Cross Laminated Timber (CLT) in Europe – from Conception to Implementation

University of British Columbia | Department of Wood Science

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Competence Centre holz.bau forschungs gmbh Graz | AT
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- ”TIMBER“ at the Graz University of Technology
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  - R&D Areas

- „European Timber Solid Construction“ – Cross Laminated Timber
  - Introduction | History
  - Use | Application Examples
  - Technology
  - Modelling and Verification (Design Process)
  - Building Physics | Leading Details
  - Future Developments

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GRAZ UNIVERSITY OF TECHNOLOGY
Austria / Europe
7 faculties | 11,264 students | staff 2,222
budget: € 150 Mill. (1/3 3rd party budget)

Faculty of Civil Engineering Sciences
17 institutes | about 1,140 students
[207 “diploma”, 693 “Bachelor”, 146 “Master”, 93 “PhD”]

Institute for Timber Engineering and Wood Technology
1991: Chair for Timber Engineering
10|2004: Institute Timber Engineering and Wood Technology
Scientific staff: 7.0 FTE | third-party-budget: € 250,000 (2008)

Competence Centre holz.bau forschungs gmbh
09|2002 Acceptance of 4-year-fundings: Competence Center Timber Engineering and Wood Technology
12|2002 Competence Centre holz.bau forschungs gmbh
09|2007 Acceptance of 5-year-fundings: K-Project “timber.engineering” | COMET-Programme
Scientific staff: 7.1 FTE | budget: € 1,000,000 (2008)
AREA 1
Timber Engineering (TE) – Design and Construction Sciences (DCS)

1.1 Shell and Spatial Timber Constructions (SSTC)

1.2 Innovative and Intelligent Connection Systems (IICS)
ARE 2
Wood Technology (WT) – Material and Structure Sciences (MSS)

2.1 Advanced Products and Test Methods (APTM)

2.2 Material Modelling and Simulation Methods (MMSM)
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Timber Solid Constructions define culture in constructions in well-wooded regions of Europe, e.g.:

- CLT – history

Timber Lightweight Construction (TLC) vs. Timber Solid Construction (TSC)

- **Load transfer**
  - Outdoor
  - Indoor
  - Insulation bearing

- **Past and Current**
  - **Bar-like** construction
    - Timber truss construction
  - **Slab-like** construction
    - Timber frame construction
  - **Bar-like** (bracing)
    - (parallel to grain)
    - Timber bar construction (especially in Scandinavia)
  - **Bar-like** (perp. to grain)
    - Timber log construction (especially in Alpine Space)

- **Tradition**
  - Stave church
  - Chalet
Timber Solid Construction (TSC) – INNOVATION based on TRADITION

**load transfer**

- **bar-like** (parallel to grain)
  - timber bar construction (especially in Scandinavia)
  - stave church
- **bar-like** (perp. to grain)
  - timber log construction (especially in Alpine Space)
  - chalet
- **slab-like** (interaction of “parallel” and “perp.” to grain)
  - Timber Solid Construction with CLT (new “European Timber Solid Construction”)
  - detached house Jeitler

**bonding**

- **Scandinavian-TSC** [longitudinal]
- **Alpine Space-TSC** [perpendicular]
- **European-TSC** [blocked]
1974 “Timber roof structures”
multi-layer composite
structure of boards & beams
[E. Cziesielski | DE]

1981 “Basics of modern timber engineering”, CLT as web in
solid-web-girders
[G. Dröge | K.-H. Stoy | DE]

1985 “board-layered plates” –
PhD, [N. Lischke | DE]

1989 “CLT as slab- and plate-
stressed deck-bearing
structure”, SAH-Meeting
[A. Steurer]

1994 „Starrer und nachgiebiger
Verbund bei geschichteten
flächenhaften Holzstrukturen”
PhD [G. Schickhofer | AT]

2000 „branding of CLT timber”
at COST E5 | Venice | IT

2002 PhD [R. Bosl | DE]

2003 R&D-programme at TUG

2004 PhD [A. Scholz | DE]

2005 PhD [A. Jakobs | DE]

2006 “6.GraHFT”, TUG | AT, Sofie, | IT

2007 “39.SAH-Meeting” | CH

2008 PhD [A. Gülzow | CH]

2009 seminars | workshops, TUG | AT

2010 PhD [T. Moosbrugger | AT]

2015 FORECAST

phase 1:
niche product

Æ

papers

seminars in Italy (promo_legno)

phase 2:
pilot projects | market launch

≈

mass product

≈ 0.6 ÷ 1.0 MILL m³

2015 FORECAST

phase 1:
niche product

Æ

phase 2:
pilot projects | market launch

≈

mass product

≈ 0.6 ÷ 1.0 MILL m³

2015 FORECAST
Cross laminated timber (CLT) changed its position – due to a continuous increasing market share in Europe – from a niche to a mass product.

Till 2015 a doubling (0.6 MILL m³) or triplication (1.0 MILL m³) of production potential world wide can be expected. New production lines in Europe – AT | DE | FI | SE – are projected or nearly in realisation.

In the long run the product CLT is going to gain the same relevance as GLT.

Famous machine manufacturer in Europe record increasing number of requests and react (late) on the booming CLT-market.

The Timber Solid Construction in CLT is not only considered by architects and engineers but agreed and attain acceptance and status of a standard construction product.
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pre-fabricated bridge deck plate

„Wandritsch“-road bridge (view)

„Wandritsch“-road bridge
(1998)
St. Ruprecht / Styria (A)

surface course 30 mm
melted asphalt 50 mm
sealant 5 mm
plywood 6 mm
“KLHmasive” (9 layers á 19 mm) 171 mm
BS18-ribbs (GL36) 160 mm

timber-timber composite

6 160 160 160 160 160

30 mm
50 mm
5 mm
6 mm
171 mm
160 mm

6 mm
“KLHmasive” (9 layers á 19 mm)
CLT – use | application examples

building technology centre (section 1)

under-stressed framework

building technology centre
section 1 (2001)
Graz / Styria (A)

innovative connection technique

production of CLT-elements
CLT – use | application examples

„Austria-House“ (2006)
Turin / Italy
CLT – use | application examples

„Austria-House“ (2010)
Vancouver / Canada

5-layer CLT-elements
t_{CLT} = 196 mm
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production process of Cross Laminated Timber (CLT) elements

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<tr>
<th>step</th>
<th>intermediate product</th>
<th>intermediate production process</th>
</tr>
</thead>
<tbody>
<tr>
<td>STEP I: log</td>
<td>cross cut</td>
<td></td>
</tr>
<tr>
<td>STEP II: board</td>
<td>grading</td>
<td></td>
</tr>
<tr>
<td>STEP III: finger-jointed lamella</td>
<td>trimming</td>
<td></td>
</tr>
</tbody>
</table>

- STEP I: log
  - Cross cut
  - 500 to 600 mm ≤
  - ≤ 150 mm
- STEP II: board
  - Grading
  - Trimming
- STEP III: finger-jointed lamella
  - Finger jointing
production process of Cross Laminated Timber (CLT) elements

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<tr>
<td>STEP III: finger-jointed lamella</td>
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</tr>
<tr>
<td>intermediate STEP: single-layer panel</td>
<td>edge gluing</td>
<td></td>
</tr>
<tr>
<td>STEP IV: Cross Laminated Timber (CLT)</td>
<td>face gluing</td>
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production process of Cross Laminated Timber (CLT) elements

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<td>intermediate STEP: single-layer panel</td>
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**bonding pressure horizontal**
approx. 0.2 N/mm²

1.25 m (to 3.0 m)
up to 16.5 m (or longer)
### Production Process of Cross Laminated Timber (CLT) Elements

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#### Bonding Pressure Vertical:
- approx. 0.6 N/mm² with hydraulic equipment
- < 0.1 N/mm² with vacuum
- approx. 0.1 N/mm² with clip connection
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design acc. limit states of …

- ultimate bearing capacity (ULS-design)
- serviceability (SLS-design)

for the CLT-slab (roof | ceiling)
e.g. 5- or 7-layered CLT ceiling-element

for the CLT-plate (wall)
e.g. 3- or 5-layered CLT-wall element

action vertical
to plane of slab

action in plane
of panel

storey height

storey width

element length

element width

$M_{\text{max}}$ $V_{\text{max}}$ $P_{\text{max}}$
CLT – modelling and verification

**ULS design …**

- $M_{\text{max}}$  bending
- $V_{\text{max}}$  shear due to transverse force
- $P_{\text{max}}$  compression perpendicular | bearing pressure

---

- design value of the **consequences** of the governing combinations of **actions** $\leq 1.00$
- design value of the **resistance** $\leq 1.00$

---

- $\sigma_{m,\text{edge},d} \leq 1.00$
- $f_{m,\text{CLT},d} \leq 1.00$
CLT – modelling and verification $[\sigma_{m,\text{edge}}]$ 

Design value of the consequences of the governing combinations of actions ... 

**BENDING STRESS** $\sigma_{m,\text{edge},d}$

Stress distribution within the cross section

**Basis:** model of the classical “Timoshenko-bar” | “transversal shear-flexible bar”

→ sufficient accurate for practical applications [15 < L / H < 30]

E.g.: 5-layer CLT-element

<table>
<thead>
<tr>
<th>Layer</th>
<th>$\alpha$</th>
<th>$E_0$</th>
<th>$G_0$</th>
<th>$t$</th>
</tr>
</thead>
<tbody>
<tr>
<td>#5</td>
<td>0</td>
<td>$E_{90}$</td>
<td>$G_{90}$</td>
<td>$t_5$</td>
</tr>
<tr>
<td>#4</td>
<td>90</td>
<td>$E_{90}$</td>
<td>$G_{90}$</td>
<td>$t_4$</td>
</tr>
<tr>
<td>#3</td>
<td>0</td>
<td>$E_0$</td>
<td>$G_0$</td>
<td>$t_3$</td>
</tr>
<tr>
<td>#2</td>
<td>90</td>
<td>$E_{90}$</td>
<td>$G_{90}$</td>
<td>$t_2$</td>
</tr>
<tr>
<td>#1</td>
<td>0</td>
<td>$E_0$</td>
<td>$G_0$</td>
<td>$t_1$</td>
</tr>
</tbody>
</table>

$E_{90}$, $G_{90}$, $E_0$, $G_0$ → shape like “saw teeth”

$\sigma_{m,\text{edge}}$ = $\sigma_{m,\text{edge}}$ (sum over all layers)

$K_{CLT}$ = $\frac{M_{\text{max,d}}}{t_{CLT} \cdot E_i}$

$K_{CLT}$ = $\sum_{i=1}^{n} (J_i \cdot E_i) + \sum_{i=1}^{n} (A_i \cdot e_i^2 \cdot E_i)$
design value of the **resistance** ...  
**BENDING STRENGTH** $f_{m,\text{CLT},d}$

**two primary system effects:**

- **laminating effect** (vertical layered, akin to GLT)
- **system effect** (horizontal, mutual acting elements)

\[
f_{m,c,05} = m \cdot f_{t,0,l,05}^{0.80} \cdot k_{\text{sys,CLT}}(n) \cdot k_{\text{CLT/GLT}} \cdot k_{d,\text{CLT}}
\]

bearing model for GLT in bending \( \cdot 1.06 \)  
\((f^{0.82} \rightarrow f^{0.80})

- **laminating effect**
- **system effect**
- **structure / assembling effects**

\[
m = 2.8 \quad \text{for GLT (vis.)}
\]

\[
f_{m,c,05} \approx 1.25 \cdot f_{m,g,05}
\]

\[
f_{m,c,k}^{1)} = 3.0 \cdot f_{t,0,l,k}^{0.8}
\]

\[
f_{t,j,k} \geq 1.2 \cdot f_{t,0,l,k}
\]

\[
f_{m,c,k}^{1)} = 3.5 \cdot f_{t,0,l,k}^{0.8}
\]

\[
f_{t,j,k} \geq 1.4 \cdot f_{t,0,l,k}
\]

for $\text{CoV}(f_{t,0,l}) = 25 \% \pm 5 \%$

for $\text{CoV}(f_{t,0,l}) = 35 \% \pm 5 \%$

1) characteristic bending strength of CLT, referred to a reference depth of $d_{c,\text{ref}} = 150 \text{ mm}$
CLT – modelling and verification [$f_{m,CLT}$]

CLT, boards C24+(vis.): GLT: $f_{m,g,05,d=600} = 24 \text{ N/mm}^2$; timber: $f_{t,0,l,05} = 14.7 \text{ N/mm}^2$; $f_{m,05,d=150} = 24 \text{ N/mm}^2$

acc. design model: \[ f_{m,c,05,d=150} = 3.5 \cdot f_{t,0,l,05}^{0.8} = 3.5 \cdot 14.7^{0.8} = 30.06 \text{ N/mm}^2 \]

acc. DIBt Zxxx: \[ f_{m,c,05,d=150} = 1.1 \cdot f_{m,g,05,d=600} \cdot \min \left\{ (600/150)^{0.14} ; 1.1 \right\} = 1.1 \cdot 24 \cdot 1.1 = 29.04 \text{ N/mm}^2 (-3\%) \]

3.2 Bemessung
3.2.1 Beanspruchung rechtwinklig zur Bauteilebene
3.2.1.1 Der Nachweis der Spannungsverteilung und der Schnittgrößen eines "HMS-Elementes" rechtwinklig zur Bauteilebene ist nach der Verbundtheorie unter Berücksichtigung von Schubverformungen zu führen.

Beim Biegespannungsnachweis ist nur die Normalspannung der Bretter am Querschnittsrand nachzuweisen, der Nachweis der Scherzustände im Brettsperholz bleibt.

Beim Biegespannungsnachweis darf die zulässige Biegespannung bzw. der Bemessungswert der Biegefestigkeit mit einem Systembeiwert $k$, multipliziert werden:

\[ \sigma_{m,BSP,d} \leq 1 \] mit $n = \text{Anzahl der nebeneinander liegenden Bretter}$

acc. ETA-09/xxx: \[ f_{m,c,05,d=150} = \min \left\{ \left\{ 3.5 \cdot f_{t,0,l,05}^{0.8} \right\} ; \left\{ 1.2 \cdot f_{m,05,d=150} \right\} \right\} = \min \{30.06; 28.80\} = 28.80 \text{ N/mm}^2 (-4\%) \]
... further ULS and SLS-design procedures:

for the CLT-slab (roof | ceiling | …)

**ULS**
- shear due to transversal force
  - in the governing layer lengthwise
    - with $f_{v,CLT,k} = 3.0 \, N/mm^2$ ($\equiv f_{v,GLT,k}$)
  - in the governing layer perp.
    - with $f_{r,CLT,k} = 1.25 \, N/mm^2$ ($\equiv$ approvals)
- compression perp. at bearings
  - with $f_{c,CLT,90,k}$ and $k_{c,CLT,90}$
- fire design
  - without gaps: $\beta_0 = 0.65 \, (1.30) \, mm/min$
  - with gaps: $\beta_n = 0.80 \, (1.60) \, mm/min$

**SLS**
- deformations | deflections
  - creep factor: $k_{def} = 0.80 \div 0.90 \, (SC1)$
    - $k_{def} = 1.00 \div 1.10 \, (SC2)$
  - shear correction factor $\kappa \approx 0.25 \, (!)$
- vibration design
  - with Lehr’sche damping coefficient
    - $D = 0.025 \div 0.040 \, [\text{--}]$

for the CLT-plate (wall | …)

**ULS**
- shear in plane direction
  - mechanism I “shear”
    - with $f_{v,CLT,k} \approx 5.0 \, N/mm^2$ ($\equiv$ approvals)
  - mechanism II “torsion”
    - with $f_{t,CLT,k} = 2.5 \, N/mm^2$ ($\equiv$ approvals)
- tension and compression
- stability design
  - buckling

**SLS**
- deformations | deflections in plane
  - without openings:
    - $G^* \approx 450 \div 500 \, N/mm^2$

→ for further information and details

CLT-handbook | 11.2009
CLT – connection techniques

connection techniques within the Timber Solid Construction …

connections of in general large-sized CLT-wall, -ceiling, -roof elements with …

- self drilling screws
- dowel type fasteners
- glued in rods
- nails
- system connector

at the contact gap …

- foundation | wall
- wall | wall
- wall | ceiling | wall
- ceiling | ceiling

exposure in the contact gaps in …

- all three main axes
- static and dynamic (earthquakes)
contact gap “foundation | wall”
connection technique:
- steel plate – timber with nails

5-layered CLT-wall element

steel angle (outside)

sealant and altitude compensation

reinforced concrete foundation

bandings due to wood protection (e.g. oak, black locust)
CLT – connection techniques

contact gap “wall | wall”
connection techniques:
- self drilling, partly or full threaded screws
- system connector | steel core and glued in rods
- system connector | hook connector

5-layered
CLT-wall element
sealing tapes
(compression band)
self drilling screws
corner joint
e.g. bearing 5-layered
CLT-wall element (outdoor)
sealing tapes
(optional)
e.g. bearing 5-layered
CLT-wall element (indoor)
hook connector
(self-centring assembling)
T-joint

wall:wall

sealing tapes
embedded steel core
longitudinal joint

corner joint
T-joint
longitudinal joint
contact gap “wall | ceiling | wall”

collection techniques:
- self drilling screws
- steel angle | nailing

- sealing tapes (compression band)
- positively tied by screws (screws in grain shall be avoided!)

noise insulation and / or separation
(impact sound insulating interlayer | elastic support in combination with a ceiling construction of:
  - floating floor
  - impact sound insulation
  - fill (split)
  - detached ceiling
**CLT – connection techniques**

**contact gap “ceiling | ceiling”**

- self drilling screws
- bonded joint
- overlapping / interlocking joint

- e.g. 5-layered CLT-ceiling element
  - overlapping / interlocking joint
  - positively tied by screws
  - sealing tapes (compression band)

- e.g. 5-layered CLT-ceiling element
  - screwing under angle (e.g. 45°)

- e.g. 5-layered CLT-ceiling element
  - on the top and underneath strapping (adhesion by screwing pressure)

**transverse force joint**

**bending stiff joint**
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building physics aspects …

→ thermal insulation
  ▪ wintry thermal insulation
  ▪ summery thermal insulation (over warming of indoor climate)

→ moisture protection | air tightness → tests at TU Graz and on-site
  ▪ condensate formation

→ noise insulation
  ▪ noise indoor | airborne noise | footfall noise | → requirements

→ fire protection (tests in cooperation with ETH Zurich | EMPA Dübendorf)

… leading details

in cooperation with the Institute for Building Construction and Building Physics at TU Graz → see CLThandbook | Annex “Leading Details”
noise protection aspects – leading detail “wall | ceiling | wall”

- airtight plain
- sealing tapes
- detached floor
  (vibration bracket)
- noise protecting support construction

noise protected support (ext. wall)
noise protected support (load bearing wall)
noise protected support (flat separating wall)
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building systems with CLT ...

folded panels with CLT

- principles concerning folded panels → construction principle from nature
- “plane-active bearing systems” acc. bionic principles
- variety of folded panel constructions and applications

half prismatic
prismatic
pattern of parallel straight lines

pyramid
raised planes

capped top
antidromic folded panels
clarification of the difference between “decisive” and “non decisive” modification: attics upgrading and expansion of Wilhelmina style houses

- reinforced concrete vs. CLT-European Timber Solid Construction (ETSC)

earthquake actions acc. to “simplified response spectrum” acc. EN 1998-1
folded panels with CLT: field of application up to 20 m free span

- column-free overspan of roof space
- short erection time and immediately usability

flexible use- and adaptable roof space

column-free overspan of roof space by triangle shaped folded panel of 5-layered CLT-elements, 140 mm thick

end wall as support of the folded panel

shear plates of 5-layered CLT-elements 140 mm thick for bearing of horizontal loads (e.g. wind)
Verification of appropriateness of the Timber Solid Construction in CLT for seismic regions [see e.g. presentation A. Ceccotti]

e.g. reconstruction L’Aquila | IT, 2009

research topic: catastrophic events _seismic_ fire_impact_wind

EU-project “Seismic Engineering Research Infrastructures for European Synergies [SERIES]”

Sub-project: “Seismic Performance of Multi-Storey Timber Buildings”

→ cooperation of three Universities (Minho | Trento | Graz)

→ involved industries in AT: MM | SET
Timber Solid Construction in CLT – “Brucknerstrasse | Graz | AT” (status: planning)

- 2 three-storey buildings with in total 22 accommodation units | completion 2011
- verification acc. EC5 including seismic design acc. EN 1998-1
- one unit constructed in hardwood → CLT_poplar | GLT_poplar+ash
- analysis of building physics:
  - leakage tests (‘blower door’)
  - moisture content & temperature as functions of time
  - vibration analysis of CLT-ceiling
R&D-necessities concerning plant construction

→ process optimisation of a CLT production line

Influences on product and production:

- base material (species & grading, e.g. 3 grading classes)
- pros and cons of edge-gluing
- FJ-geometry and –position within the board or single panel
- influence of pressure for edge and surface target: reduction of the requ. minimum pressure in dependency of adhesive type → “lightweight press”
- one press for two and more products (CLT, GLT, DUO / TRIO, …)

**current requ. pressure 0.6 N/mm² → high loads!**

**CLT | 3-layers**

e.g. 3 x 30 mm → $t_{CLT} = 90$ mm

**GLT | vertical laminated**

 e.g. 3 x 30 mm → $t_{GLT} = 90$ mm

shifted, edge-glued laminations
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  - Technology
  - Modelling and Verification (Design Process)
  - Building Physics | Leading Details
  - Future Developments

- Summary
after 20 years from idea to **first national technical approvals and prototypes in 1998** followed further 10 years of intensive R&D beside **more approvals in Europe** and the **establishment and distribution of the European Timber Solid Construction technique (ETSC)**

the next 5 to 10 years indicate **industry sector projects** in regard to **standardisation, R&D, marketing and transfer**

- **standardisation**
  - standardisation portfolio consisting of regulations concerning test-, product-, design- and construction procedures

- **R&D**
  - development of construction systems
  - design procedures for special cases
    - pin-supported slabs | special design procedures for supports
    - **earthquake design acc. EN 1998 | preparation for practice**
  - building physics in regard to CLT
    - non-stationary moisture transport through a CLT cross section
    - fire design | standardisation of charring rates

- **marketing and ”know how”-transfer**
  - technical meetings | seminars | workshops
THANK YOU FOR
YOUR ATTENTION
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