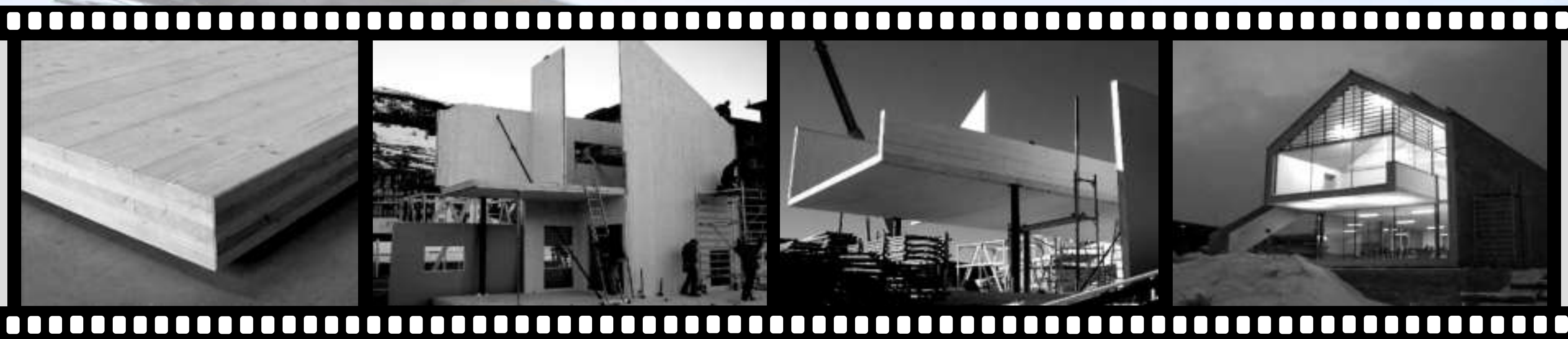
CLT – Research and Testing at TU Graz



Cross-Laminated Timber Symposium
Vancouver Convention Center

Univ.-Prof. Dipl.-Ing. Dr.techn. Gerhard Schickhofer
Dipl.-Ing. Dr.techn. Alexandra Thiel
Institute for Timber Engineering and Wood Technology, Graz University of Technology | AT
Competence Centre holz.bau forschungs gmbh Graz | AT

CONTENT

- Research Topics on Cross Laminated Timber (CLT)
  - Point supported Ceilings and Roofs
  - Verifications regarding Serviceability Limit State (SLS)
  - In-Plane Shear Capacity and Verification Methods
  - CLTdesigner – Software Tool for Designing CLT Elements [A. Thiel]
- Summary | Outlook

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Compression Perpendicular to the Grain

design value for compression stress perp. to grain

$$\sigma_{c,clt,90,d} = \frac{F_d}{A_{c,90}}$$

with: $A_{c,90}$ ... contact area

point supported

© Picture: DI R. Salzer (AUT)

point supported

© Picture: Architect Reinberg (AUT)

line supported

© Picture: TU Graz (AUT)

Compression Perpendicular to the Grain

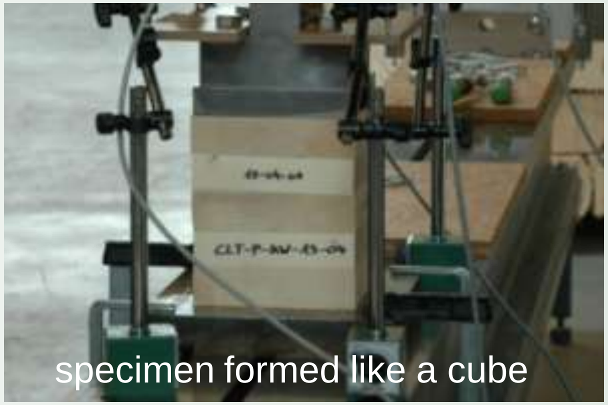
material resistance against compression perp. to grain ($f_{c,clt,90,d}$)

publications regarding CLT:

- Y. Halili | TU Graz, 2008
- E. Serrano | Linnæus University, 2010
- C. Salzmann | TU Graz, 2010

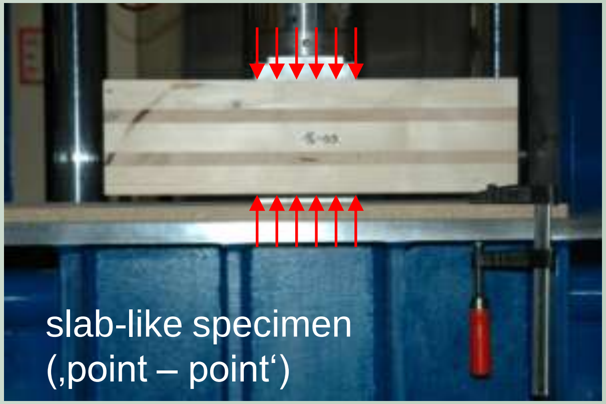
characteristic parameters:

- $f_{c,clt,90,d}$ | cube | slab-like specimen
- $k_{c,clt,90}$ (`hang-in effect´)
- $E_{c,clt,90,mean}$



specimen formed like a cube

slab-like specimen

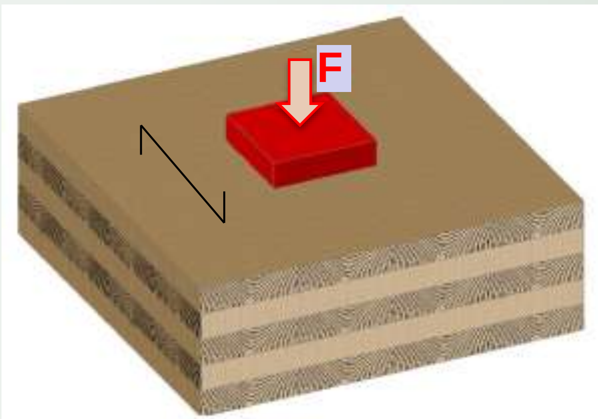


slab-like specimen (‚point – point‘)

Compression Perpendicular to the Grain

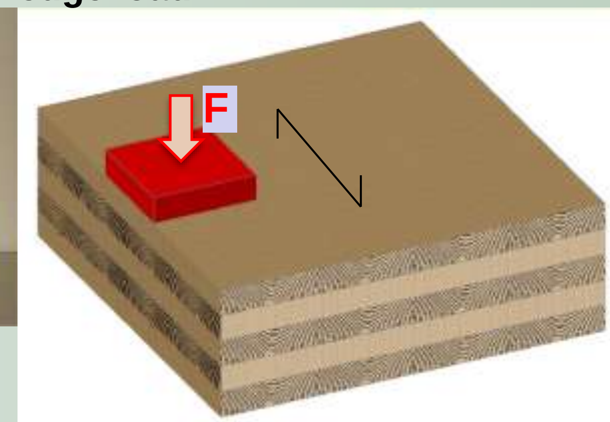
different loading situations | configurations on CLT elements

center load

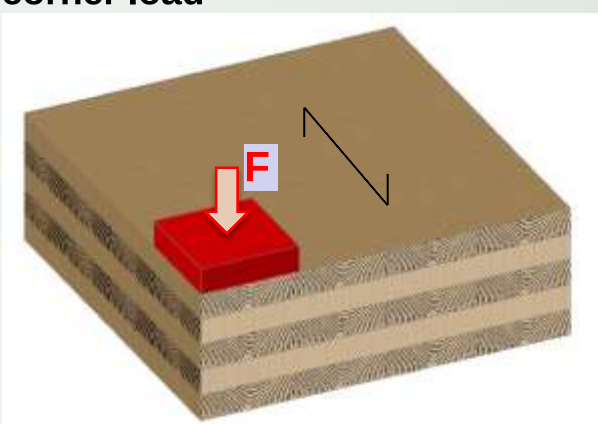


\`hang-in effect´
(two sides)

edge load

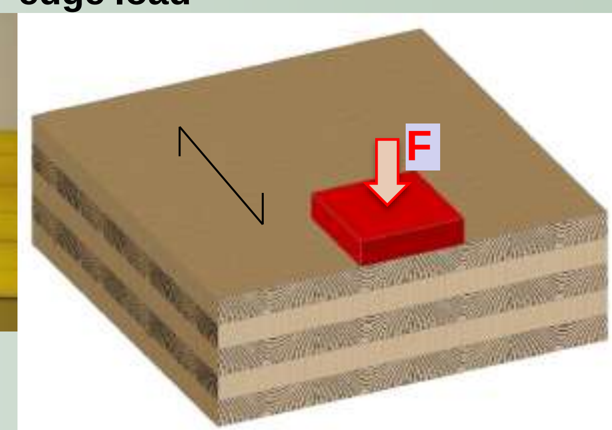


corner load



\`hang-in effect´
(one side)

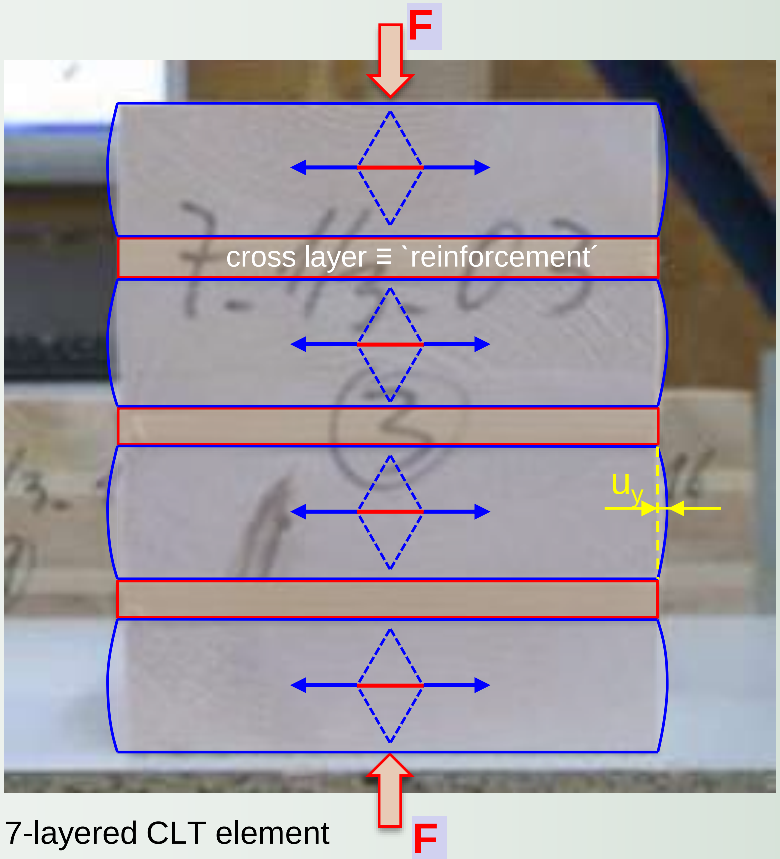
edge load



Compression Perpendicular to the Grain

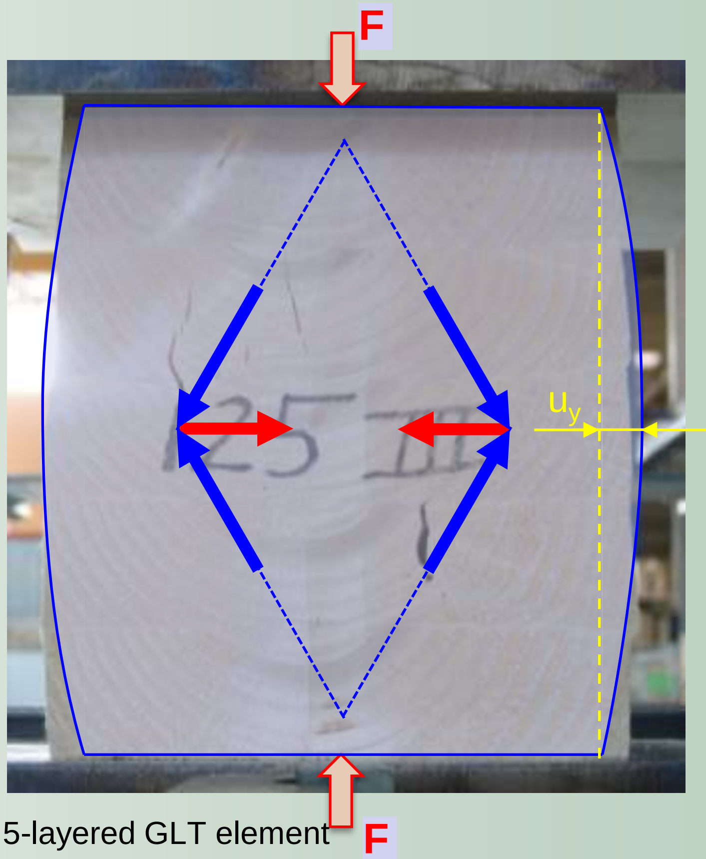
`framework model´

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

Compression Perpendicular to the Grain

The cross layers cause a `locking effect´ and therefore a reduction of deformation.

comparison of CLT to GLT at the same load level

- ✓ CLT shows reduced deformation perp. to grain (u_y) concentrated on each single layer
- ✓ CLT shows higher stiffness and lower stresses in tension perp. to grain

result:
lower failure probability at the same load level and **higher load bearing capacity** perpendicular to the grain

Compression Perpendicular to the Grain

strength determined on standardised full-loaded prismatic specimen

GLT

CLT

$\mathbf{f_{c,glt,90,k} = 2.1 \ldots 2.4\ N/mm^2}$ [res. publ.]

$\mathbf{f_{c,clt,90,k} = \ldots 3.0 \ldots 3.1\ N/mm^2}$

$f_{c,glt,90,k} = 2.5\ N/mm^2$
(prEN 14080)

$f_{c,clt,90,k} = 3.0\ N/mm^2$
(proposal TU Graz)

basic value for design

Compression Perpendicular to the Grain

bearing capacity in constructions

GLT

CLT

edge
\`line supported´

centric
\`point supported´

GLT

$k_{c,glt,90}$ = 1,0 ... 1,5 ... 1,75

$f_{c,glt,90,k} \cdot k_{c,glt,90}$ = 3.75 N/mm²

proposal TU Graz

$k_{c,clt,90}$ = ~ 1.5 = ~ 2.0

$f_{c,clt,90,k} \cdot k_{c,clt,90}$ = 4.5 ... 6.0 N/mm²

+ 20 %

+ 60 %

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Process for Design of Vibration acc. to EN 1995-1-1

1st eigenfrequency: $f_1 \geq 8$ Hz — NO → **special investigation**

YES ↓

specification of performance

↓

limits for deflection w and vibration velocity v

↓

stiffness: $w(1kN) \leq w_{limit} = a$ — NO → **verification not fulfilled**

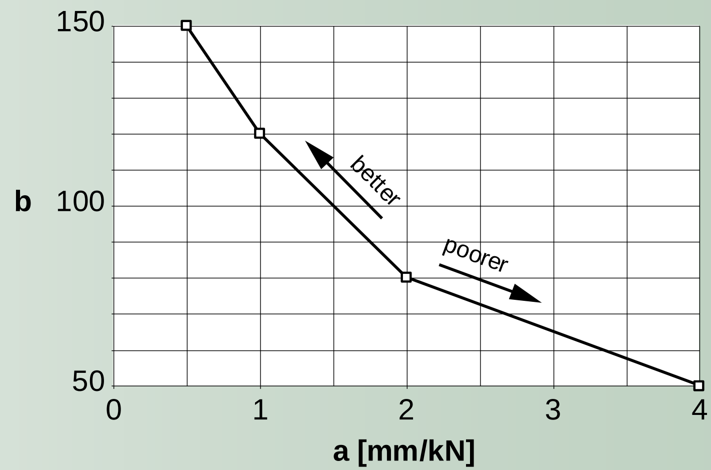
YES ↓

vibration velocity: $v \leq v_{limit} = b^{(f_1 \zeta - 1)}$ — NO → **verification not fulfilled**

damping ratio (ζ)

YES ↓

verification fulfilled



Eigenfrequency of a Single Span Girder

$$EJ \cdot u''''(x,t) + m \cdot \ddot{u}(x,t) = 0$$

$$(\ )' = \frac{\partial}{\partial x} \qquad (\ )^{\bullet} = \frac{d}{dt}$$

$$u(x,t) = c \cdot \sin\frac{\pi}{l} x \cdot \sin\omega \cdot t$$

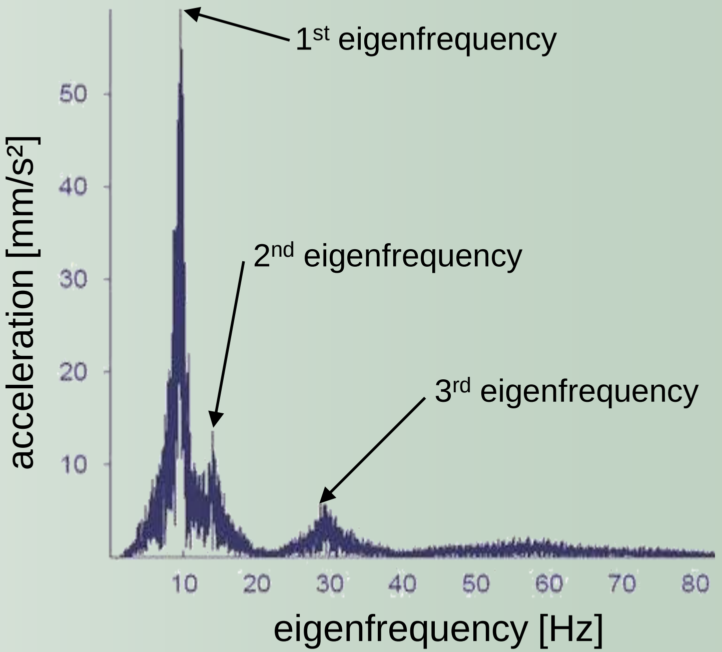
$$f = \frac{\omega}{2\pi} = \frac{\pi}{2l^2} \cdot \sqrt{\frac{EJ}{m}}$$

EJ … bending stiffness [Nm²]
m … mass [kg/m]
l … length of the single span girder [m]

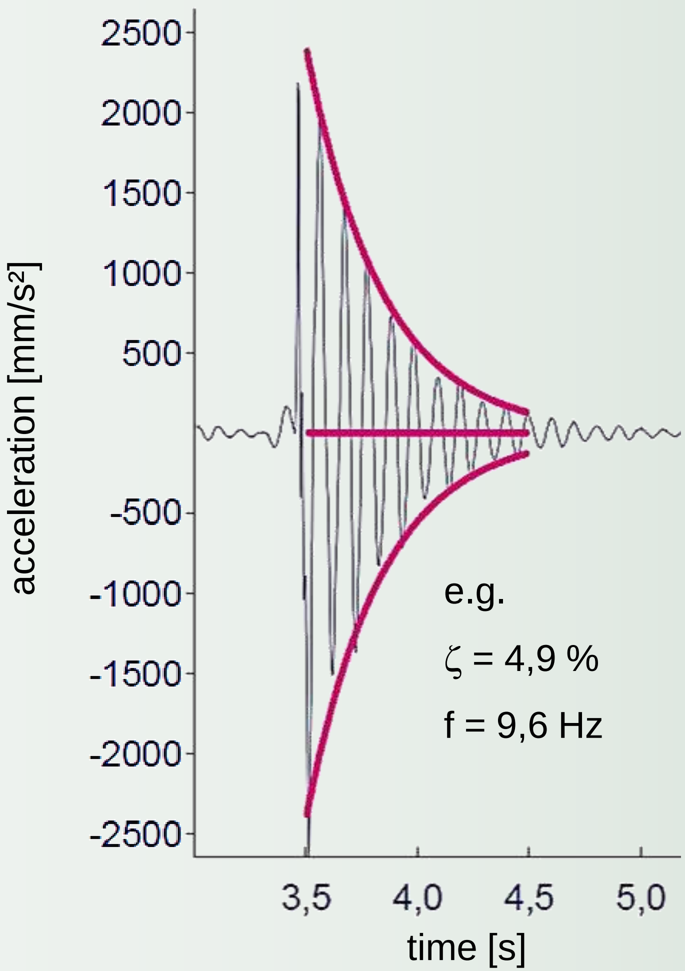
identification of eigenfrequencies by **FFT**:

in situ determination of eigenfrequency requires various test methods, e.g.:

- **´heeldrop´**
  (frequencies 0 ÷ 30 Hz)
- **´punch from underneath´**
  (frequencies > 30 Hz)



Proposal for the Damping Ratio for CLT



support	construction	test results ζ_{50} [%]	proposal ζ_{CLT} [%]
2 side	heavy	2.77	**2.50**
4 side	light	3.95	**3.50**
4 side	heavy	3.71	

damping ratio

- damping ratio depends on the position and type of excitation
- calculation by means of $2^{nd} \div 11^{th}$ amplitude

damping ratio needed e.g. for

- determination of maximum vibration velocity v_{limit} acc. to EC 5

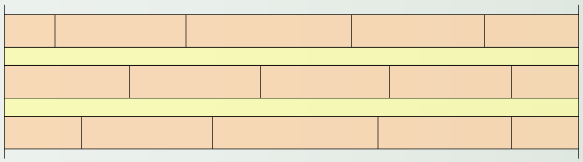
$$v \leq b^{(f_1 \cdot \varsigma - 1)}$$

Vibration tests on CLT slabs – Test Configurations

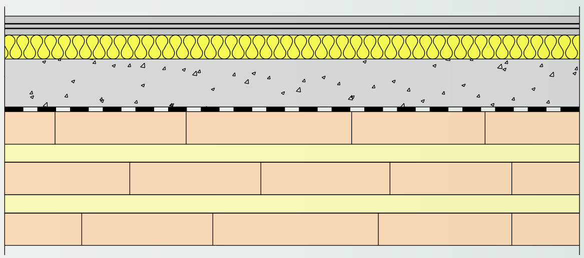
(in cooperation with Munich University of Technology)

cross sections

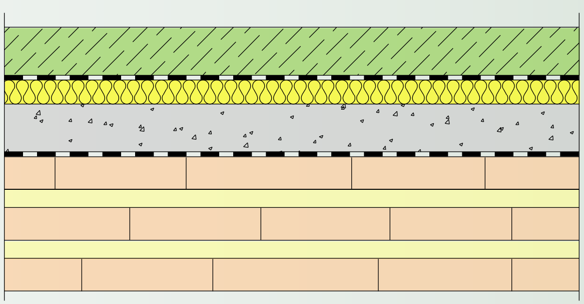
clt | - 5-layered CLT element



clt | l with light floor construction (gypsum board)

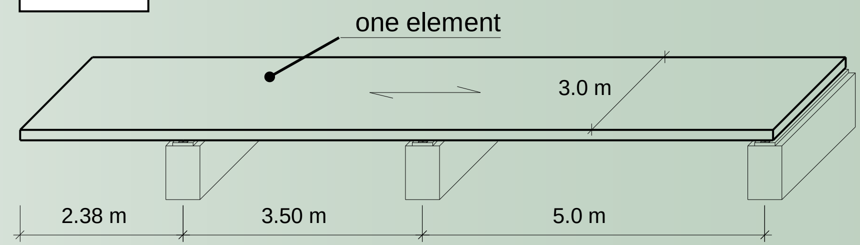


clt | h with heavy floor construction (floating floor)

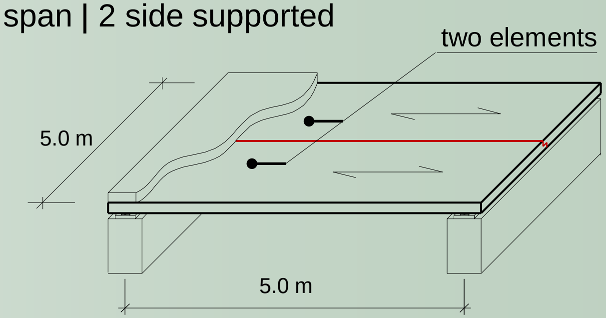


systems

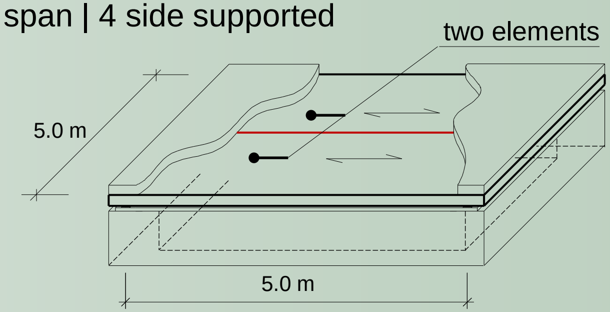
cont continuous beam with 2 fields and cantilever



2s single span | 2 side supported



4s single span | 4 side supported



Vibration tests on CLT slabs – Test Configurations

(in cooperation with Munich University of Technology)

joints

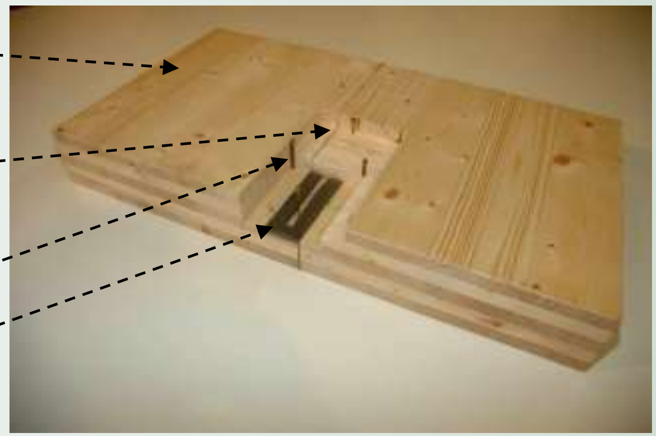
v transverse force joint

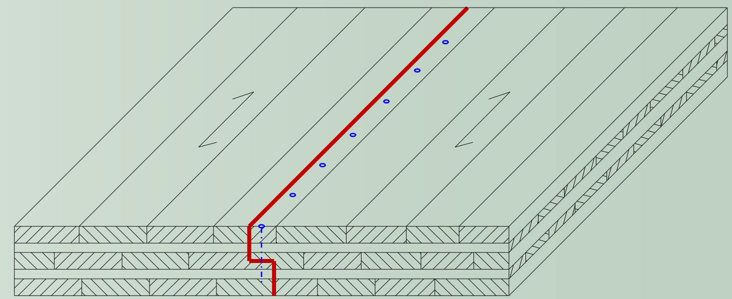
5-layered CLT element

overlapping / interlocking joint

positively tied by screws

sealing tapes (compression band)

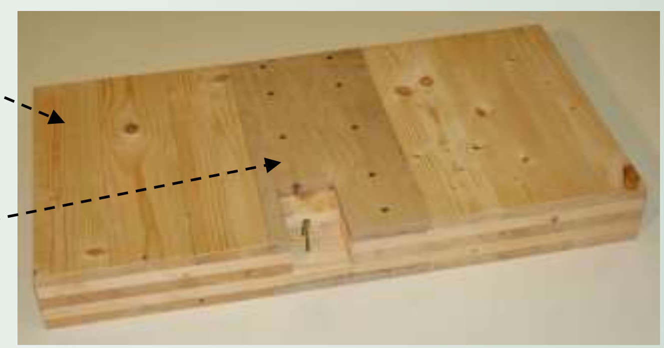


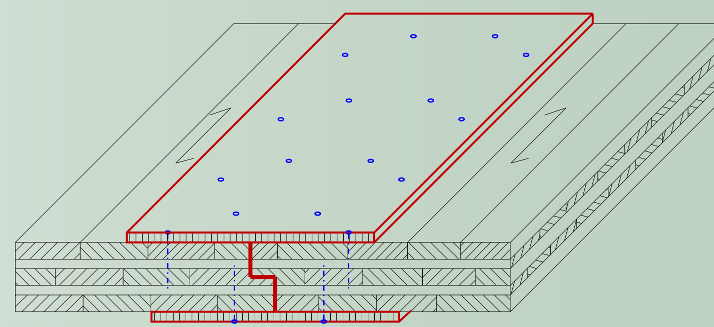


m bending resistant joint

5-layered CLT element

on top and underneath strapping (adhesion by screwing pressure)





Some Impressions of the Test Configurations

5-layered CLT element (clt|-)

roller support

continuous beam with cantilever and measurement equipment (cont;clt|-)

single span | 4 side supported with light floor construction (4s;clt|l)

single span | 4 side supported with heavy floor construction (4s;clt|h)

Eigenfrequencies

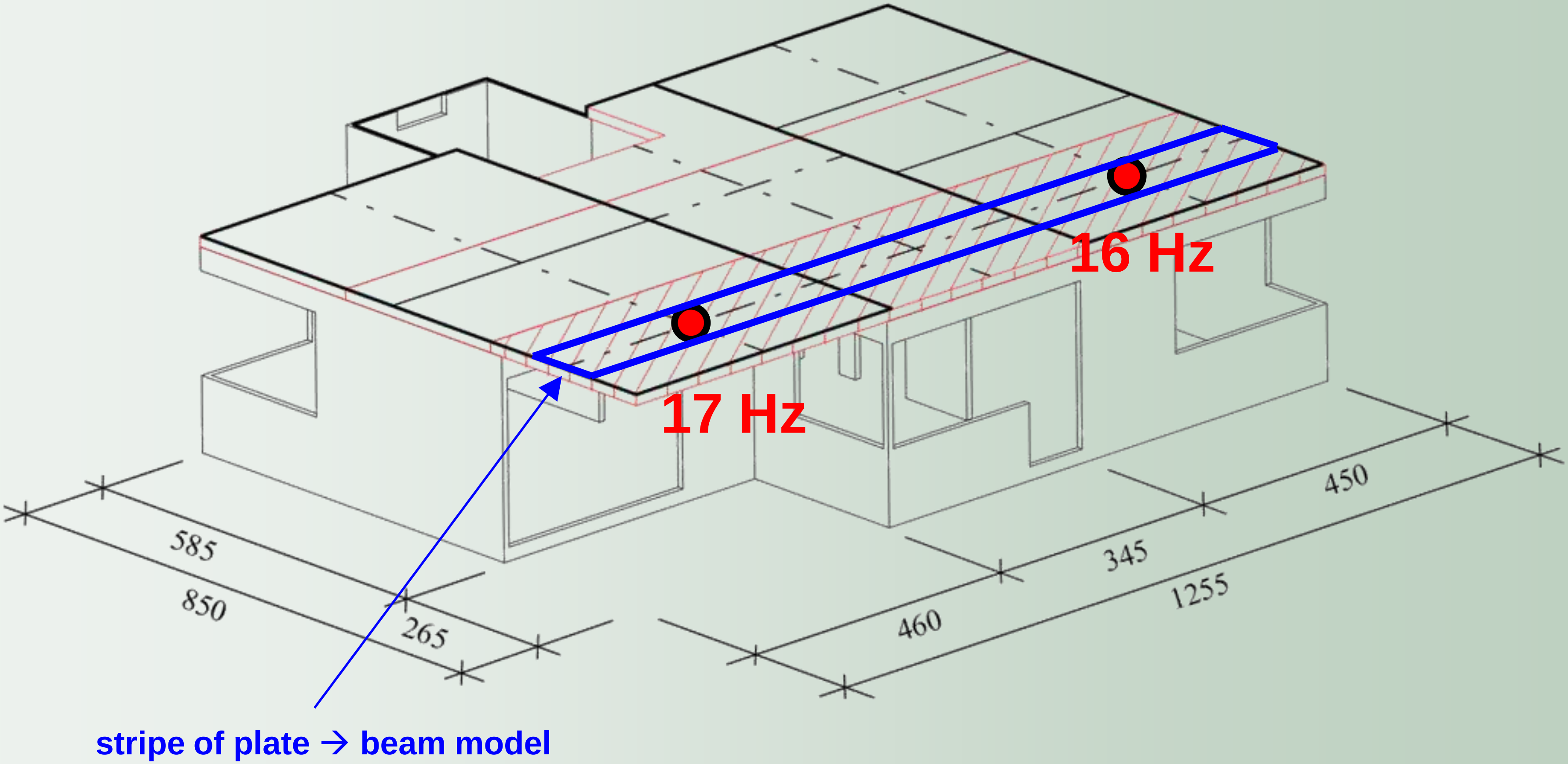
comparison between test configurations and numerical modeling (FEM)

configuration			1st eigenfrequency		
system	cross section	joint	testing [Hz]	FEM [Hz]	diff [%]
cont	clt | -	-	11.10	11.11	0.06
2s	clt | -	v	12.00	12.00	0.03
2s	clt | h	v	7.90	7.41	-6.25
4s	clt | -	v	15.71	15.49	-1.39
4s	clt | l	v	9.70	9.92	2.28
4s	clt | h	v	10.00	9.92	-0.77
4s	clt | -	m	16.68	16.72	0.23

→ The numerical results and the tests show a high compliance!

Residential Building

eigenfrequency measurements in situ



Residential Building

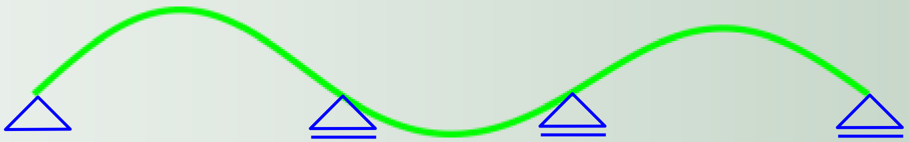
eigenfrequency acc. to EC 5

(beam theory including shear flexibility)

results, based on simple beam model

construction	mass [kg/m²]	bending stiffness [MN·m²/m]	1st eigenfrequency [Hz]
with screed	214	$3.038 \cdot 10^6$	**9.7**
without screed	214	$2.588 \cdot 10^6$	**9.0**

1st eigenmode



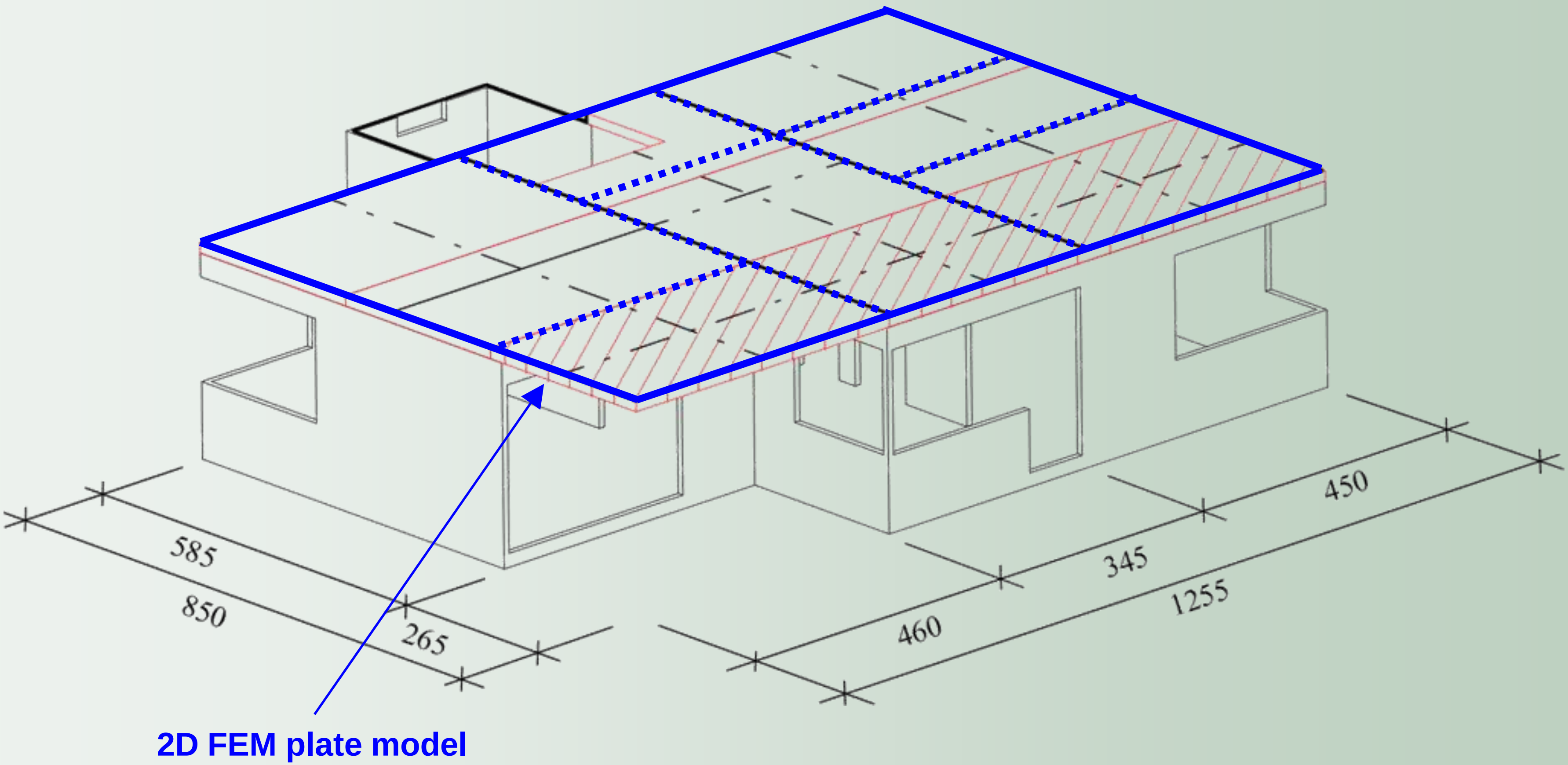
conclusio:

remarkable differencies between measured and calculated (simple beam model) eigenfrequencies

→ detailed investigation in modeling (2D FEM plate model, hinge / fixed support, …)

Residential Building

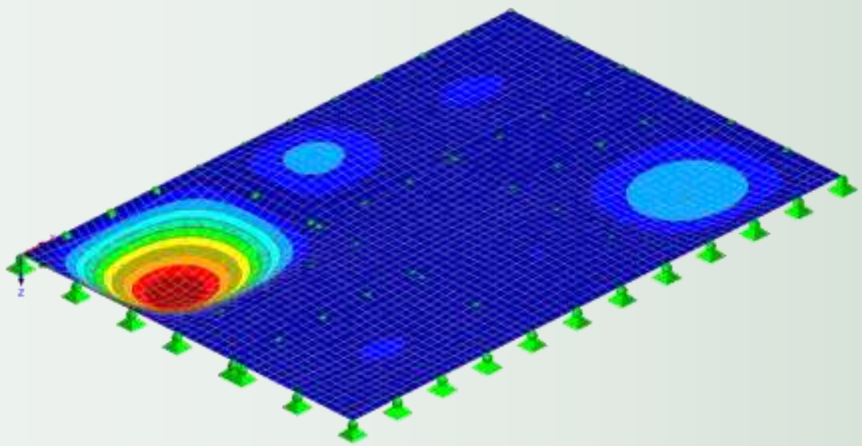
special investigation with FEM plate theories



Residential Building

special investigation with FEM plate theories

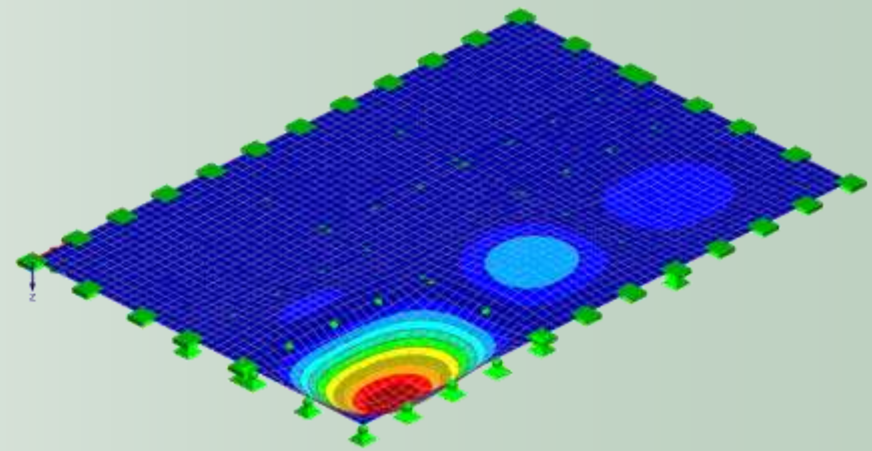
investigation of 8 different models of CLT slab, range of values [10.9 Hz ÷ 17.0 Hz]



calc. eigenfrequency: **13.8 Hz**

model details:

- **not considered** stiffness of **screed**
- interior boundaries are modeled with hinge support
- **hinge support** of exteriour boundary



calc. eigenfrequency: **17.0 Hz**

model details:

- **considered** stiffness of **screed**
- interior boundaries are modeled with hinge support
- **fixed support** of exterior boundary

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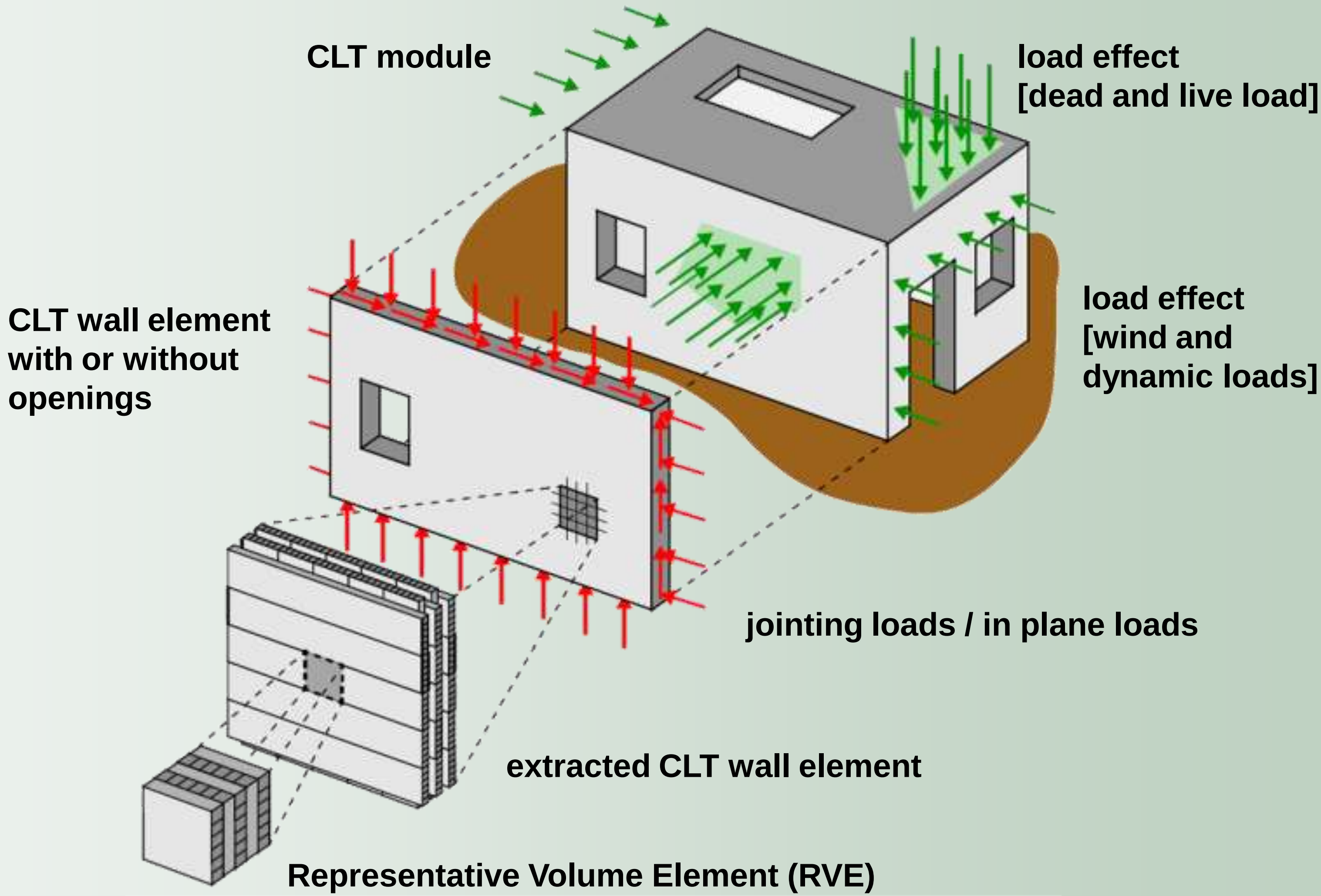
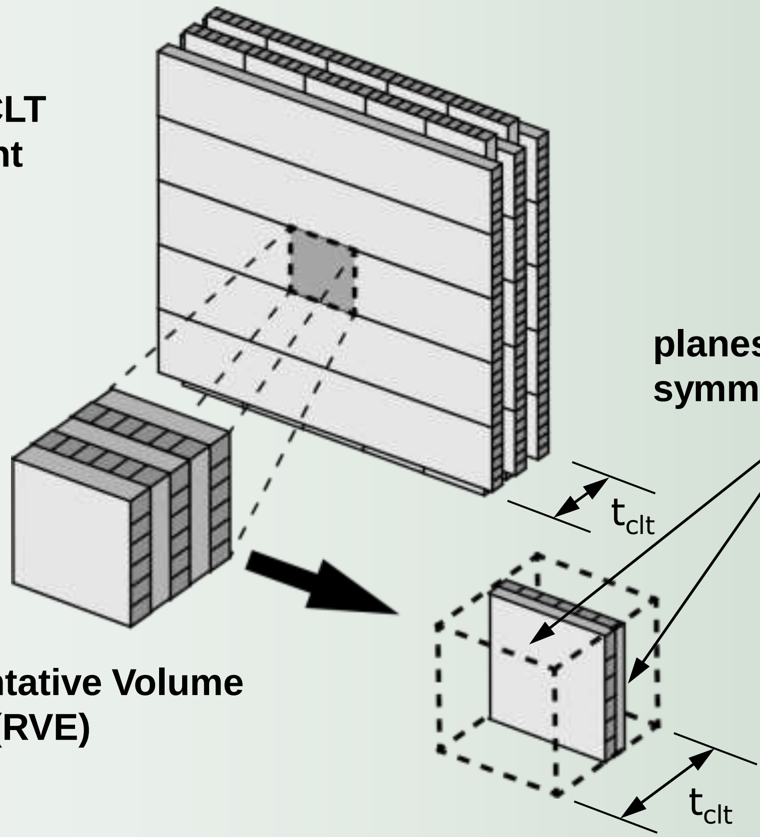
From the Building to the Representative Volume Sub-Element (RSVE)



From the Building to the Representative Volume Sub-Element (RSVE)

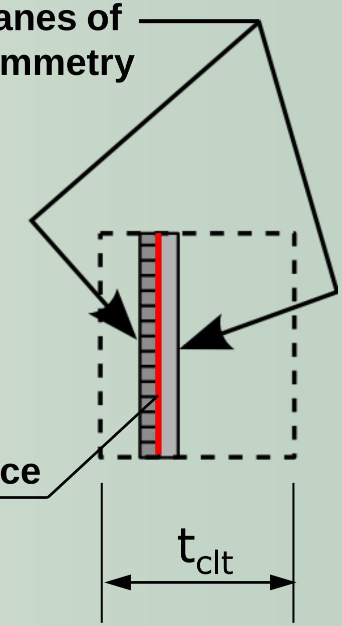
extracted CLT wall element



Representative Volume Element (RVE)

Representative Volume Sub-Element (RVSE)

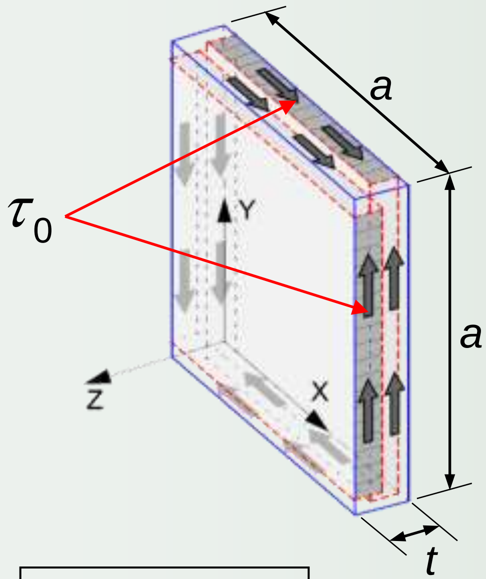
RVSE



Shear Stresses in RVSE

determination for infinite number of layers

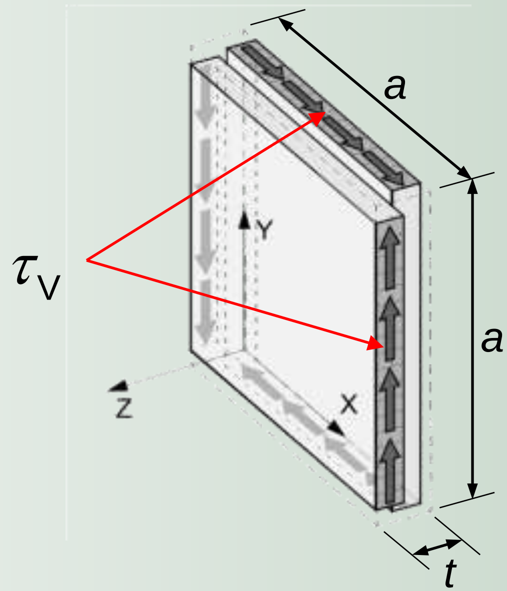
edge bonded



$$\tau_0 = \frac{n_{xy,RVSE}}{t}$$

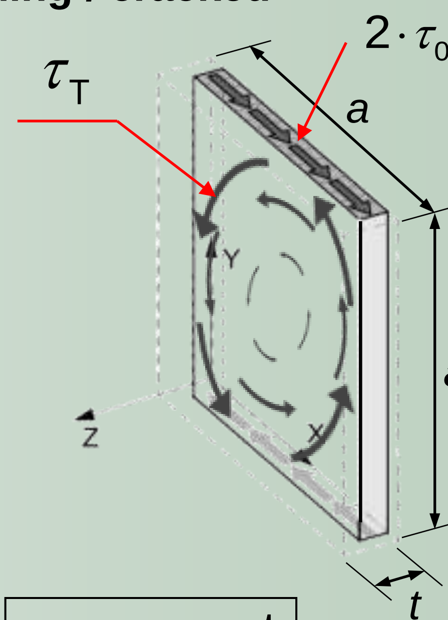
τ_0 … nominal shear stress in plane

without edge bonding / cracked



$$\tau_V = 2 \cdot \tau_0$$

τ_V … shear stress in cross section



$$\tau_T = 3 \cdot \tau_0 \cdot \frac{t}{a}$$

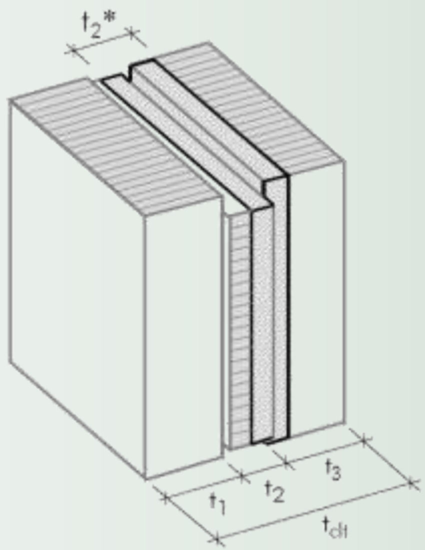
τ_T … shear stress due to torsional moment in glueing interface

Shear Stresses in RVSE

determination of the substituted thickness for each RVSE, denoted with t_i^*

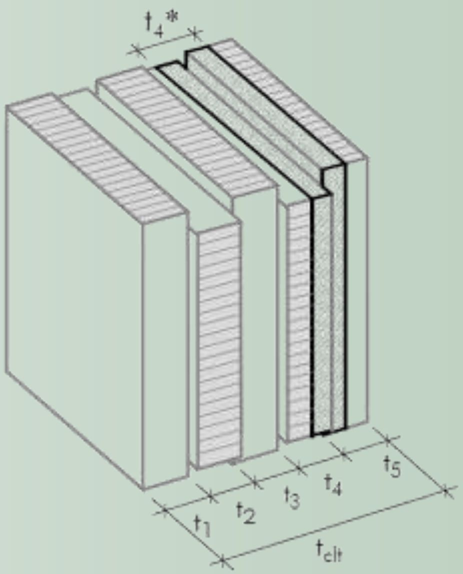
3-layered
CLT element

e.g. RVSE-2



5-layered
CLT element

e.g. RVSE-4



# of RVSE	substituted thickness t_i^*
1	$t_1^*=\min(2\ t_1;t_2)$
2	$t_2^*=\min(t_2;2\ t_3)$

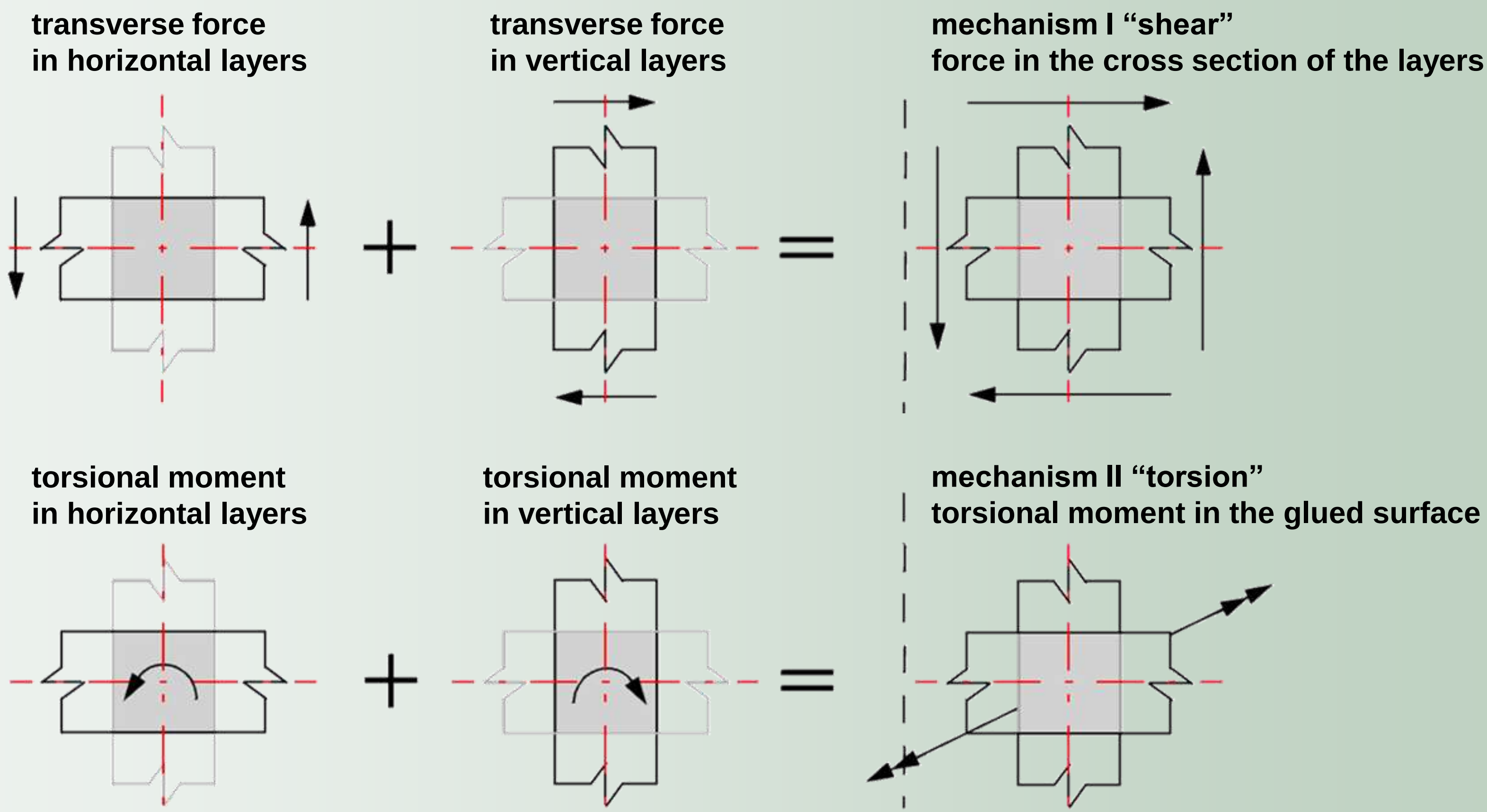
$$\tau_0^* = \frac{n_{xy}}{\sum^{n-1} t_i^*}$$

$$\longrightarrow \tau_V^*, \tau_T^*$$

# of RVSE	substituted thickness t_i^*
1	$t_1^*=\min(2\ t_1;t_2)$
2	$t_2^*=\min(t_2;t_3)$
3	$t_3^*=\min(t_3;t_4)$
4	$t_4^*=\min(t_4;2\ t_5)$

Determination of in Plane Shear Strength Properties for CLT

mechanism I `shear´ and mechanism II `torsion´



Both mechanisms are interacting and have to be verified!

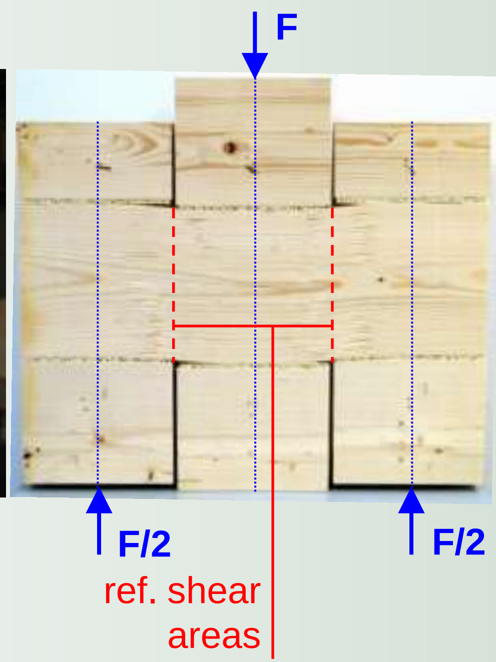
Determination of Shear Strength Properties for Mech. I `Shear´

(diploma thesis by B. Hirschmann – ongoing)

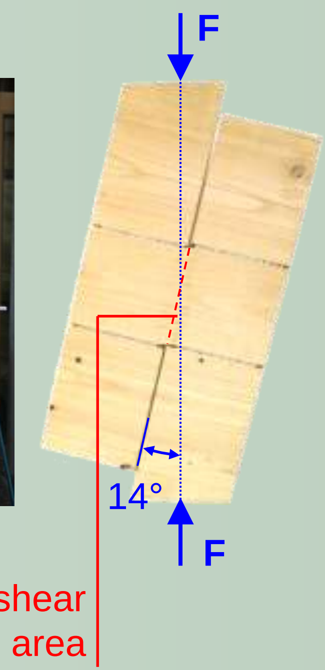
$f_{v,clt,k} \leq 5{,}2$ N/mm²

… acc. current technical approvals, based on tests performed acc. to the CUAP procedure (→ bending failure)

configuration 1 (C1)
(R. Jöbstl, CIB-W18:2008)



configuration 2 (C2)
(based on EN 408 and EN 789)



Determination of Shear Strength Properties for Mech. I `Shear´

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configuration 1 (C1)
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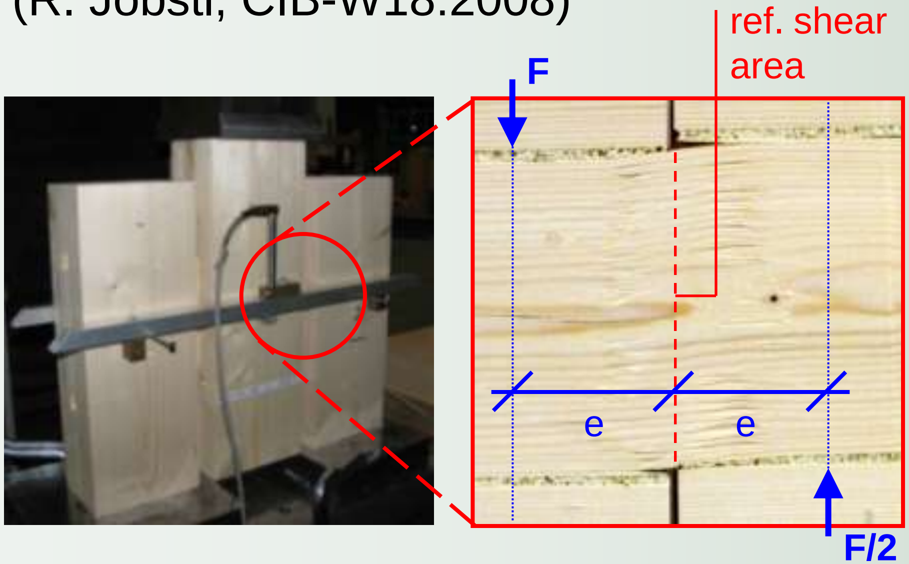
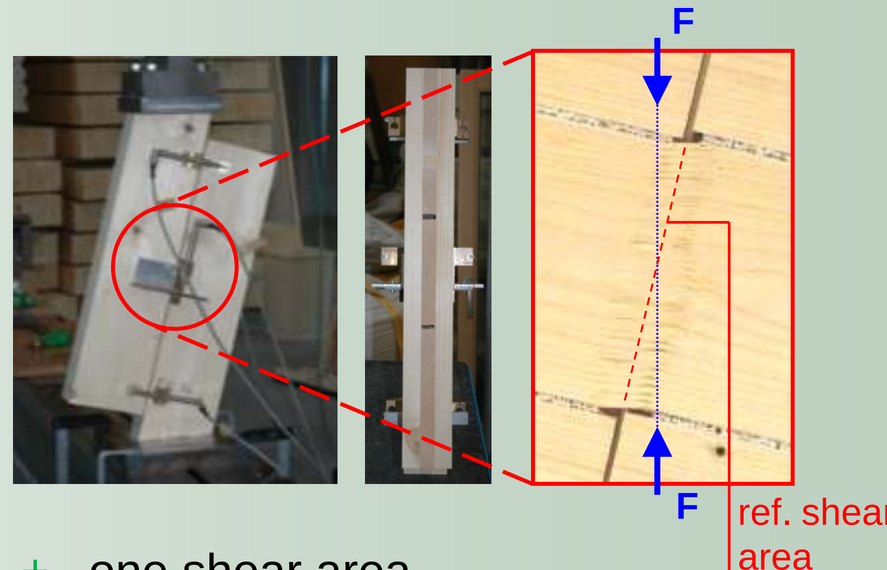


- shear failure up to t = 20 mm
- interaction between bending and shear

configuration 2 (C2)
(based on EN 408 and EN 789)



+ one shear area
+ shear failure up to t = 40 mm
- interaction between compression in fibre direction and shear

→ **recommended test configuration for mechanism I `shear´**

Shear Strength Test – Mechanism I `Shear´

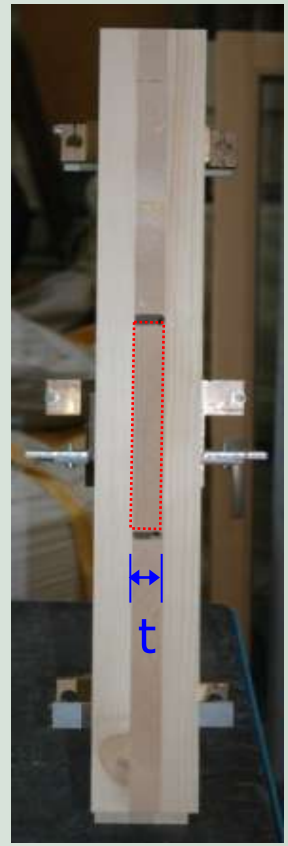
overview

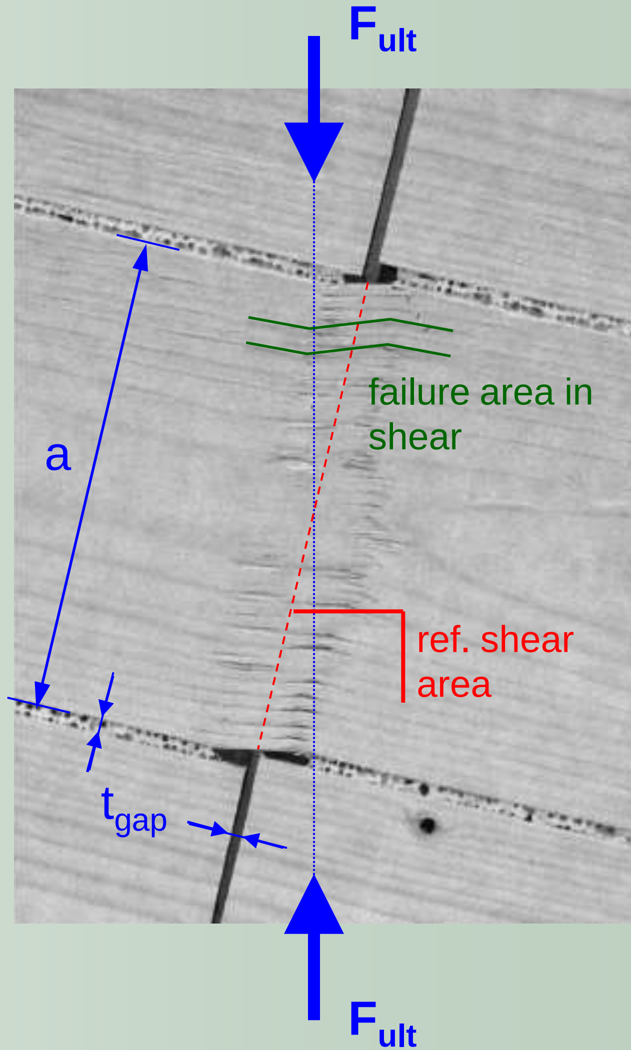
investigated parameters:

a [mm]	150	200	-
t [mm]	10	20	30
t_{gap} [mm]	1,5	5	25

$$f_{v,clt} = \frac{F_{ult} \cdot \cos(14°)}{a \cdot t}$$

ref. shear area





Shear Strength Test – Mechanism I `Shear´

comparison of configuration C1 and C2

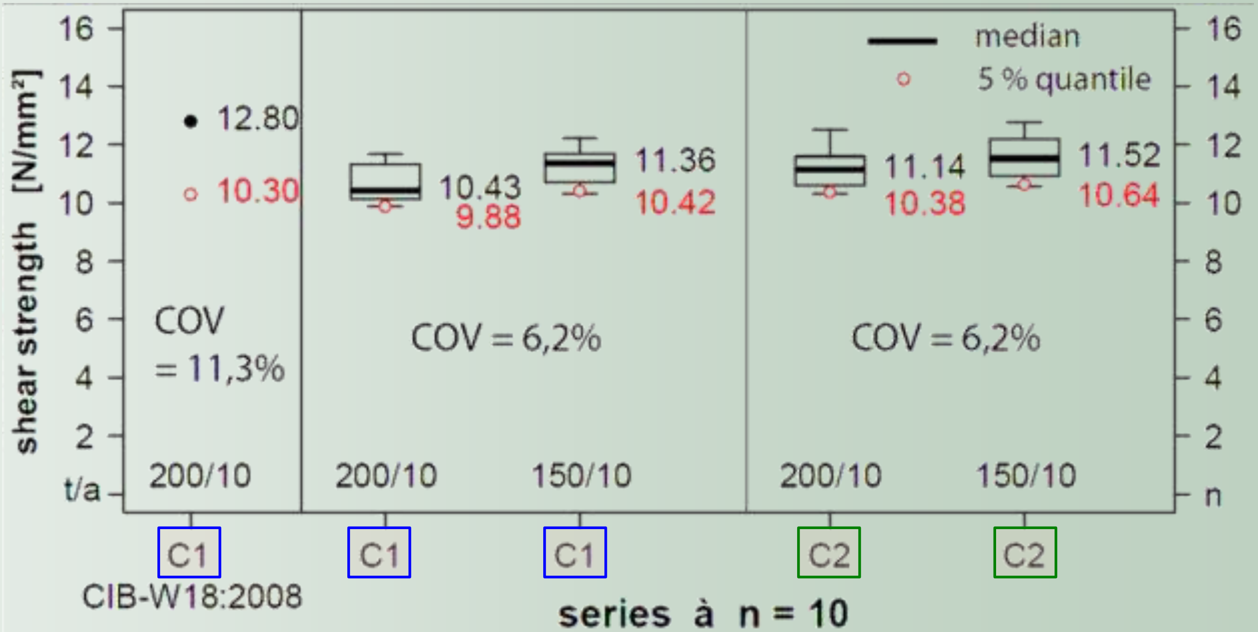
parameter and variations

a [mm]	150	200
t [mm]	10	
t_{gap} [mm]		5

fixed parameters

varied parameters

results:



- **influence of width `a´ [reference dimension: a = 150 mm] (not relevant in practice)**
- **$f_{v,clt,05,t=10}$ = 9.9 ÷ 10.6 N/mm²**

Shear Strength Test – Mechanism I `Shear´

comparison of configuration C1 and C2

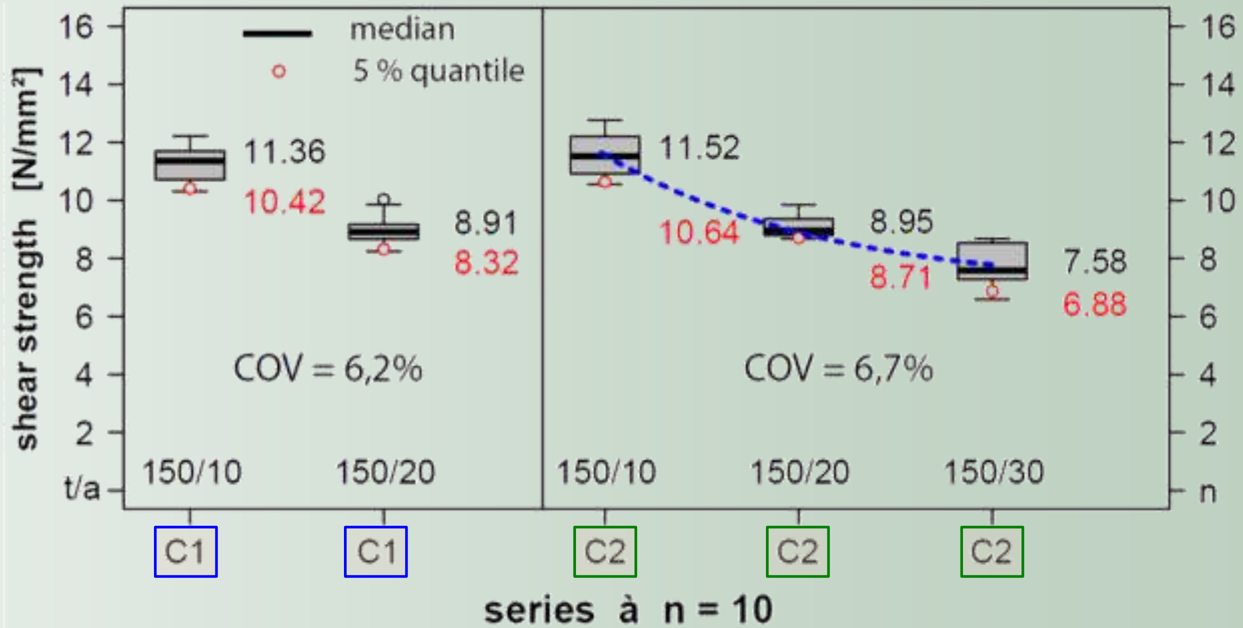
parameter and variations

a [mm]	150		
t [mm]	10	20	30
t_{gap} [mm]		5	

fixed parameters (red)

varied parameters (green)

results:



- **significant influence of thickness `t´ (<u>size and boundary effects!</u>)**
- **$f_{v,clt,05,a=150}$ ~ 10.6 (t=10) | ~8.7 (t=20)**
  ~ 6.9 (t=30) | ~5.2 (t=40) N/mm²
- **recommended value for "mech. I" $f_{v,clt,k}$ ~ 5.0 N/mm² (→ CLTdesigner)**

Shear Strength Test – Mechanism II `Torsion´

overview

torsional test configuration

test specimen

torsional shear stresses in the glueing interface

$$\tau_{T,max} = \frac{M_T}{I_P} \cdot \frac{1}{2} \cdot a = \frac{3 \cdot M_T}{a^3}$$

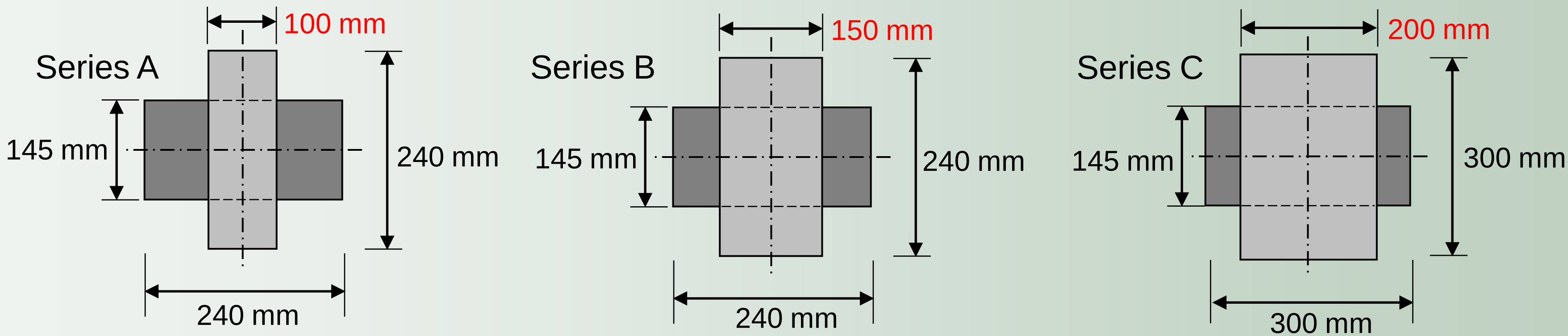
with $J_P = \frac{a^4}{6}$

M_T … torsional moment
J_P … polar sectional moment
… of glueing interface
a … dimension of RVE

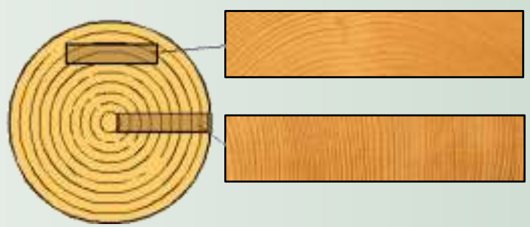
2004: diploma thesis G. Jeitler
„Versuchstechnische Ermittlung der Verdrehungskenngrössen von orthogonal verklebten Brettlamellen" (in German)

Shear Strength Test – Mechanism II ˋTorsion´

variation of glued surface geometry



annual ring gradient
spruce



flat grained boards (SW)

edge-grained boards (RB)

shear stresses in the gluing interface

series	annual ring orientation	5%-quantile [N/mm²]
A	edge grained	3.67
A	flat grained	2.79
B	edge grained	3.20
B	flat grained	2.69
C	edge grained	2.98
C	flat grained	3.10

$$\tau_{T,max} = \frac{3 \cdot M_T}{a^3}$$

$$f_{T,clt,k} = 2.5\ N/mm^2$$

remark:
Value generally accepted!

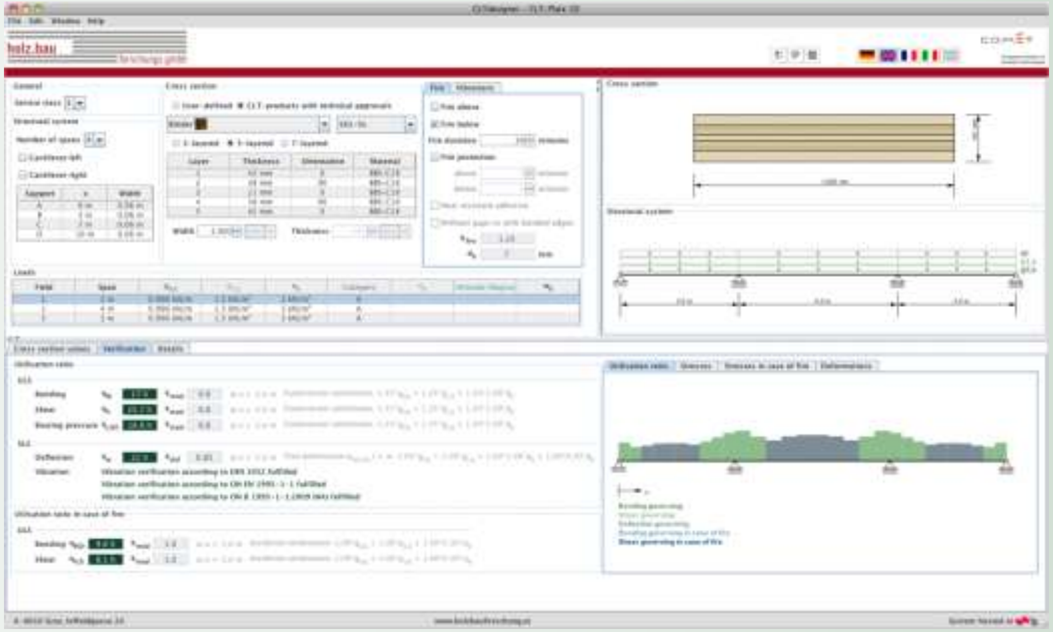
CONTENT

- Research Topics on Cross Laminated Timber (CLT)
  - Point supported Ceilings and Roofs
  - Verifications regarding Serviceability Limit State (SLS)
  - In-Plane Shear Capacity and Verification Methods
  - CLTdesigner – Software Tool for Designing CLT Elements [A. Thiel]
- Summary | Outlook

CLTdesigner – The Software Tool for Designing Cross Laminated Timber Elements (CLT) based on Eurocode 5

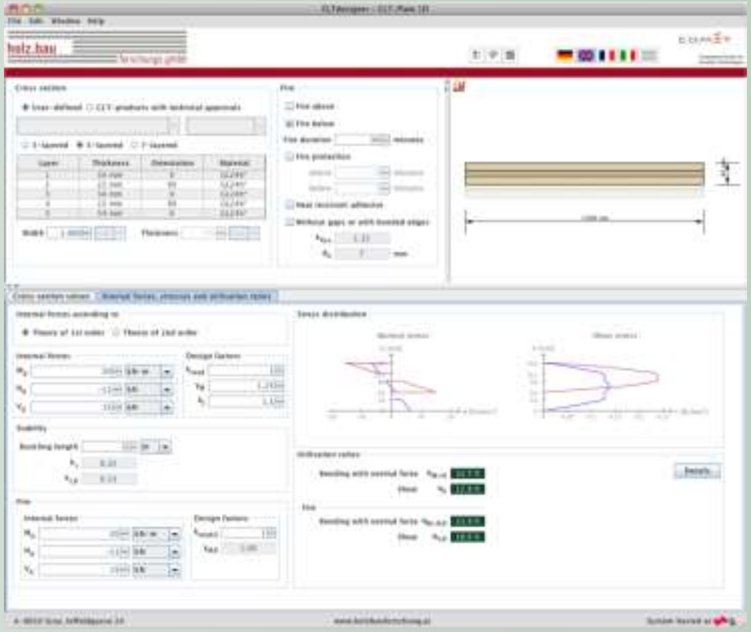
CLT plate 1D – continuous beam

- ULS: bending, shear, bearing pressure, fire design
- SLS: deflection and vibrations



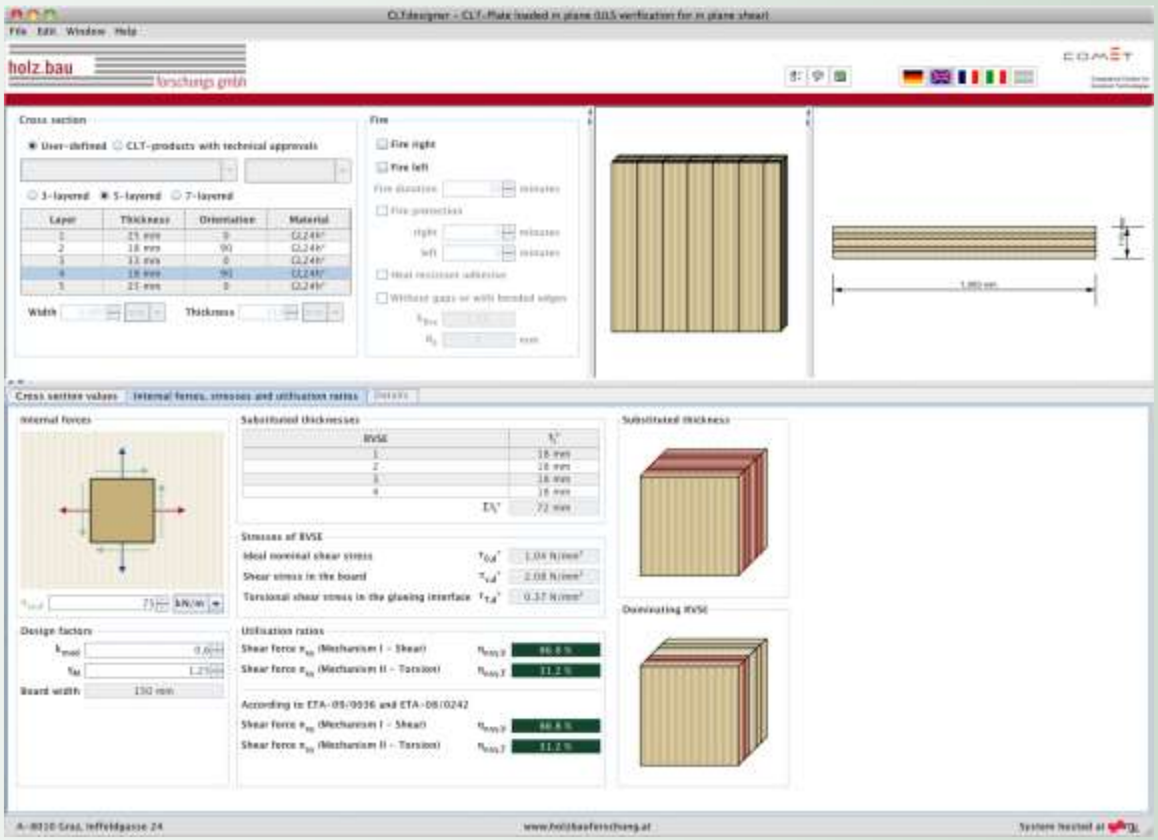
CLT plate 1D – internal forces

- ULS: normal and shear stresses including stability, fire design



CLTdesigner – The Software Tool for Designing Cross Laminated Timber Elements (CLT) based on Eurocode 5

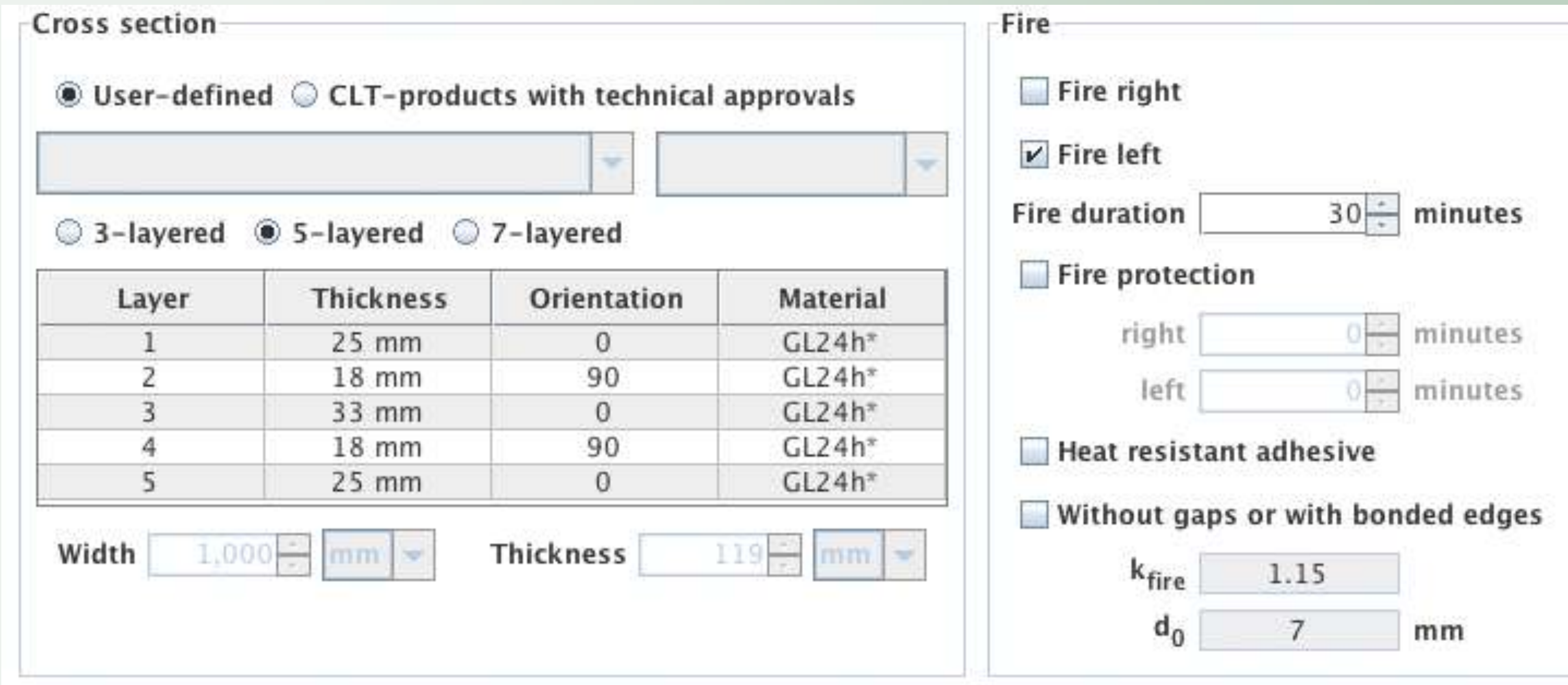
CLT plate – ULS verification for in plane shear (will be published in March 2011)



ULS verification with respect to in plane shear forces for permanent and transient loads as well as accidental design situations (fire)

CLTdesigner – The Software Tool for Designing Cross Laminated Timber Elements (CLT) based on Eurocode 5

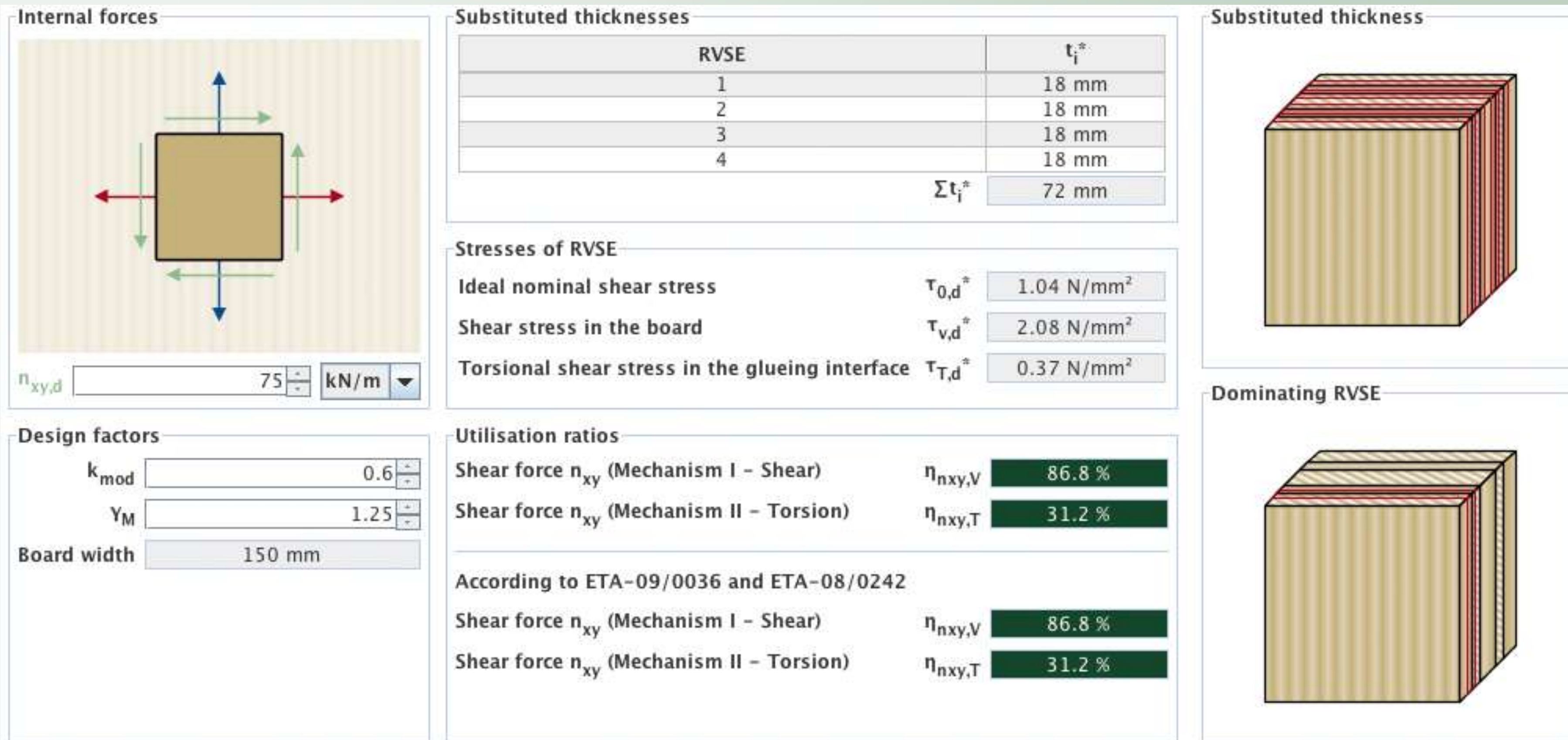
CLT plate – ULS verification for in plane shear



Layer	Thickness	Orientation	Material
1	25 mm	0	GL24h*
2	18 mm	90	GL24h*
3	33 mm	0	GL24h*
4	18 mm	90	GL24h*
5	25 mm	0	GL24h*

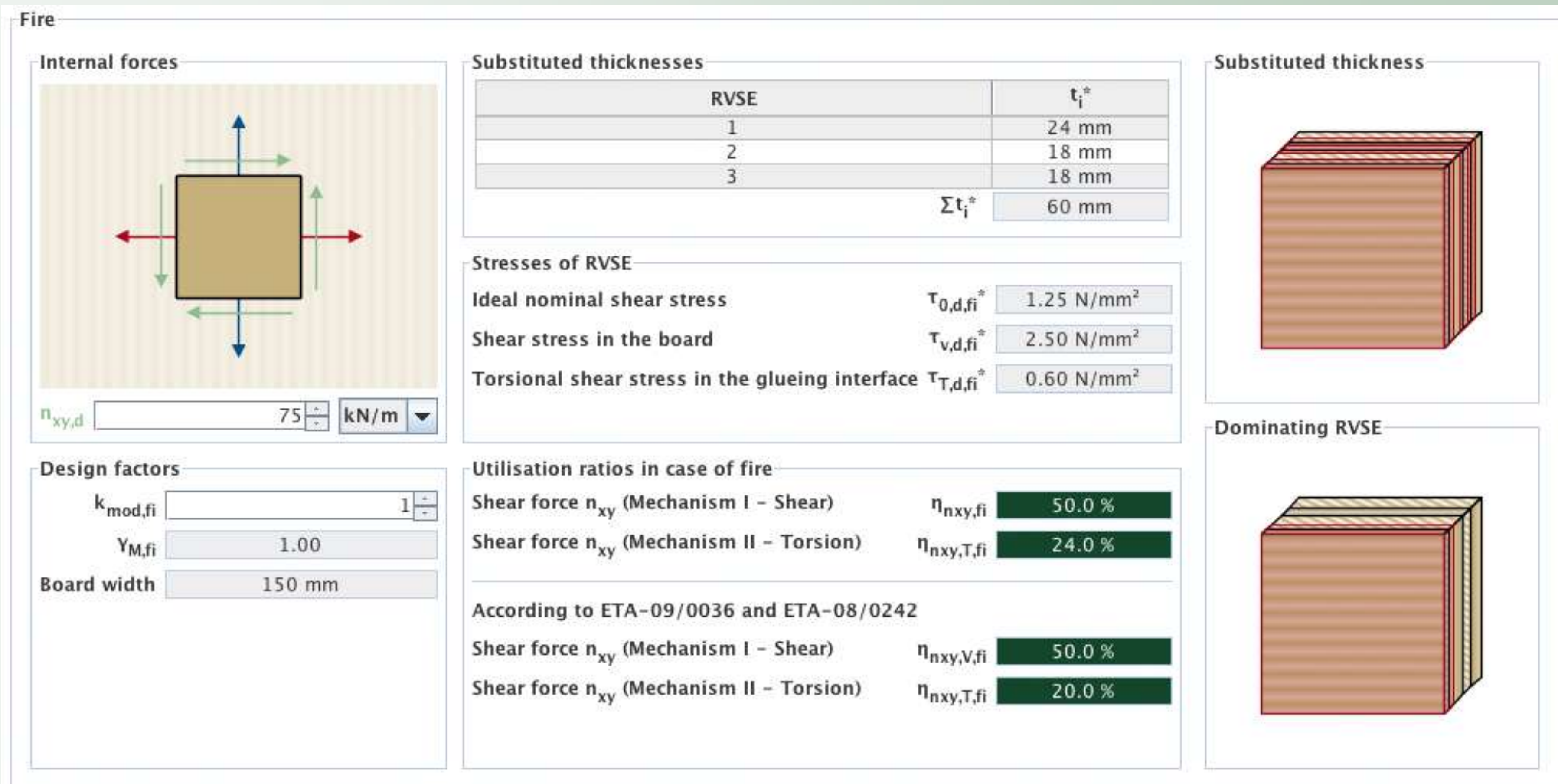
CLTdesigner – The Software Tool for Designing Cross Laminated Timber Elements (CLT) based on Eurocode 5

CLT plate – ULS verification for in plane shear

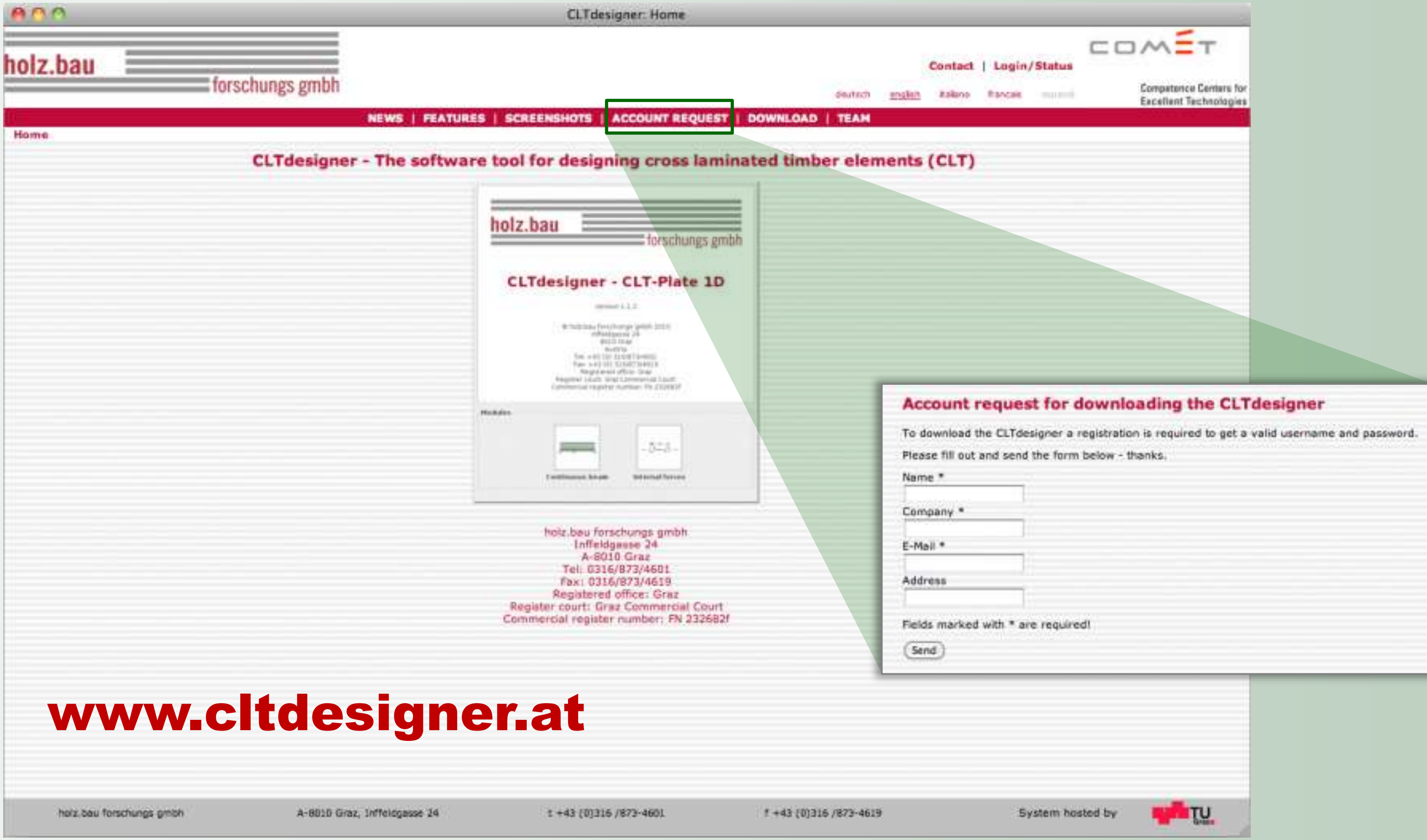


CLTdesigner – The Software Tool for Designing Cross Laminated Timber Elements (CLT) based on Eurocode 5

CLT plate – ULS verification for in plane shear in case of fire



CLTdesigner – The Software Tool for Designing Cross Laminated Timber Elements (CLT) based on Eurocode 5



www.cltdesigner.at

CONTENT

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CLT | Product

- **CLT_standardization** and definition of minimum requirements for the production and quality management (**CLT_qm**)
- **CLT_harmonization** of test procedures for the investigation of product properties and models (**CLT_models**)
- **CLT_diversity** regarding the use of different wood species (e.g. **CLT_poplar**)

3-storey building
Graz | AUT, 2011/12
one appartment: CLT poplar
(ongoing)

CLT | Systems

- use of **folded CLT elements** for different applications
  e.g. bridges, restoration, attic conversion, …

bridge | Bruneck | IT
(transport)

bridge | Bruneck | IT
(mounted bridge)

loft | Graz | AUT
(Arch. DI Zinganel)

- development of **1D connection systems**
  (useable for statically and dynamically loaded CLT elements)

CLT | Transfer

- **CLT_handbooks** are published and **CLT seminars** are realized
  - in Europe (e.g. TU Graz, SAH, FH Biberach, promolegno, ...) and
  - Canada (e.g. FPInnovations, UBC, ...)
- **CLT_designer** → software tool for designing CLT elements

P R O P O S A L

- **CLT_summer_school**
- **CLT_bachelor_ | CLT_master_courses**
  in the frame of the program
  \`EU / CA co-operation in higher education and training´
  - development of innovative curricula (60 ECTS)
    at least two Univ. of Europe and two of Canada are required
    → mobility of teaching staff and students

dynamic tests | heeldrop

compression perp.to grain | TU Graz

slab shear tests | TU Graz

THANK YOU FOR

YOUR ATTENTION

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