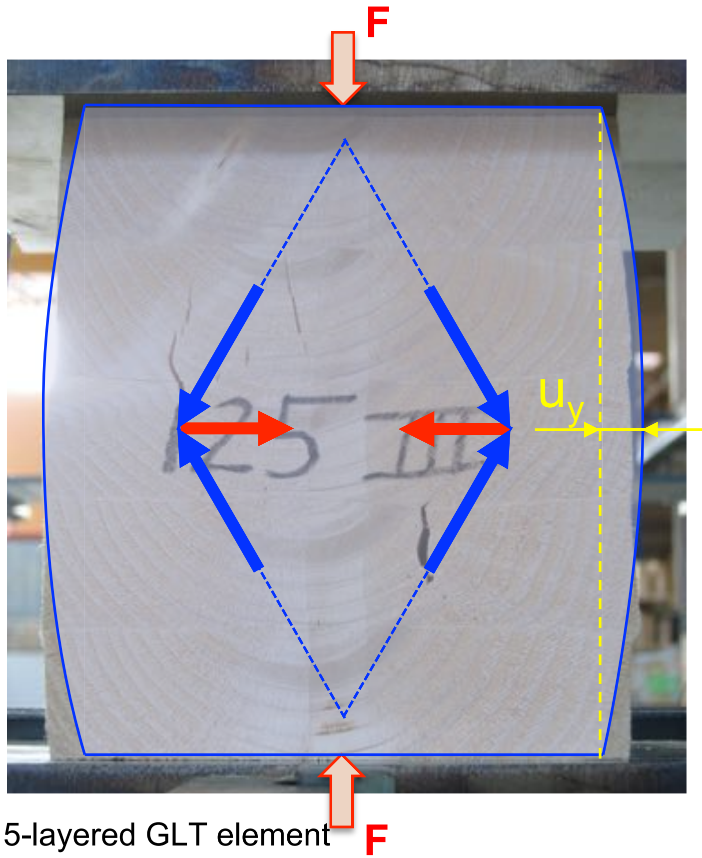
Compression Perp. to Grain | General

CLT cubes
failure mode:
deformation at defined failure stage



7-layered CLT element

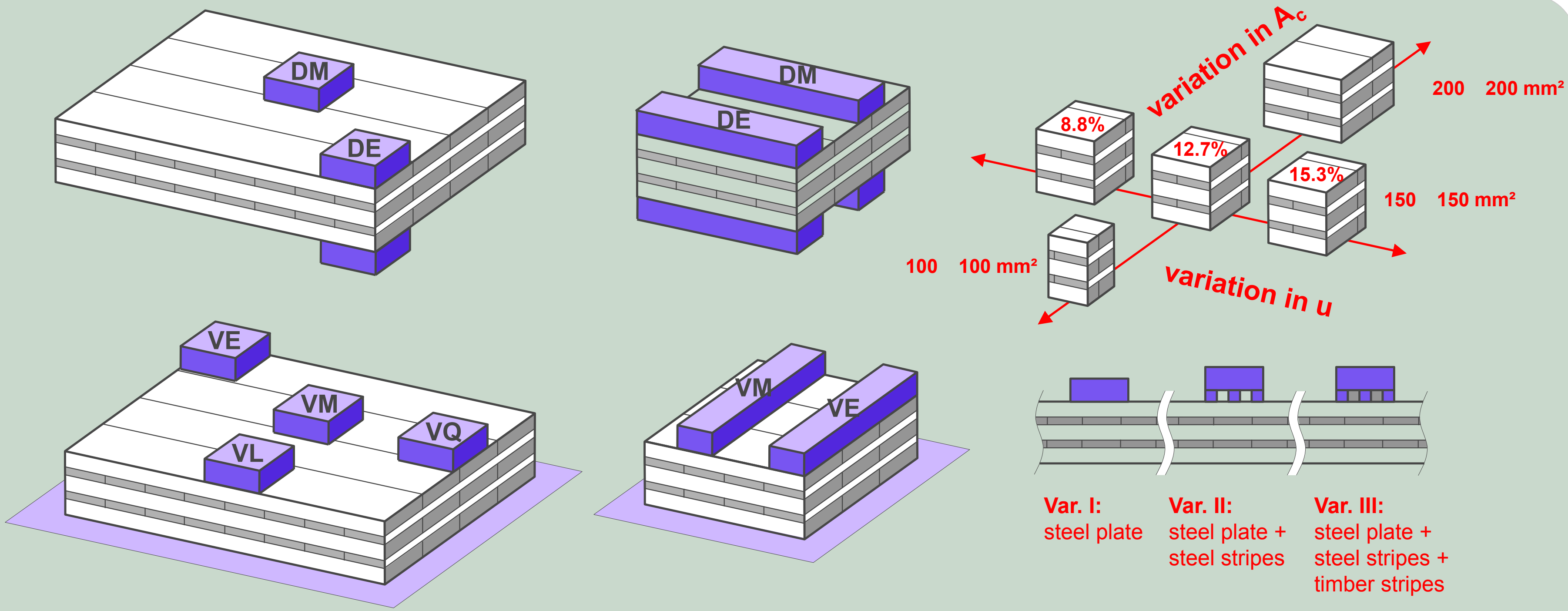
GLT cubes
failure mode:
e.g. tension perp. to grain



5-layered GLT element

Characteristic Properties

Compression Perp. to Grain | MA Ciampitti (2013)



Brandner R., Schickhofer G. (2014) *Properties of cross laminated timber (CLT) in compression perpendicular to grain*. paper 47-12-5 presented at the first INTER conference at University of Bath, UK.

PROPOSED specimen: 5 layers, t_l = 30 mm, A_c = 150² mm², t_{CLT} = 150 mm

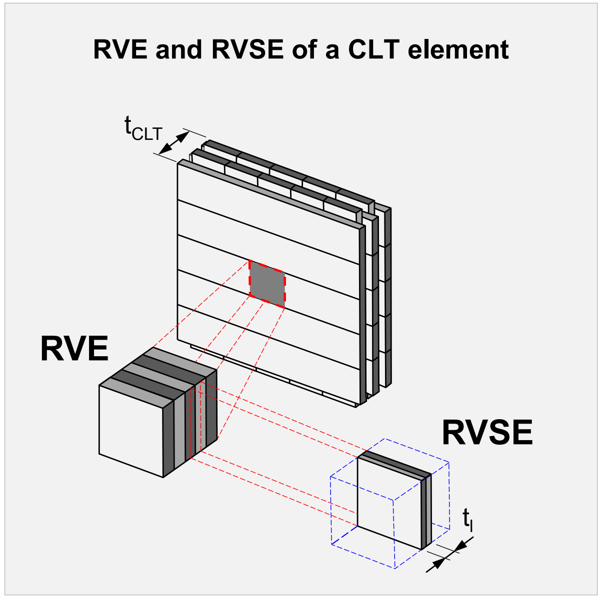
PROPOSED basic values: $f_{c,90,12,k}$ = 3.0 N/mm² | $E_{c,90,12,mean}$ = 400 N/mm²

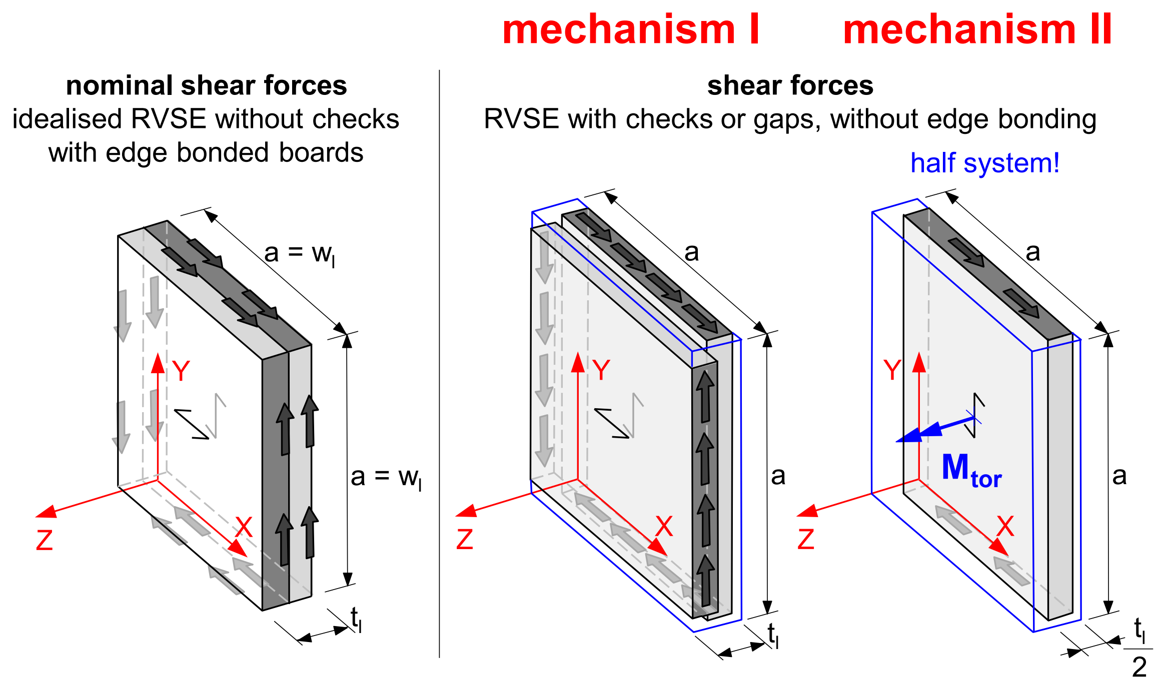
base material	T14	
CV [ft,0,l]	25 % ± 5 %	35 % ± 5 %
	CLT strength class	
property	**CL 24h**	**CL 28h**
$f_{m,CLT,k}$	24	28
$f_{t,0,CLT,net,k}$	16	18
$f_{t,90,CLT,k}$	0.5	
$f_{c,0,CLT,net,k}$	24	28
$f_{c,90,CLT,k}$	3.0	
$f_{v,CLT,IP,k}$	5.5	
$f_{T,node,k}$	2.5	
$f_{v,CLT,OP,k}$	3.5	
$f_{r,CLT,k\,-}\ b/t \geq 4{:}1$	1.25	
$f_{r,CLT,k\,-}\ b/t < 4{:}1$	0.70	

... research work is needed

Shear Mechanisms on an RVSE | General

- **Mechanism I „net-shear“**
  transfer of shear via board‘s cross sections $\boldsymbol{\tau_{net} = 2 \cdot \tau_0}$
- **Mechanism II „torsion“**
  torsional shear stresses in gluing interface $\boldsymbol{\tau_{tor} = 3 \cdot \tau_0 \cdot (t_l / a)}$

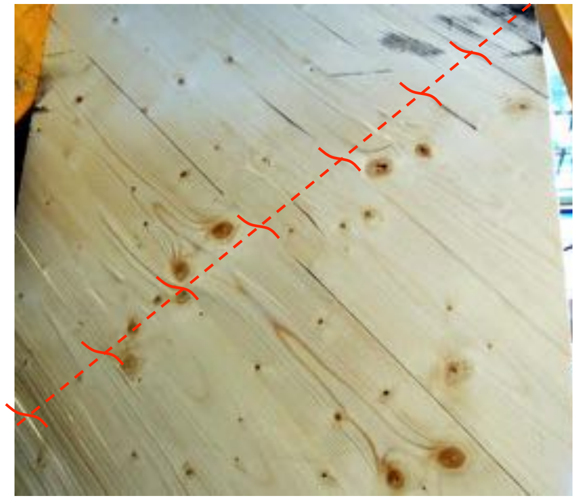




Characteristic Properties
MA Dröscher (2014)

Overview

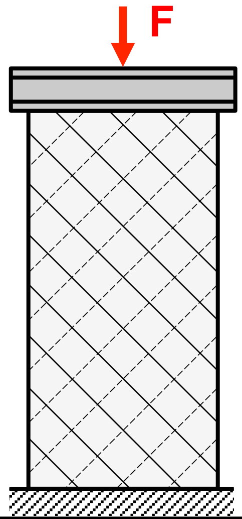
- CLT element 1,500 x 500 x var. mm
- config. & analysis acc. to **Kreuzinger (2013)**
  - failure acc. to mechanism I „net-shear“
  - interaction compression perp. to grain and shear considered



For edge-bonded boards:

➔ gross shear strength $f_{v,gross,k}$ = 3.50 N/mm²

➔ gross shear modulus G_{mean} = 640 N/mm²



For gaps between boards (w_{gap} ≤ 5 mm):

➔ net shear strength $f_{v,net,k}$ = 5.00 ÷ 5.50 N/mm²

➔ net shear modulus G_{mean} = 300 ÷ 480 N/mm²

Characteristic Properties

Selected Topics | Latest Findings

base material	T14	
CV [ft,0,l]	25 % ± 5 %	35 % ± 5 %
	CLT strength class	
property	**CL 24h**	**CL 28h**
$f_{m,CLT,k}$	24	28
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$f_{v,CLT,OP,k}$	3.5	
$f_{r,CLT,k} – w_B/t_B \geq 4:1$	1.25	
$f_{r,CLT,k} – w_B/t_B < 4:1$	0.70	

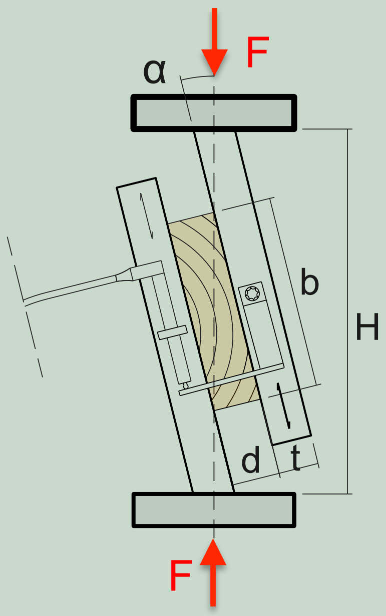
... research work is needed

Characteristic Properties

Rolling Shear | MA Ehrhart (2014)

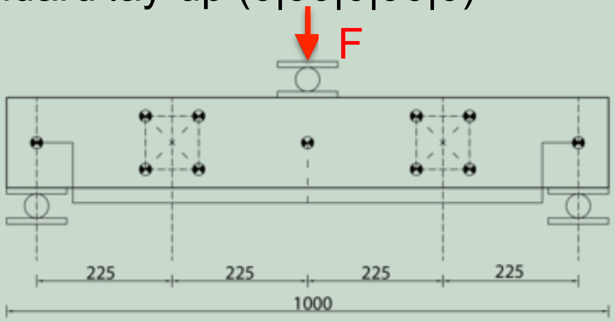
tests according to **EN 408**

- varied parameters:
  - wood species, log positions, b/d-ratios, no. of boards



3-point bending tests

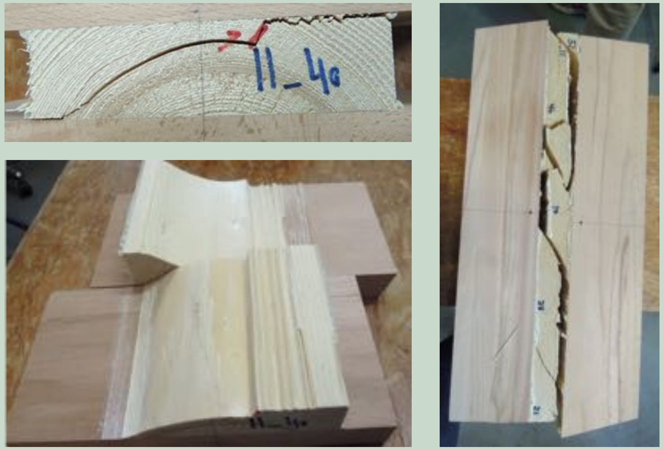
- varied parameters:
  - three inner layers perp. to span length vs. standard lay-up (0|90|0|90|0)



Characteristic Properties

Rolling Shear | MA Ehrhart (2014)

tests according to **EN 408**



➔ **rolling shear strength**

$w_B/t_B < 4$: $f_{r,CLT,k} = 0.80\ N/mm^2$

$w_B/t_B \geq 4$: $f_{r,CLT,k} = 1.40\ N/mm^2$

➔ **rolling shear modulus**

$G_{r,CLT,mean} = 100\ N/mm^2$

3-point bending tests

➔ **rolling shear strength**

$f_{r,CLT,k} = 1.10 \div 1.50\ N/mm^2$

➔ **rolling shear modulus**

$G_{r,CLT,mean} = 110\ N/mm^2$

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Design of CLT

Overview

Design criteria for in- and out-of-plane loaded CLT elements

		CLT element loaded ...	
		in-plane	out-of-plane
ULS	bending	☒ 4)	☒ 1) 2) 5)
	tension	☒ 1) 2) 6)	☒
	compression	☒ 1) 2) 6)	☒ 1) 2)
	shear	☒ 1) 2) 6)	☒ 1) 2)
SLS	deflections	☒ 1) 2)	☒ 1) 2)
	vibration	☐	☒ 1) 2) 3)

1) Schickhofer et al. (2010)
2) Thiel (2013)
3) Hamm et al. (2010)
4) Blaß and Flaig (2012); Flaig (2013)
5) Jöbstl et al. (2006); Jöbstl (2007)
6) Bogensperger et al. (2010)

ULS – CLT loaded out-of-plane

Calculation of stresses and deformations

For CLT in particular the **shear flexibility of the transverse layers** has to be considered.

known procedures (approximative methods)

- γ-method
- shear analogy method
- transverse shear-flexible beam according to Timoshenko

Within a practical relevant range of $\mathbf{l_{CLT} / t_{CLT} \geq 15}$ are all applicable.

Design of CLT

ULS – CLT loaded out-of-plane

Normal stress

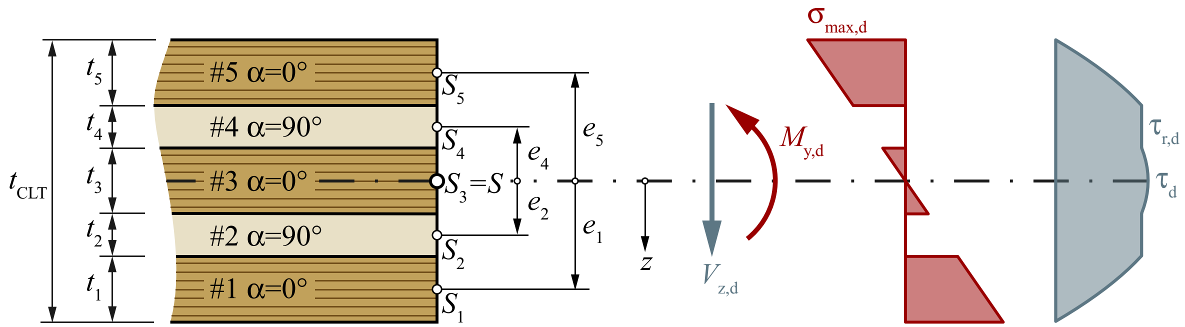
$$\frac{\sigma_{\max,d}}{f_{m,\mathrm{CLT},d}} \leq 1.0 \qquad \sigma_{\max,d} = \max\left[\frac{M_{y,d}}{K_{\mathrm{CLT}}}\, z\, E_{\mathrm{mean}}(z)\right]$$

Shear stress

$$\frac{\tau_{\max,d}}{f_{v,\mathrm{CLT},d}} \leq 1.0 \qquad \frac{\tau_{r,\max,d}}{f_{r,\mathrm{CLT},d}} \leq 1.0 \qquad \tau(z_0) = \frac{V_z \int_{A_0} E(z)\, z\, \mathrm{d}A}{K_{\mathrm{CLT}}\, b(z_0)}$$

Bending stiffness

$$K_{\mathrm{CLT}} = \sum (E_i\, I_i) + \sum (E_i\, A_i\, e_i^2)$$



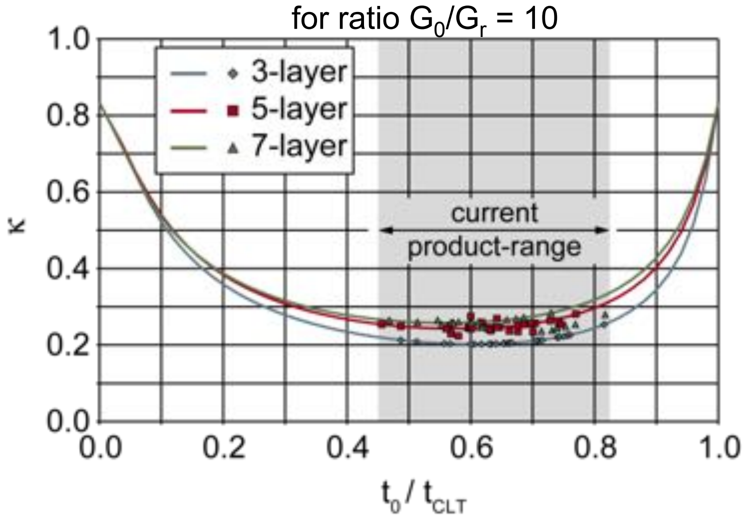
Deflections

Due to shear-flexible cross layers, it is essential to also include deformations caused by shear.

$$w_{\text{ges}} = \frac{1}{K_{\text{CLT}}} \int \left(M\ \overline{M} \right)\ \mathrm{d}x + \frac{1}{S_{\text{CLT}}} \int \left(V\ \overline{V} \right) \mathrm{d}x$$

Shear stiffness S_{CLT}

$$S_{\text{CLT}} = \kappa\ S_{\text{tot}} = \kappa \sum (G_i\ b_i\ t_i)$$



For G_0/G_r = 10 the shear correction coefficient is nearly constant and about ¼ of an unidirectional rectangular cross section.

Design of CLT

SLS – CLT loaded out-of-plane

Vibration

For CLT elements with spans larger than 4 m, vibration usually governs the design.

Most common known procedures in Europe:

- EN 1995-1-1 (2009)
- suggestions of Hamm and Richter (2010)

Primarily they verify the **natural frequency**, the **stiffness criteria** and the **vibration acceleration**.

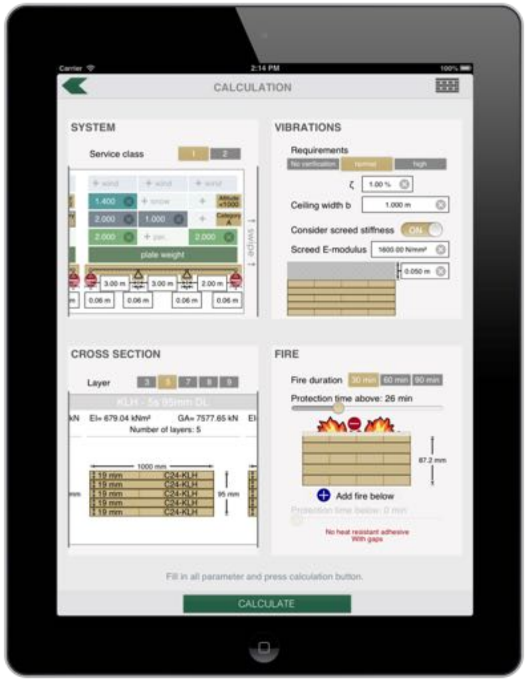
CLTdesigner

holz.bau forschungs gmbh

www.cltdesigner.at

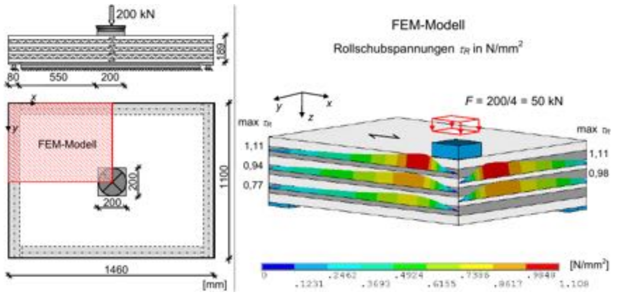
CLTcalculator

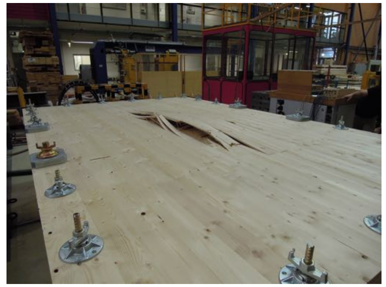
for iPhone and iPad by Aladin Mikara



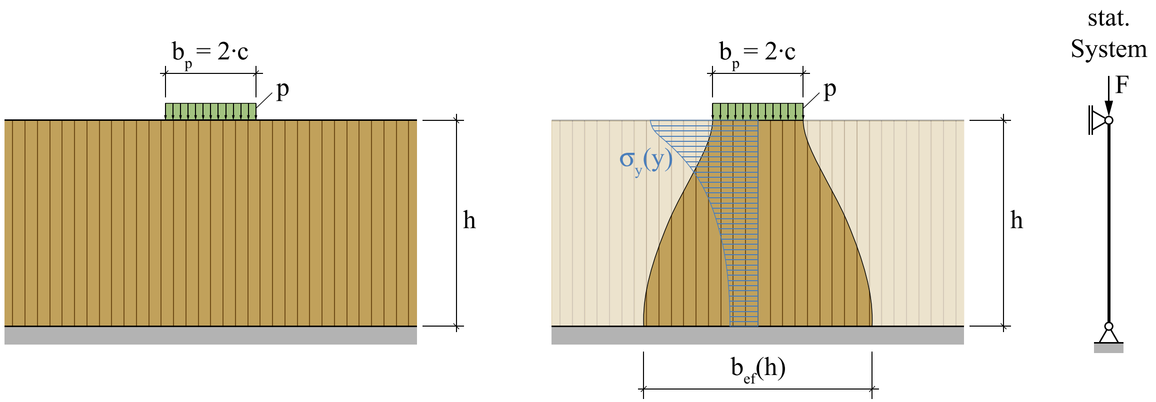
Download on the App Store

Concentrated loads on floors – Mestek (2011), Bogensperger (2014a)





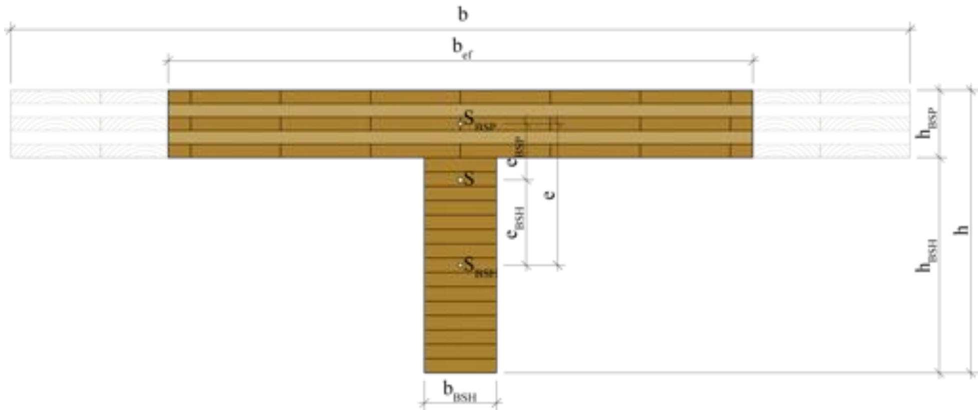
Concentrated loads on walls – Bogensperger (2014b)



Design of CLT

Special design proposals

Rib floors as composite of CLT and GLT – Bogensperger (2013)



Openings in CLT beam elements (loaded in-plane) – Flaig (2014)

Content

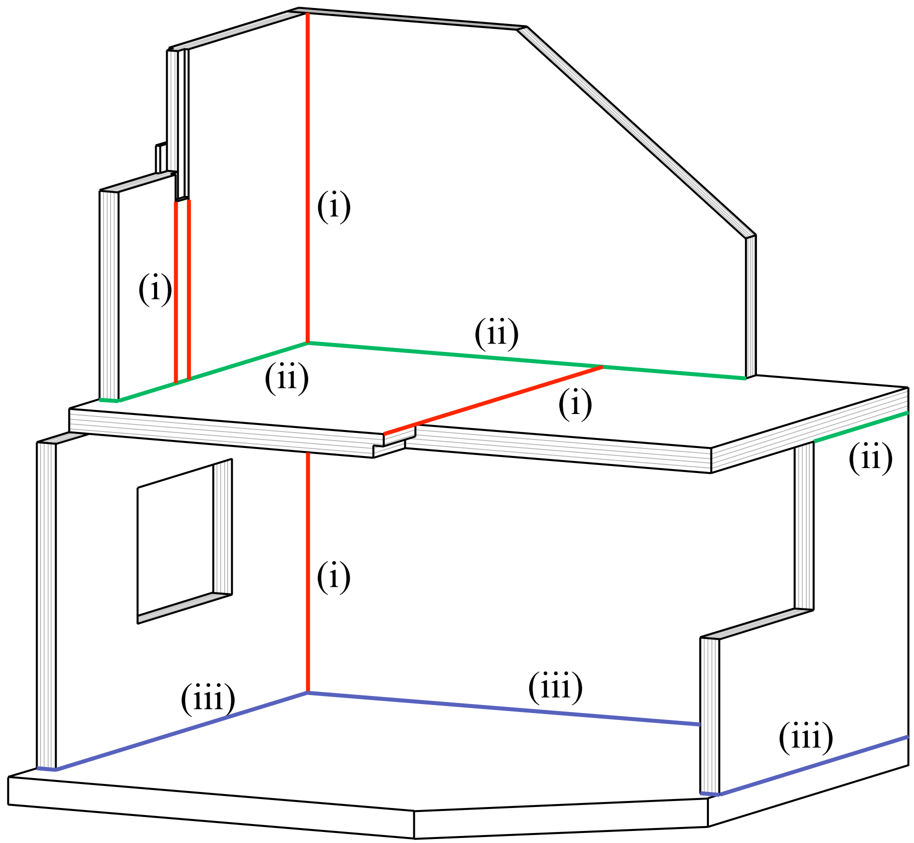
- Introduction
- Production & Technology
- Characteristic Properties
- Design
- Connections
- Conclusions

Connections

General

Joints within a CLT structure

(i) wall-to-wall or floor-to-floor
(ii) wall-to-floor
(iii) wall-to-foundation



Topics at TU Graz

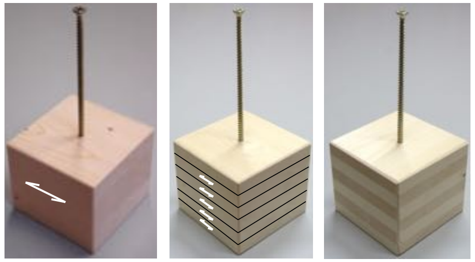
(a) base parameter of single fastener
(b) performance and application of connections

Connections

Base parameters - 6 main research projects

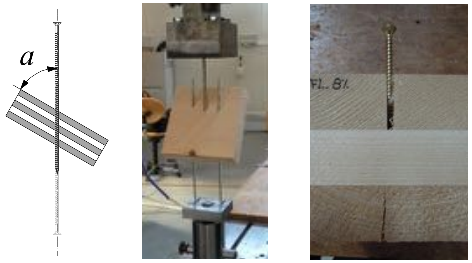
k_{sys}

ST GLT CLT



k_{90} | k_{gap}

CLT - side face

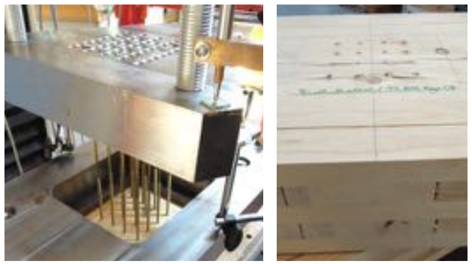


k_{90} | k_{gap}

CLT - narrow face

n_{ef} | block shear

CLT - side face

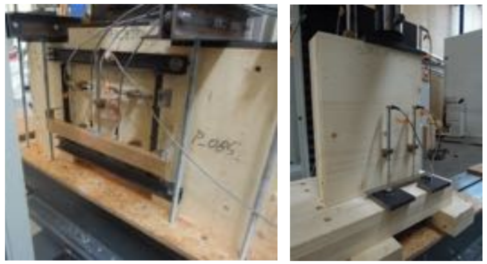


n_{ef}

CLT - narrow face

joint behaviour

CLT - side and narrow face

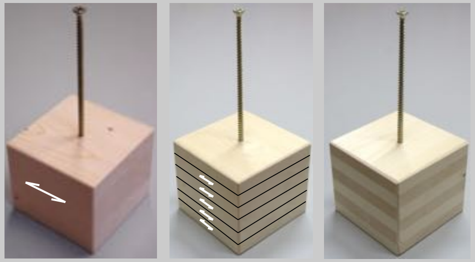


Connections

Base parameters - 6 main research projects

k_{sys}

ST | GLT | CLT



k_{90} | k_{gap}

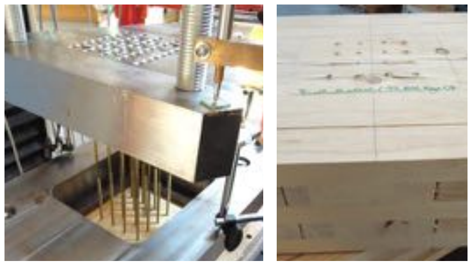
CLT - side face

k_{90} | k_{gap}

CLT - narrow face

n_{ef} | block shear

CLT - side face



n_{ef}

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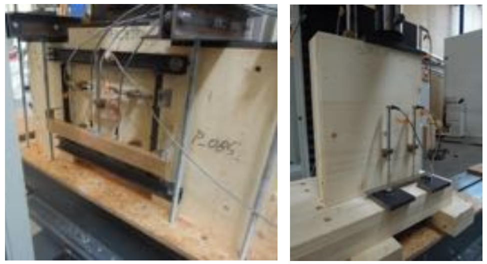


Proposal of an universal model approach

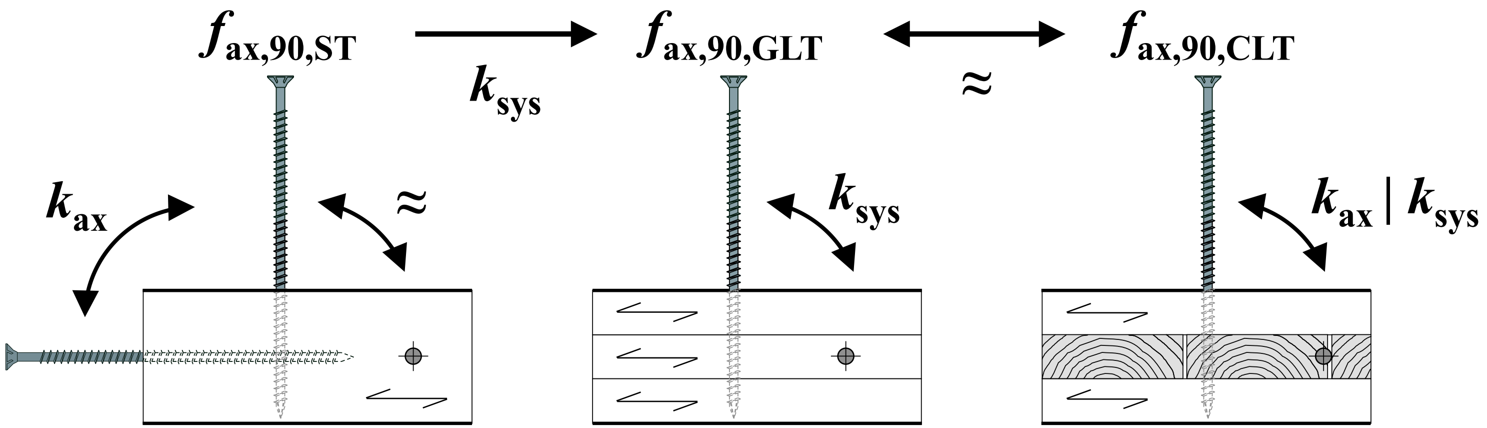
$$\boldsymbol{f}_{\mathbf{ax}} = \boldsymbol{k}_{\mathbf{ax}} \cdot \boldsymbol{k}_{\mathbf{sys}} \cdot \boldsymbol{f}_{\mathbf{ax,90,ST}}$$

$$k_{\text{sys}} = f(N)$$

$$k_{\text{ax}} = k_{90} \cdot f(\alpha, k_{\text{gap}})$$

$$k_{\text{gap}} = \begin{cases} 1{,}00 & ST, GLT \\ f(d, w_{\text{gap}}) & CLT \end{cases}$$

$$k_{90} = \frac{f_{\text{ax,90}}}{f_{\text{ax,0}}} = f(d, \rho)$$

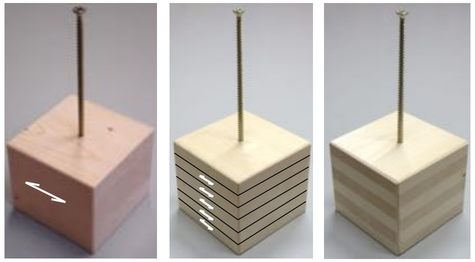


Connections

Base parameters - 6 main research projects

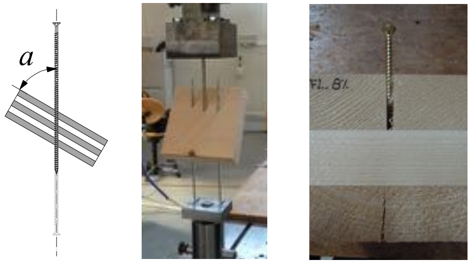
k_{sys}

ST GLT CLT



k_{90} | k_{gap}

CLT - side face



k_{90} | k_{gap}

CLT - narrow face

n_{ef} | block shear

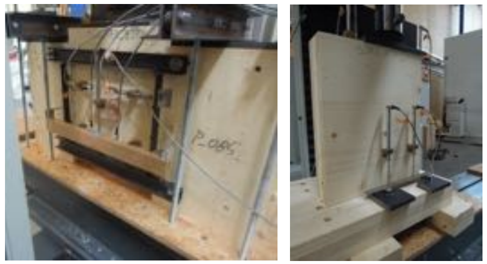
CLT - side face

n_{ef}

CLT - narrow face

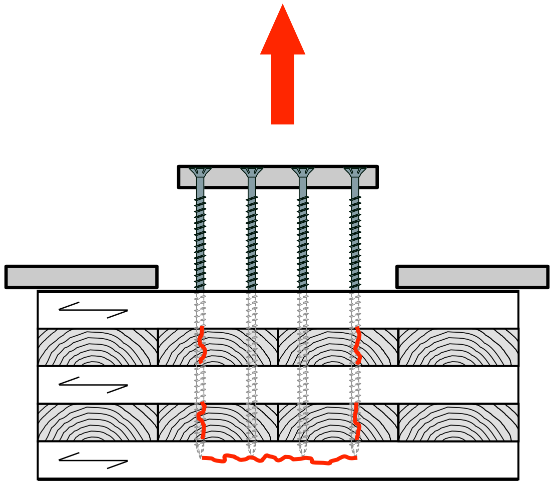
joint behaviour

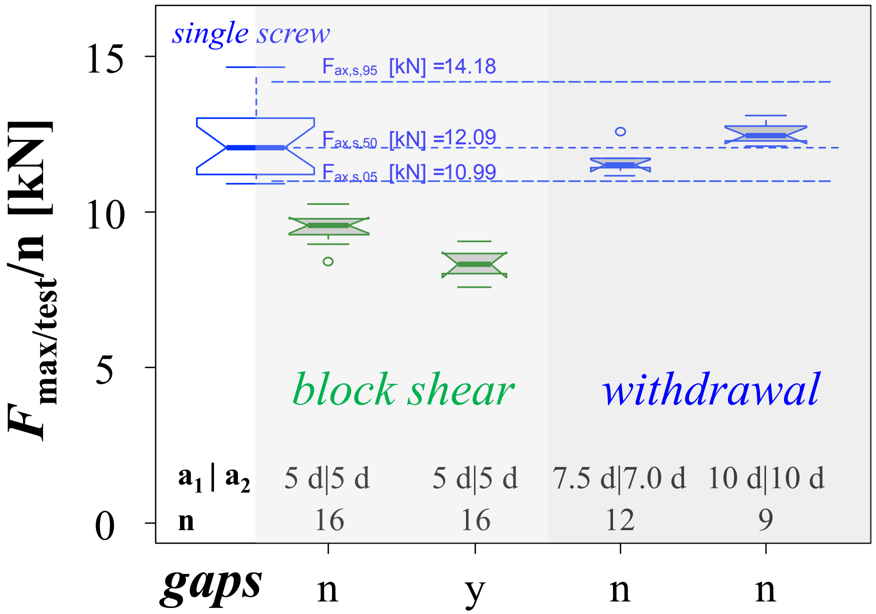
CLT - side and narrow face



Connections

Block shear failure mode in CLT side face





$$a_1 \mid a_2 = 5 \cdot d \mid 5 \cdot d$$

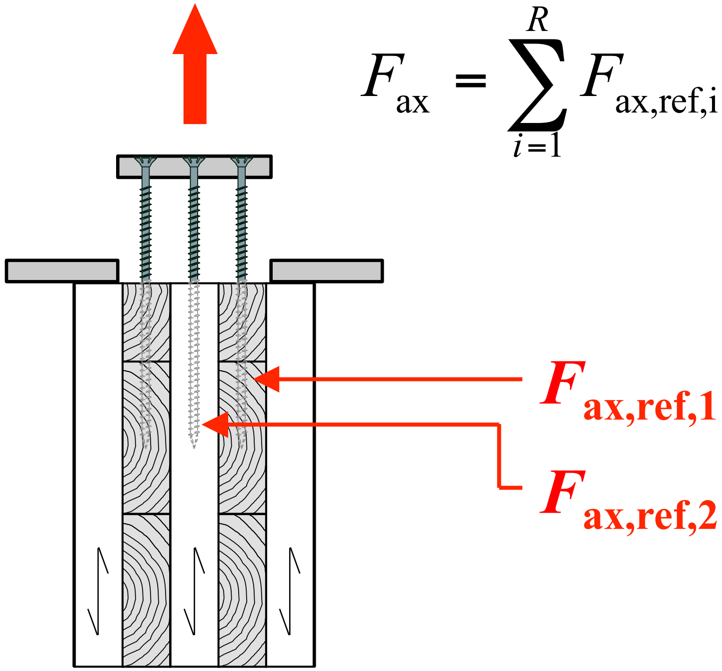
$$a_1 \mid a_2 \geq 7.5 \cdot d \mid 7 \cdot d$$

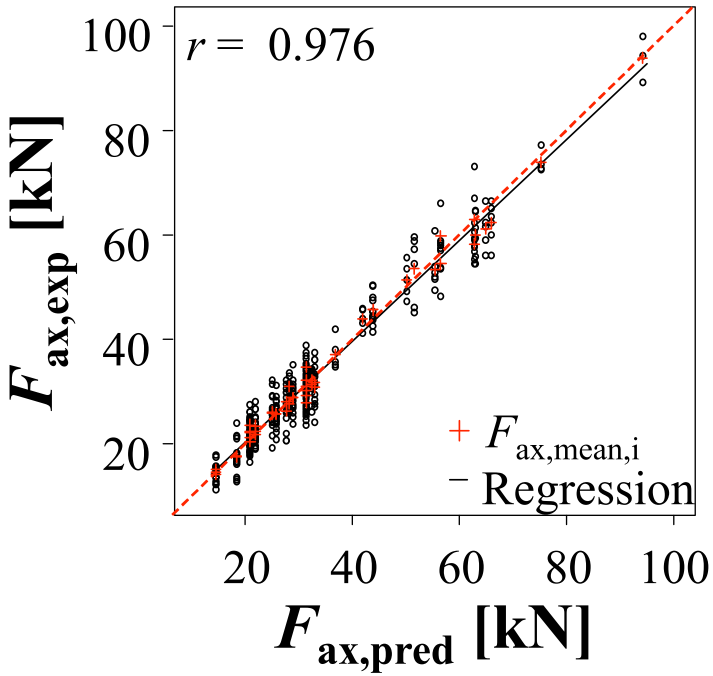
Block shear can occur!

$$F_{ax,CLT,SF,n} = 0.9 \cdot n \cdot F_{ax,CLT,SF,1}$$

Withdrawal (group) failure in CLT narrow face

$$F_{ax} = \sum_{i=1}^{R} F_{ax,ref,i} \cdot n_i$$





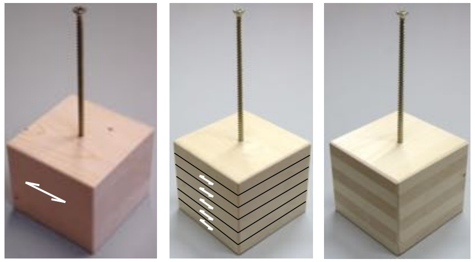
Proposal $F_{ax} = 0.9 \cdot (n_{\alpha} \cdot F_{ax,1,\alpha} + m_{\beta} \cdot F_{ax,1,\beta})$

Connections

Base parameters - 6 main research projects

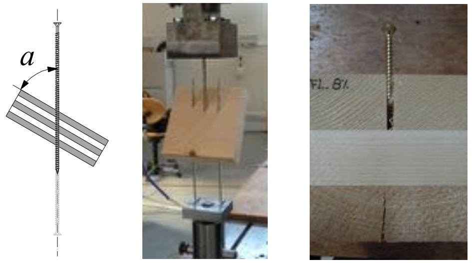
k_{sys}

ST | GLT | CLT



k_{90} | k_{gap}

CLT - side face

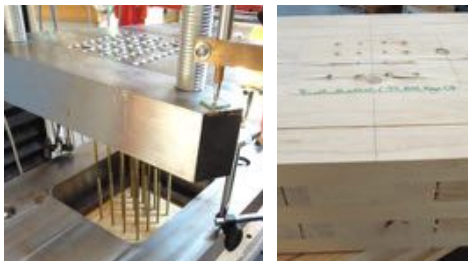


k_{90} | k_{gap}

CLT - narrow face

n_{ef} | block shear

CLT - side face



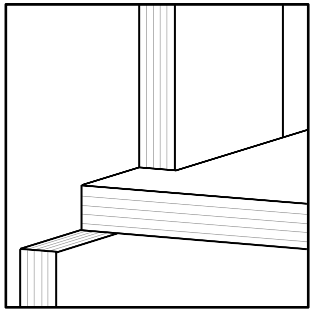
n_{ef}

CLT - narrow face

joint behaviour

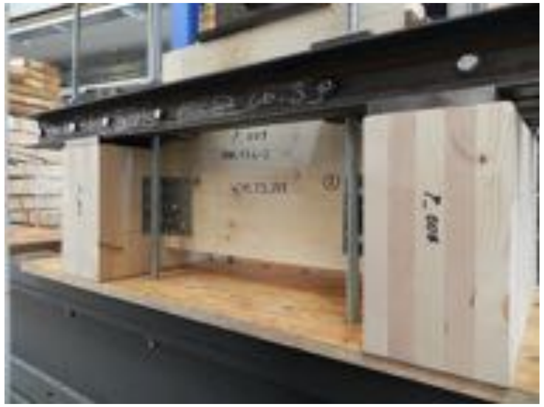
CLT - side and narrow face

Test campaigns of TU Graz



SINGLE JOINT TESTS

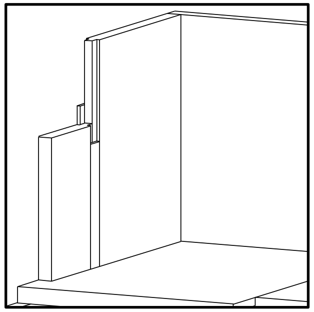
- angle brackets, hold-downs and screws
- CLT/CLT as well as CLT/concrete or steel
- shear and tension | monotonic and cyclic
- overall 215 tests on single joints



Connections

Performance & Application

Test campaigns of TU Graz



WALL TESTS

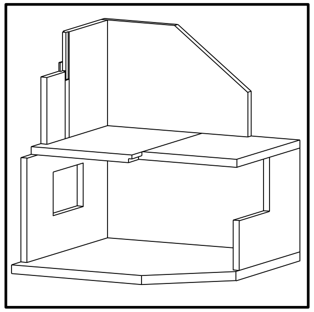
- 5 configurations – 17 tests
- variation of connections and vertical loads
- walls with and without vertical joints and openings




Connections

Performance & Application

Test campaigns of TU Graz



SHAKING TABLE TESTS

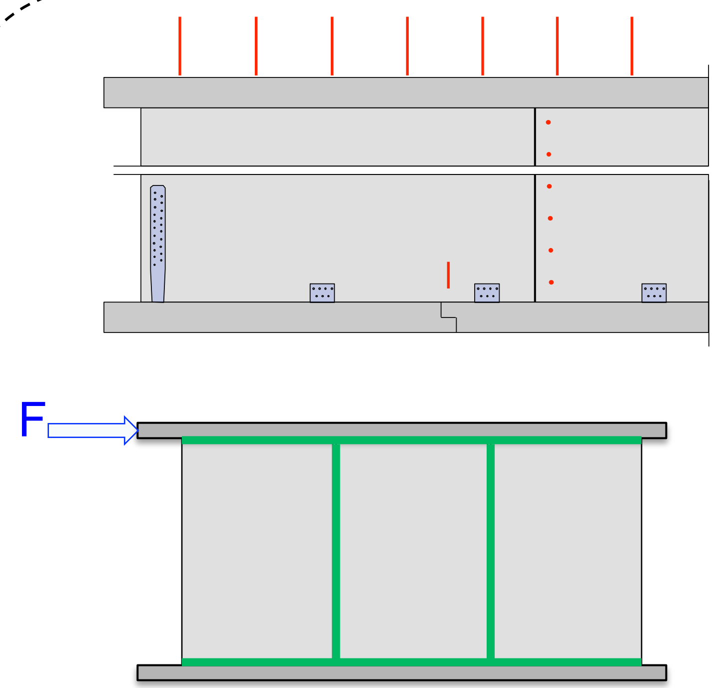
- full scale three-storey CLT building
- European Union project SERIES
  (**S**eismic **E**ngineering **R**esearch **I**nfrastructures for **E**uropean **S**ynergies)
- 32 earthquakes up to 0.5 g without major damages




Importance of clear defined screwed joints

About 60% of all CLT joints are usually realised with screws.

Screw joints designed to be ductile, enable a single-wall-behaviour.

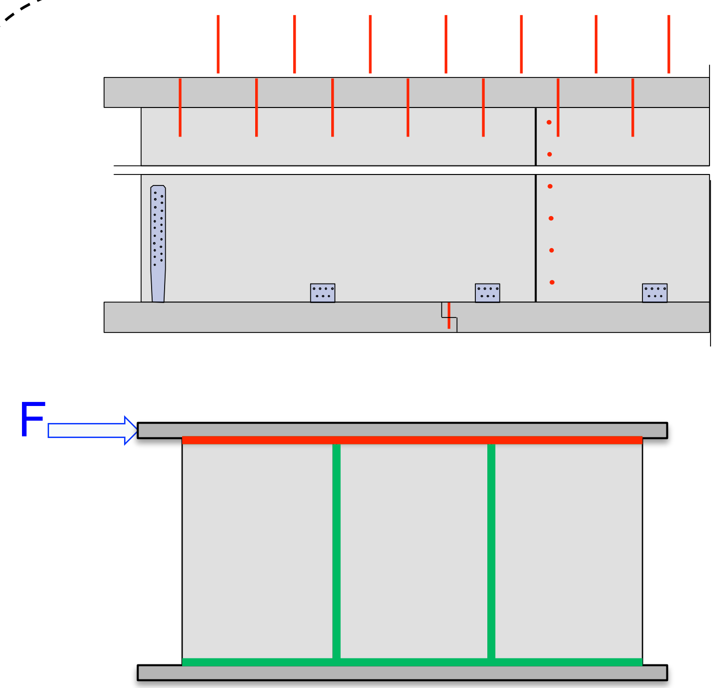


Importance of clear defined screwed joints

About 60% of all CLT joints are usually realised with screws.

Screw joints designed to be ductile, enable a single-wall-behaviour.

Screw joints designed with over-strength prevent high deformations.



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Conclusions I/III

DEVELOPMENT | GENERAL

- **accelerated rise in worldwide production volume** expected within coming decade
- for product | testing | design | detailing | joining | use **standardization is mandatory**

PRODUCTION

- dominated by (modular) **hydraulic press systems**
- AIM: **minimizing gaps**
- **assembling stations & engineering** as logical further vertical extensions

Conclusions II/III

PRODUCT | DESIGN

- **harmonized load-bearing models**
  → prediction of CLT properties based on base material properties
- **CLT strength class system**
- **harmonized design procedures** (e.g. ULS/SLS bending out-of-plane)

JOINING

- **differentiation in side and narrow face is mandatory**
- **CLT adequate connection technique is missing**
  (e.g. line instead of punctual connections)
    - allowing for energy dissipation, e.g. in seismic loading
    - high flexibility & short assembling time
    - high degree of utilization (comparable to CLT capacity)

CLT …

→ opens new possibilities and horizons in timber engineering!

→ enables renaissance of timber engineering in our cities!

→ peculiarities of timber (e.g. moisture) need to be addressed!

THANK YOU FOR YOUR KIND ATTENTION!