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Canadian CLT Design Provisions

Seminar on CLT Design, including Connections, and Resistance to Lateral and Gravity Loads

Moncton, NB

December 1, 2015

Recent Trends/Opportunities

Strong interest to re-specify wood in non-res. & mid- & high-rise buildings (i.e., renaissance in wood construction)

- **Key drivers:**
  - Availability of new generation of innovative EWP, connection systems & design tools
  - Recent changes to building codes
  - Environmental concerns (i.e., climatic changes)- favors wood
  - Development of CLT

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A Wealth of EWP

- Panels
  - Plywood, OSB (Structural)
  - MDF or HDF (Non-structural panels)
- Wood I-Joists (since 1970)
- Wood trusses
- Glulam (since 1893)
- Structural Composite Lumber (since 1980)
  - LVL, PSL, LSL
- Cross Laminated Timber (CLT)

Innovative Connection Systems for Timber Constructions













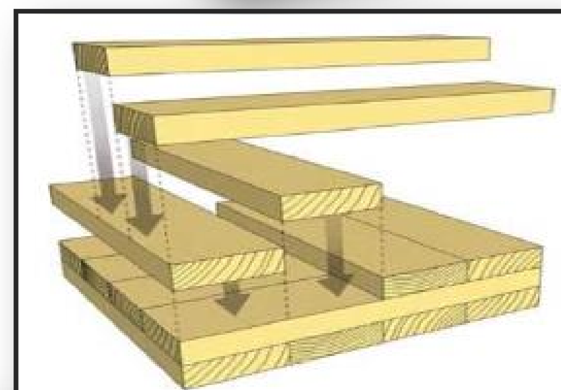
What is Possible to Build with Wood?!

- LWF Construction (up to 6 storeys)
- Mass Timber Frame (e.g. P&B glulam)
- Massive Timber Plates (e.g., CLT, LVL, etc.)
- Hybrid Systems



Cross-laminated Timber (CLT)

- Lightweight & prefab. panels
- Wood strips stacked crosswise on top of each other (glued or nailed)
- Thicknesses vary from 50 to 600 mm
- Panels are 2-3 m wide x 18 m long



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Manufacturing of CLT

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Cross-laminated Timber (CLT)

- Cross lamination minimizes swelling & shrinkage
- Increases considerably the loadbearing capacity
- Two way action such as concrete slab
- Good seismic & fire resistance – heavy timber construction (i.e., inherent fire resistance)

Additional Advantages of CLT Panels

- o Produced with precision CNC machines
- o Quick on-site assembly

(One storey/week or less per avg. size floor plan)

- Min site Noise (equipment/personal)
- Min site Waste (high level of prefab.)
- Ideal for dense urban in-fill projects
- Health and safety benefits

- o Cost competitive in certain applications
- o Renewable material from sustainable forests

One of the most promising wood alternative to concrete assemblies..

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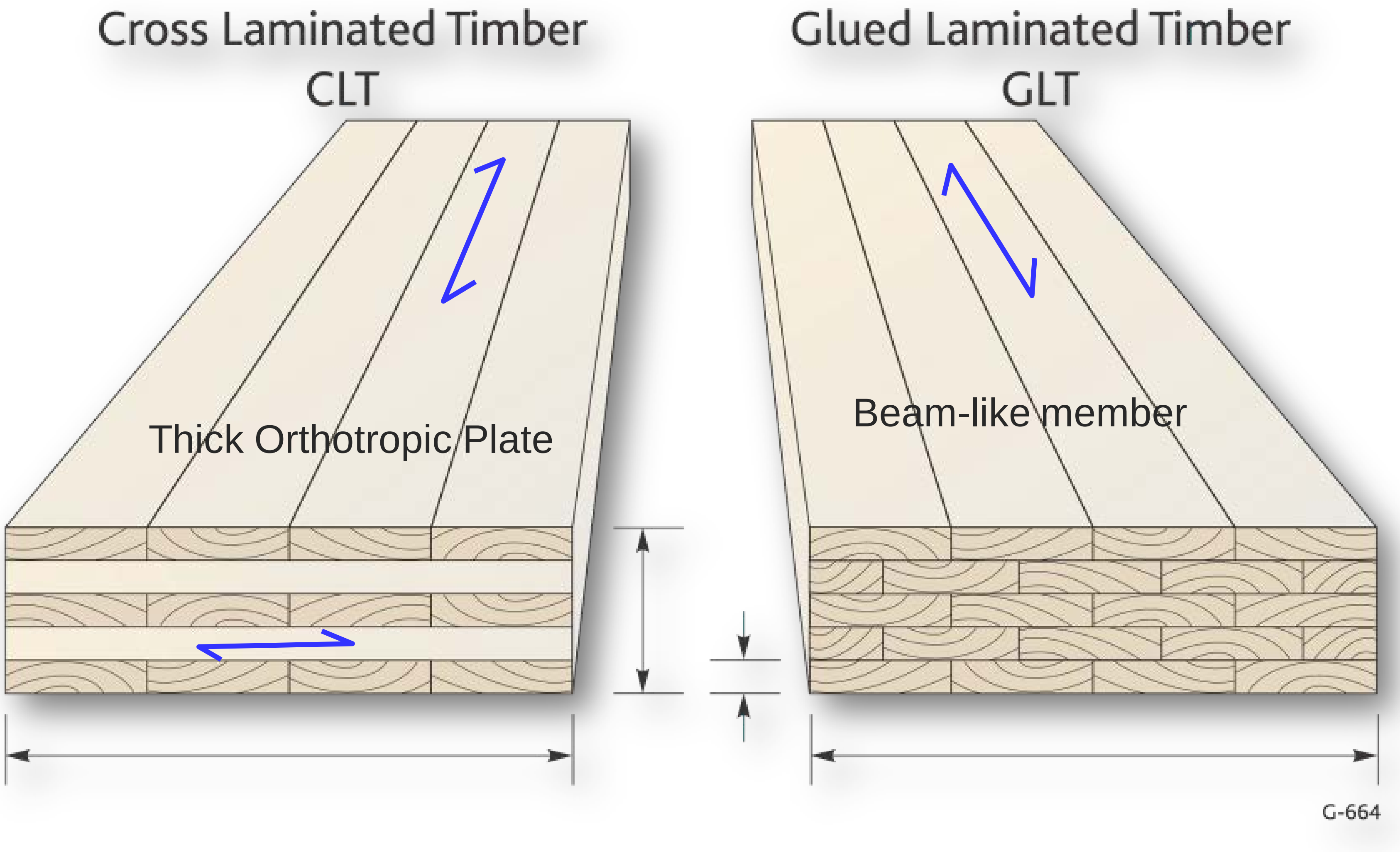
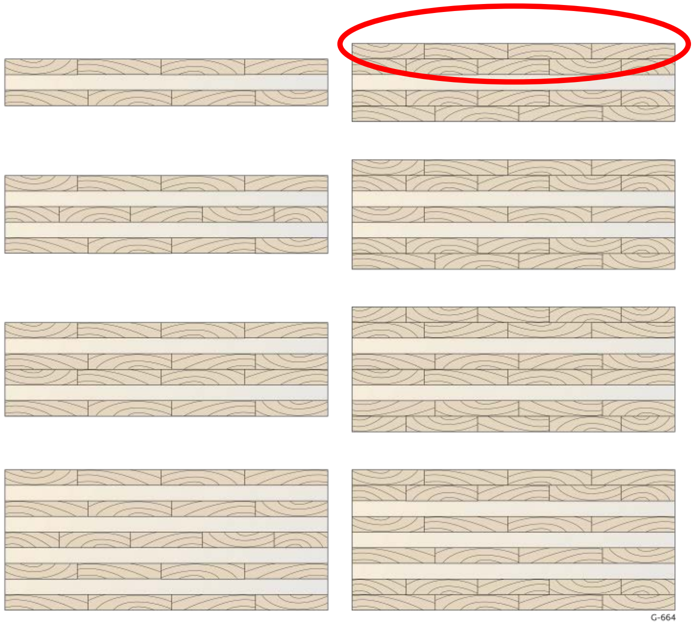
Why CLT is Different than Glulam?!

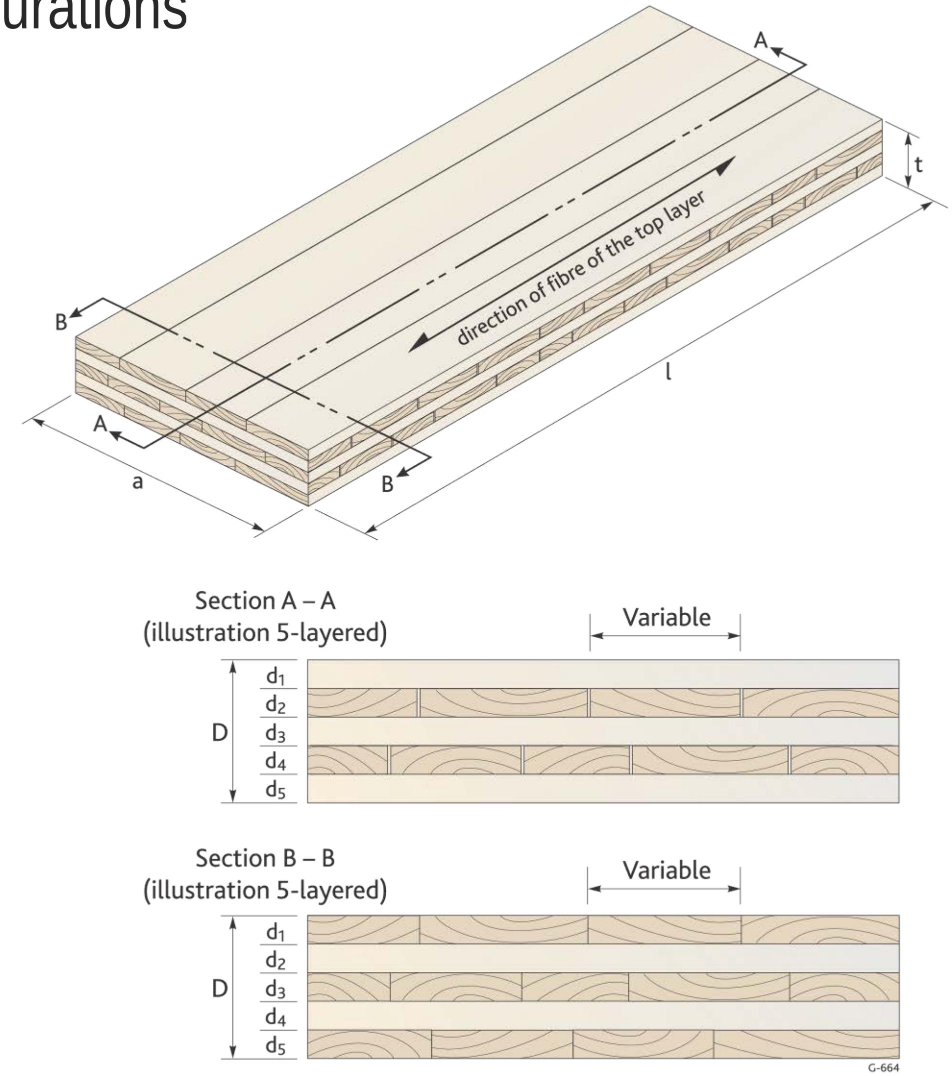


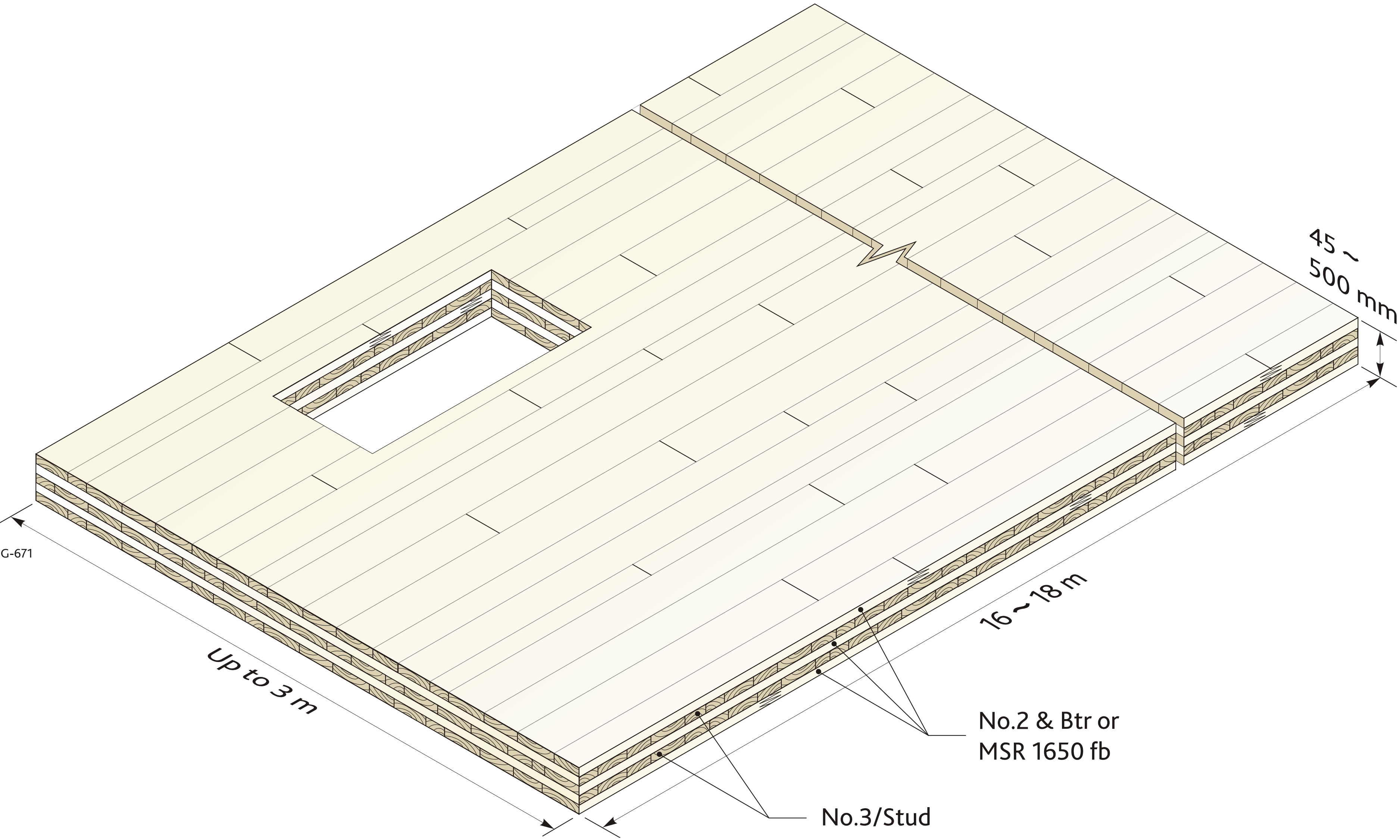
Configurations

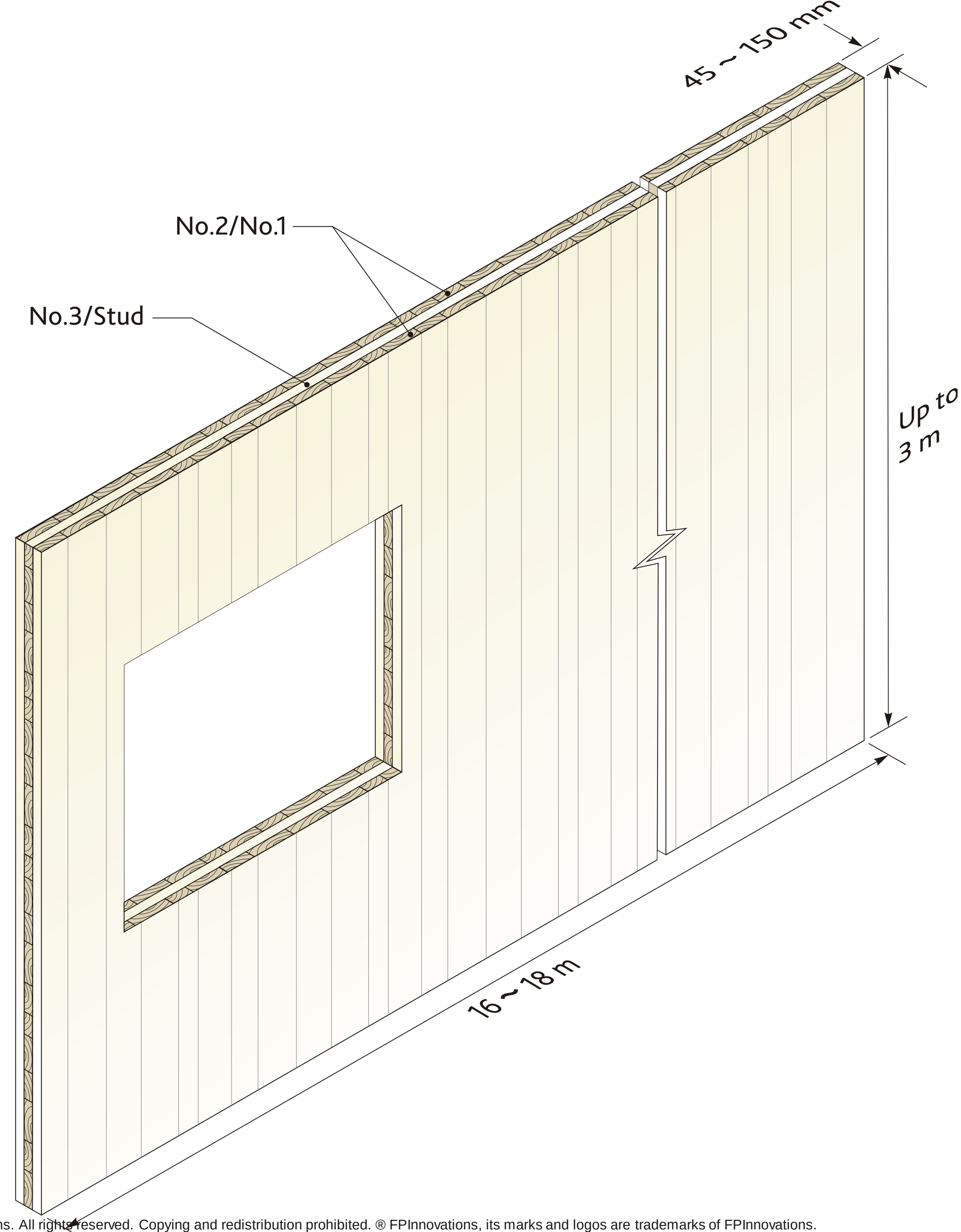
Some possible configurations

Single outer ply | Multiple outer plies





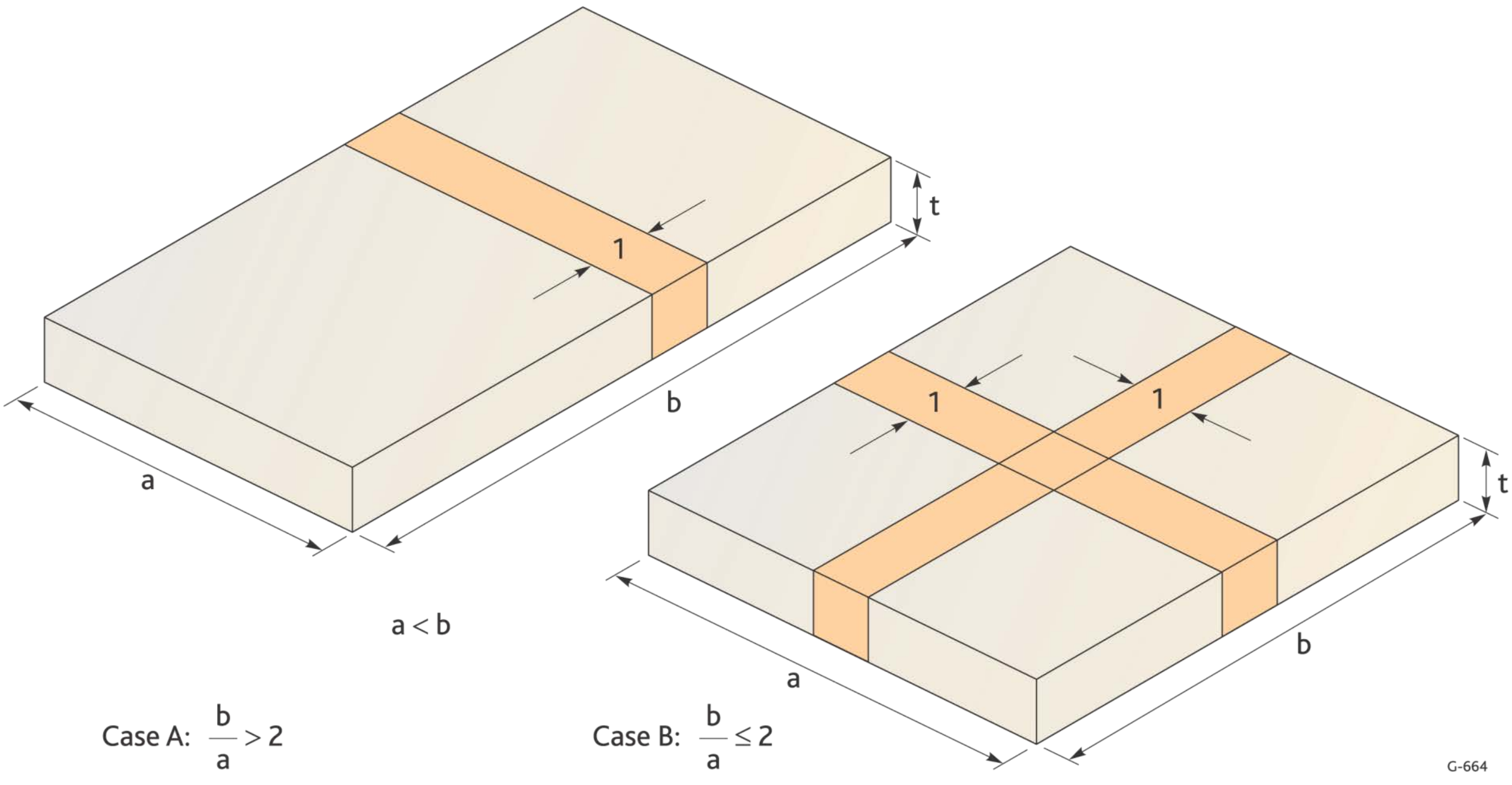

45 ~ 500 mm
16 ~ 18 m
Up to 3 m
No.2 & Btr or MSR 1650 fb
No.3/Stud
G-671



G-671

One-Way or Two-Way Slab Action

≈Two way action capability as concrete slab



CLT System in Mid-Rise

Non-residential Applications

CLT Roof on Top of Concrete/Steel Building, Quebec

CLT in Hybrid Construction

- CLT with concrete stairwells

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CLT in Hybrid Construction (Parking Garage)

CLT in Canada

- CLT introduced to Canada in 2005/6
- Canadian-made CLT is commercially available (2 manufacturers + 1 coming up soon!!)
- Over 40 projects that utilizes CLT, either designed or built across Canada
- Extensive R&D by FPI, Universities (NEWBuildS), NRC and Industry Associations (CWC): Mostly funded by NRCan, industry (BSLC/SLB) & provinces (QC, BC)
- Strong interest in CLT among designers, building officials, governments & developers

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CLT R&D Activities in Canada

Investigating the structural (including seismic & connections), fire, durability & serviceability performance of Canadian-made CLT

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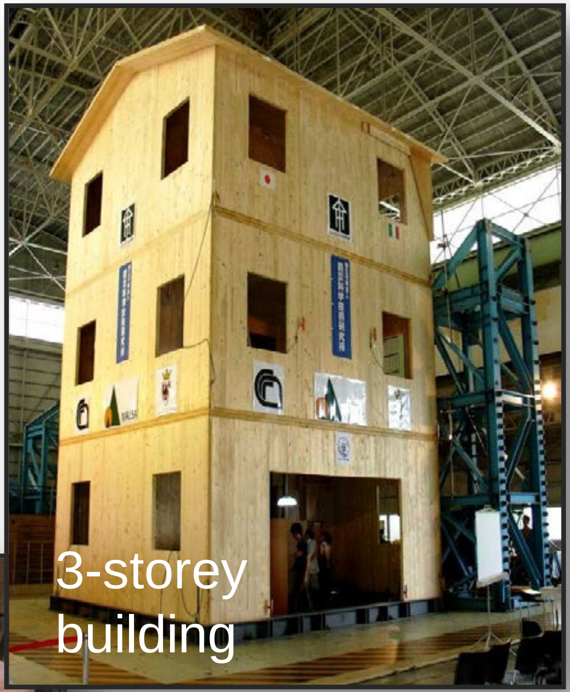
Developing Design Guidelines CLT Handbook & TWB Guide

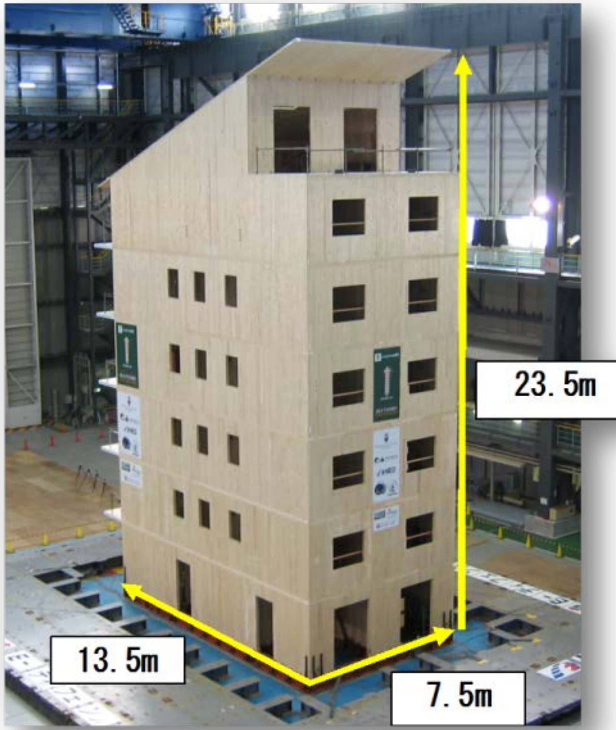
CLT Handbook and TWB Guide provide design guidelines for Canada under « Alternative Solutions »

http://www.fpinnovations.ca/Pages/CltForm.aspx

Sponsored by NRCan, BSLC and other partners

Shake Table Tests on CLT Assemblies





7 storeys

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IVALSA SOFIE Project: CLT Against Earthquakes

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CLT Behaviour in Fire Conditions

Probabilities of fire spread beyond room of fire origin is reduced in CLT assemblies

- Huge amount of fire compartmentalization due to a “honeycomb-type” system
- Fewer concealed spaces (cavities)

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FPInnovations Research Project on CLT

Fire Resistance of CLT Assemblies

- Integrity criterion (**E**) (video)

Fire Resistance of CLT Assemblies

- Walls
  - 3-plys (114 mm) protected + 2 x ½" Type X : 106 min
  - 5-plys (105 mm) unprotected : 57 min
  - 5-plys (175 mm) unprotected : 113 min

- Floors
  - 3-plys (114 mm) protected + 2 x ½" Type X : >77 min*
    - * Test stopped due to safety concerns. Failure has not been reached.
  - 3-plys (105 mm) + ⅝" Type X : 86 min
  - 5-plys (175 mm) unprotected : 96 min
  - 5-plys (175 mm) + ⅝" Type X : 124 min (2 hrs Rating !!!)
  - **7-plys (245 mm) unprotected : 178 min (≈ 3 hrs Rating !!!)**

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Full-Scale CLT Fire Tests

Validation of the "Encapsulation" concept on CLT

(*NRC/CWC/FPI Mid-rise project consortium*)

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Full-Scale Shaft Demonstration Fire

Demonstrating the fire performance of CLT shafts for TWBs

(Under NRCan's TWB demo project funded by Quebec)

Full-scale Demonstration Fire

Fire Protection: Research Areas

- Fire resistance tests
- Composite mass wood-concrete floor systems
- Firestops in wall and floor penetrations
- Room fires and risk modeling




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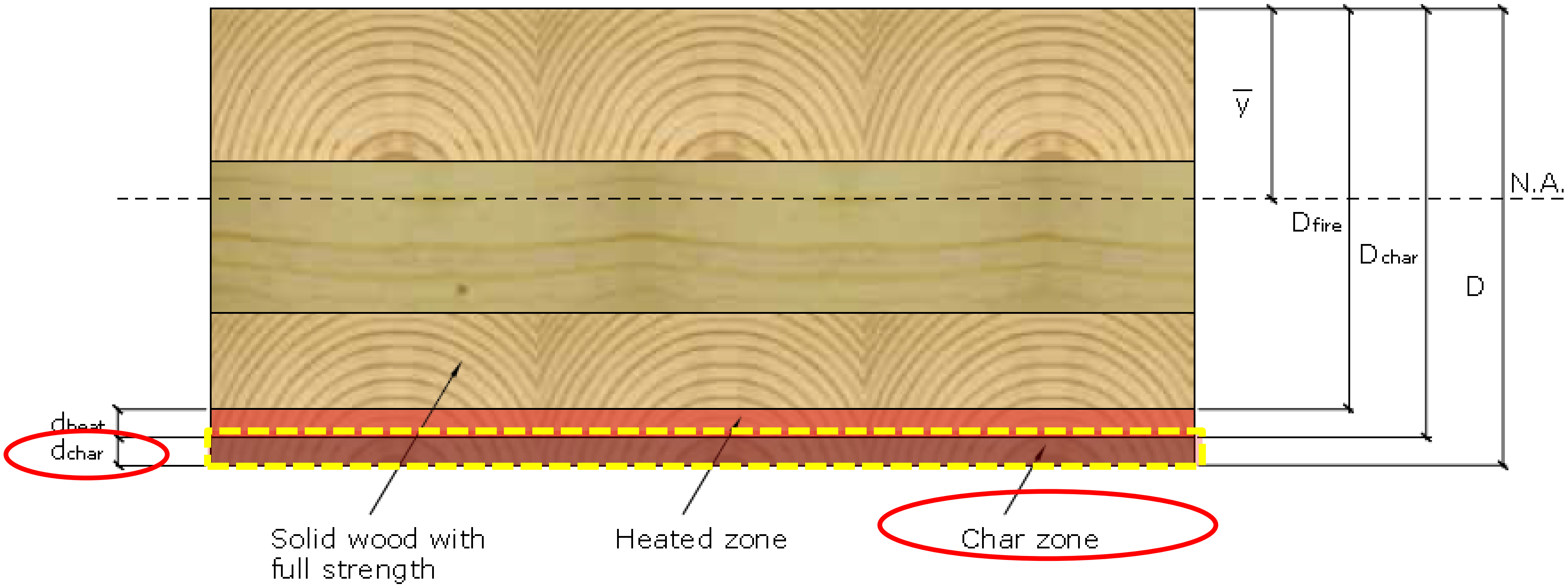
Fire Resistance of CLT Assemblies

- Analytical Method

Calculation of the char depth and capacity of residual strength

$$d_{char} = \beta_o t$$



Summary of Fire Performance of CLT

- CLT superior fire performance facilitates Code acceptance when using "**Alternative Solutions**"
- CLT & heavy timber behaves the same way in fire conditions…
  - Predictable charring rates
  - Reduced X-section as a function of time
  - Concealed connections are recommended

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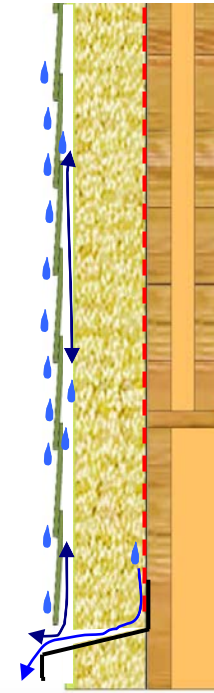
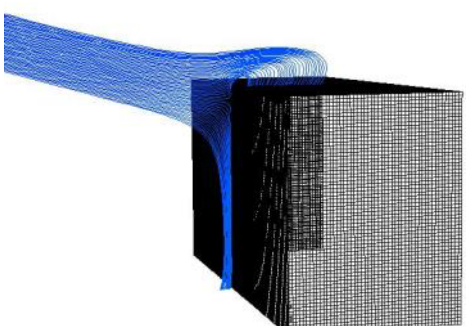
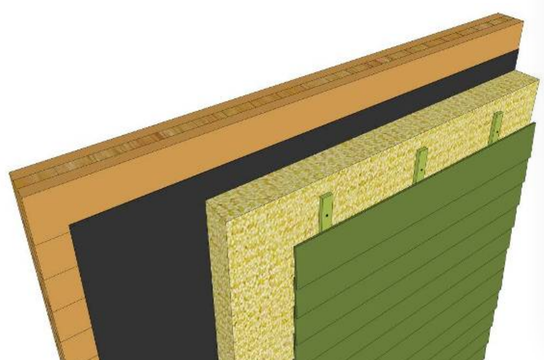
Building Envelope/Durability of CLT (NEWBuildS/FPI)

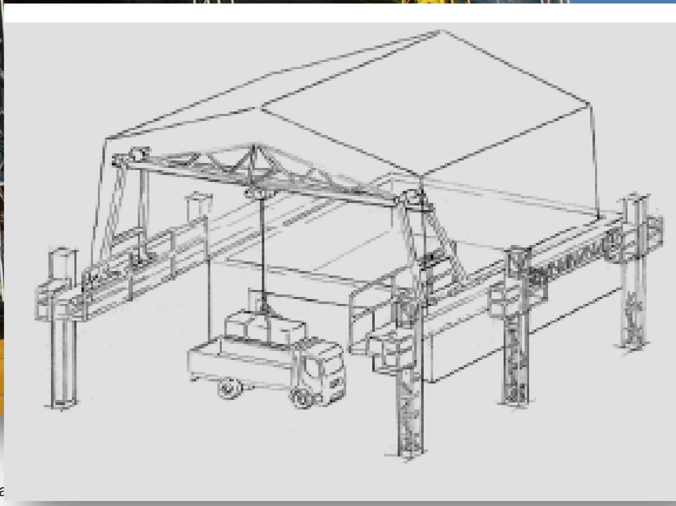
- Characterizing wind-driven rain load on mid-rise buildings
- Developing durable building envelope assemblies for CLT construction
- Drying performance of CLT







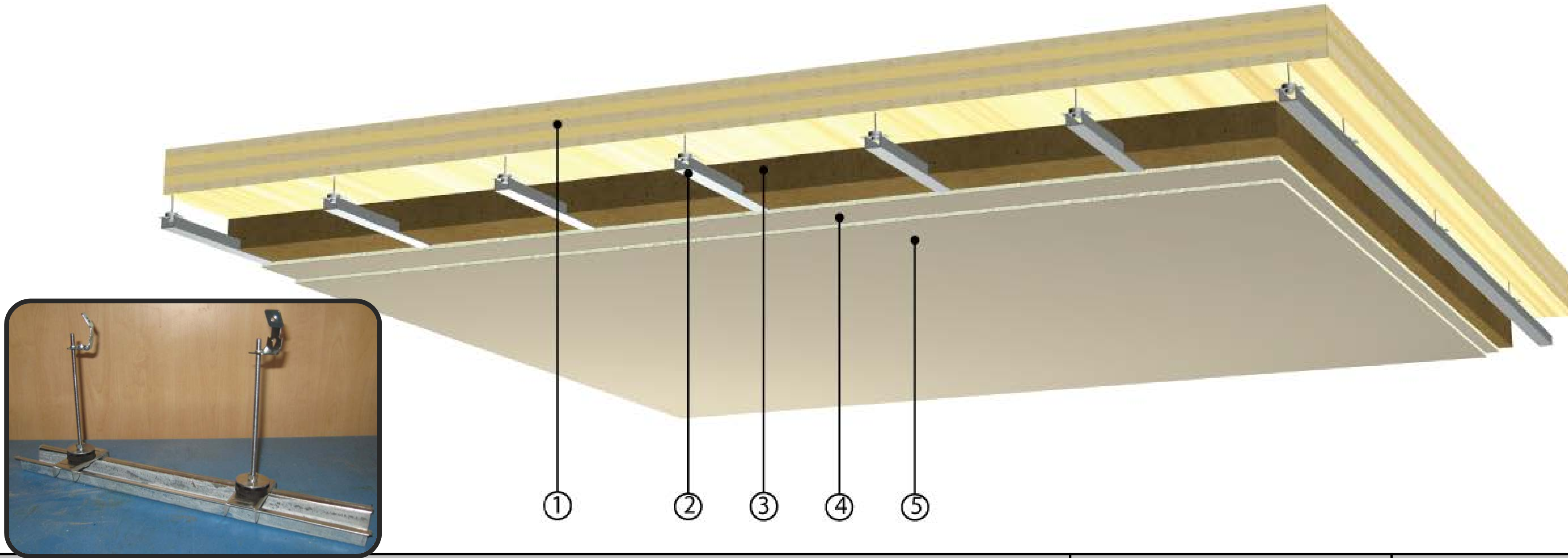
Controlling Moisture During Construction



Serviceability Research

- A challenge to designers & occupants in taller buildings (IIC, STC, floor & building vibrations, etc.)
- Acoustics, floor vibrations & wind-induced vibrations
- On-site measurements and monitoring activities

Source: Binder



Floor Composition	Airborne (STC)	Impact (IIC)
1 5-layer CLT panel 146 mm 2 Resilient supports and rails (100 mm) 3 Sound insulation material (100 mm) 4 Gypsum board 13 mm 5 Gypsum board 13 mm	64	59

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Inspiring Modern Tall Wood Buildings

9-Storey buildings, London, UK
1st storey concrete, 8 storeys CLT

2 @ 8 storeys CLT buildings, Oslo, Norway

4 CLT residential buildings/social housing @ 9 storeys, Milan, Italy

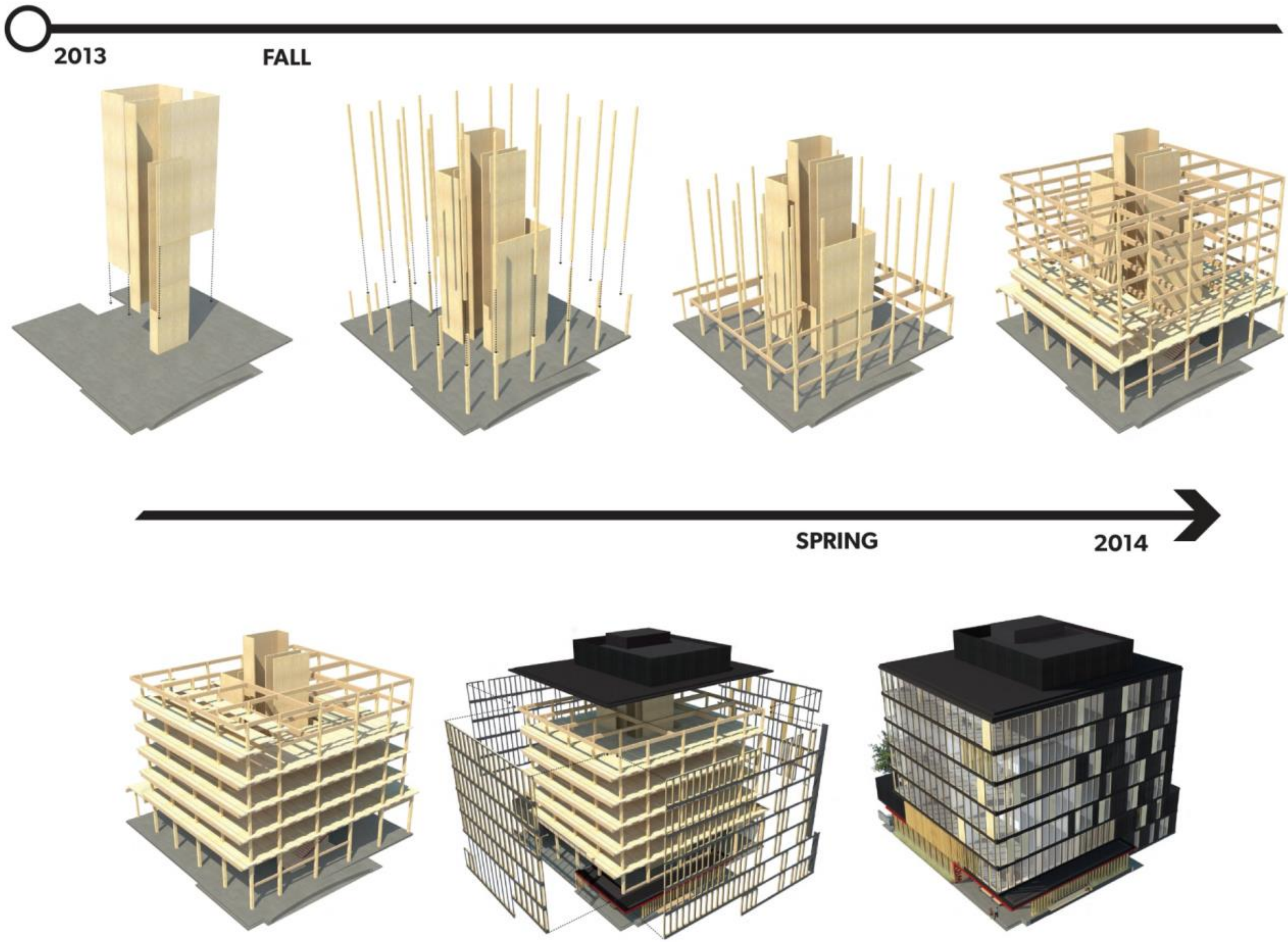
14-Storey Building in Norway Currently Under Construction

- Hybrid CLT, Glulam, LWF
- Adopting timber bridges structural systems
- Compartmentalization concept with concrete slab every 5th floor (i.e., podium)
- CLT encapsulated mostly. CLT shaft

WOOD DESIGN INNOVATION CENTRE

MGA

Courtesy of MGA + Equilibrium



Courtesy of MGA + Equilibrium


Courtesy of MGA + Equilibrium

https://www.youtube.com/watch?v=be1LVts-yjU

Courtesy of MGA + Equilibrium

World's Largest Residential Project in CLT, Montreal Canada

- 597,560 ft^2
- condos and townhouses
- 3 @ 8-storey buildings with a total of 434 condo & townhouses
- Planned for completion by fall 2017

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NRCan's TWBs Demo Initiative
Origine: Quebec City/Canada

- 13-storey mass timber (12 + 1 concrete podium)
- 800 m² floor area, 40 m tall
- Incorporates a CLT core

- Fire (resistance, firestopping, exterior walls, etc.), structural & acoustics testing, <u>in addition to a demo fire on CLT shaft performed to support design/approval</u>

Forêts, Faune et Parcs Québec

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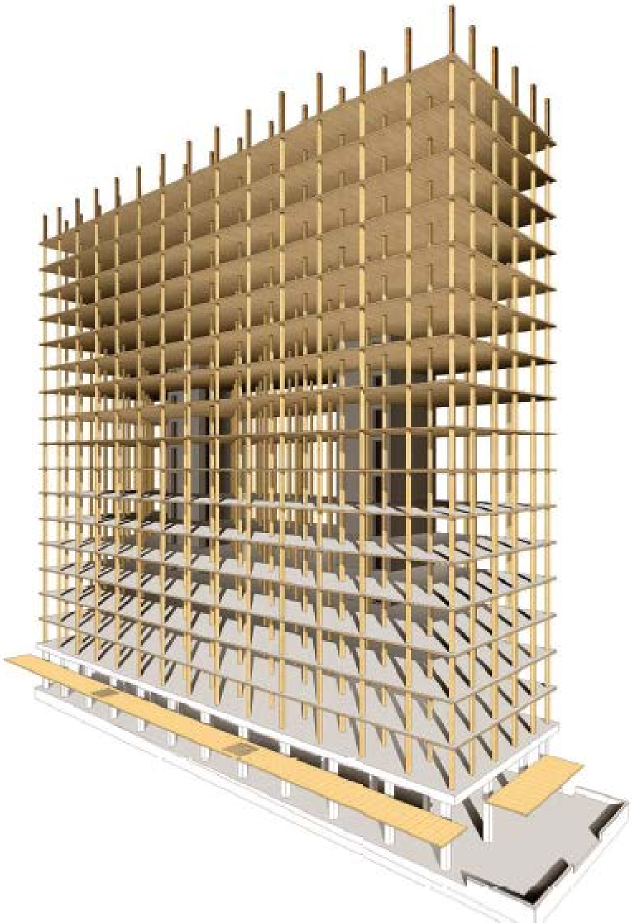
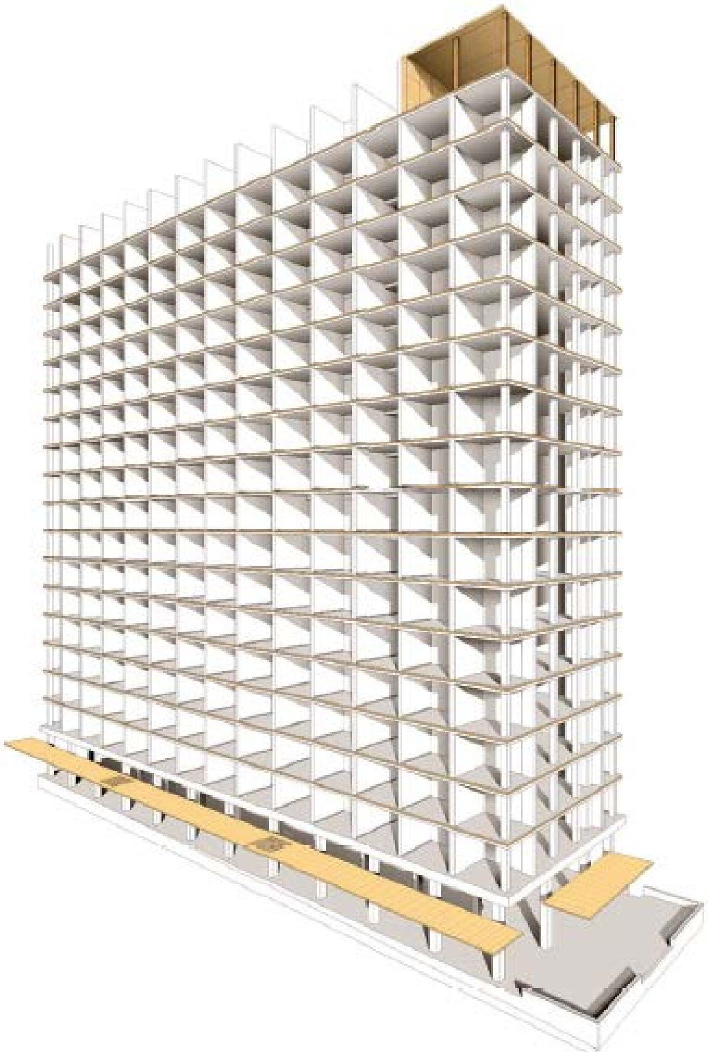
UBC Residence Will be Among World's Tallest Wood Buildings

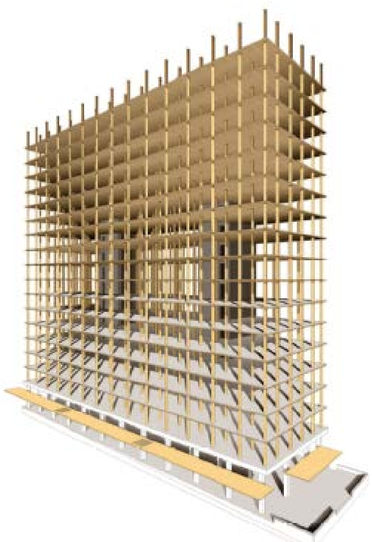




UBC Residence TWB

- 18 Storeys: 1 concrete+ 2 concrete cores supporting 17 storeys of mass timber
- A steel connector allows for a direct load transfer between the columns and also provides a bearing surface for the CLT panels.
- Encapsulated CLT and glulam columns- **NO BEAMS**!
- The floor comprised of 5-ply CLT panels that are point-supported on glulam columns on a 2.85m x 4.0m grid.
- Mock-up built to verify constructability

UBC TWB Mock-up



CLT floor slabs with glulam columns and steel connectors

partial encapsulation during construction

completed construction

Impressive CLT- Glulam Beams

CESM Soccer Stadium in Montreal

Modern Timber Bridges in Canada

CLT in NA Codes and Standards

- **US:** CLT adopted in the 2015 editions of IBC and NDS
- **Canada:** Lack of design guidlines has been slowing down the implementation of CLT in codes and standard
  - NA CLT manufacturing standard developed (PRG 320-12)
  - CLT: used under « *Altetrnative Solutions*»
  - Attempts made to implement CLT in the 2015 NBCC (LLRS)
  - Design provisions proposed at CSA O86 (CSA O86 2016 Supplement)
  - Extensive R&D by FPI, NEWBuildS, CWC/WWS, NRC, etc
  - Discussions on the implemenation of mass timber in the 2020 NBCC

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CLT in CSA O86-14 (Place Holder for CLT)

8. Cross-laminated timber (CLT)

Clause 8 has been reserved for design provisions which will cover CLT manufactured in accordance with ANSI/APA PRG 320 standard

Note: *A CWC commentary is planned to follow the inclusion of design provisions of Clause 8.*

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PRG 320: Primary CLT Stress Grades for Canada

CLT Stress Grade	Wood Species /Type of Lay-up
E1	1950f-1.7E SPF MSR lumber in all parallel layers and No. 3 Spruce-pine-fir lumber in all perpendicular layers
E2	1650f-1.5E Douglas fir-Larch MSR lumber in all parallel layers and No. 3 Douglas fir-Larch lumber in all perpendicular layers
E3	1200f-1.2E Northern Species MSR lumber in all parallel layers and No. 3 Eastern Softwoods, Northern Species, or Western Woods lumber in all perpendicular layers
V1	No. 2 Douglas fir-Larch lumber in all parallel layers and No. 3 Douglas fir-Larch lumber in all perpendicular layers
V2	No. 1/No. 2 SPF lumber in all parallel layers and No. 3 SPF lumber in all perpendicular layers

**Custom CLT grades are permitted when approved by an approved agency in accordance with the qualification and mechanical test requirements specified in ANSI/APA PRG 320-12*

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Specified Strengths & MOE of CLT Lamination, MPa
(ANSI/PRG 320 based on current lumber values in CSA O86)

Stress Grade	Major Strength Direction						Minor Strength Direction					
	$f_{b,0}$	E_0	f_t	f_c	f_v	$f_{s,0}$	$f_{b,90}$	E_{90}	f_{tp}	f_{cp}	$f_{v,90}$	$f_{s,90}$
E1	28.2	11700	15.4	19.3	1.5	0.50	7.0	9000	3.2	9.0	1.5	0.50
E2	23.9	10300	11.4	18.1	1.9	0.63	4.6	10000	2.1	7.3	1.9	0.63
E3	17.4	8300	6.7	15.1	1.3	0.43	4.5	6500	2.0	5.2	1.3	0.43
V1	10.0	11000	5.8	14.0	1.9	0.63	4.6	10000	2.1	7.3	1.9	0.63
V2	11.8	9500	5.5	11.5	1.5	0.50	7.0	9000	3.2	9.0	1.5	0.50

Notes:

(1) Tabulated values are based on the following standard conditions:

(a) dry service conditions; and

(b) standard term duration of load

** Tabulated values are not permitted to be increased for the lumber size adjustment factor. The design values shall be used in conjunction with section properties provided by the CLT manufacturer based on the actual layup used in manufacturing the CLT panel*

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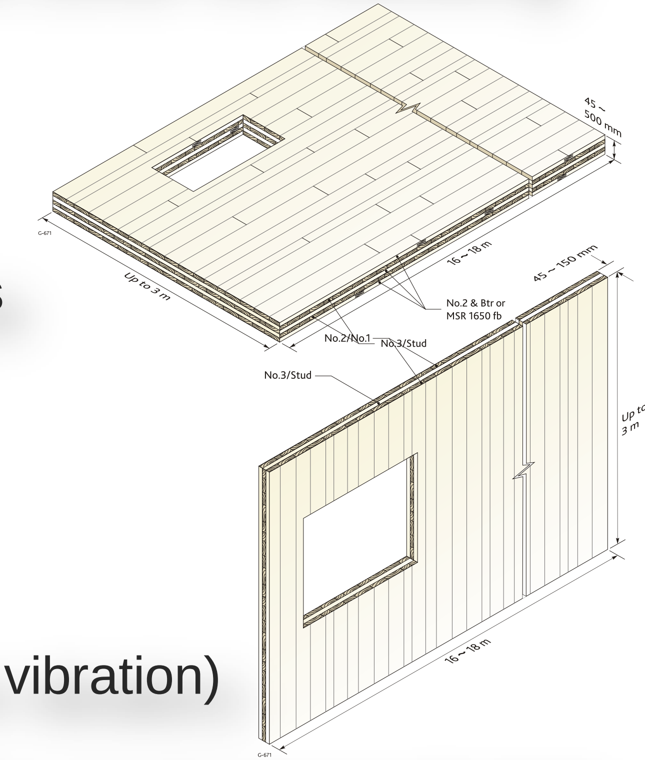
Design Provisions for CLT (CLT Handbook)

- Design provisions in the CLT Handbook cover the following:
  - ✓ Bending capacity
  - ✓ Shear
  - ✓ Comp. strength // to major strength axis
  - ✓ Bearing
  - ✓ Fastenings capacity
  - ✓ CLT as a LLRS
  - ✓ Serviceability design (deflection & floor vibration)



Some basic design info provided in the CLT Handbook for use of as beams & Lintels.

More testing is needed

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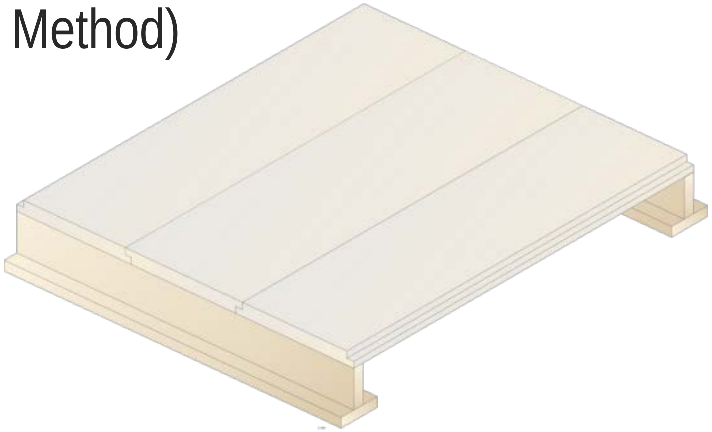
Proposed Analytical Design Methods for CLT Elements used in Floor and Roof Systems

- European proposed design methods for CLT



1) Mechanically Jointed Beams Theory (Gamma Method)
   - Bending strength & stiffness
   - Shear Strength

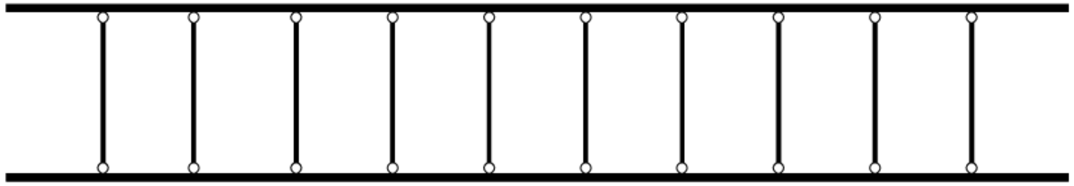
2) Composite Theory (k Method)
   - Bending strength & stiffness
   - Commonly used in plywood

3) Shear Analogy (Kreuzinger)
   - Bending Stiffness and Shear Stiffness
   - Adopted in ANSI PRG 320 standard

Proposed Analytical Design Methods for CLT Elements used in Floor and Roof Systems

Shear Analogy (Kreuzinger)

- Consider the different modulus of elasticity and shear modulus of individual layers (both directions)
- The effect of shear deformations is <u>not</u> neglected
- Stiffness of cross layers is taken as $E_{90} = E_0 / 30$
- Multi-layer CLT panels are separated into two virtual beams A and B



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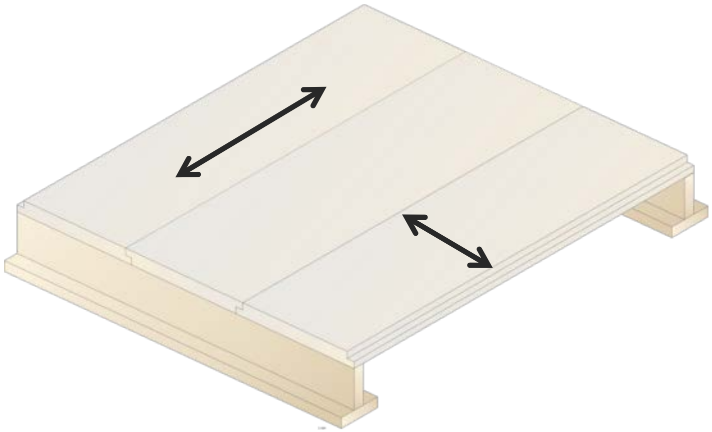
Strength and Resistance

Bending moment resistance of CLT slabs

$$M_r = \phi F_b S_{eff} K_L K_{rb}$$



$$\phi = 0.9$$

$$F_b = f_b (K_D K_H K_{Sb} K_T)$$

Effective Section Modulus

$$S_{eff} = \frac{(EI)_{eff}}{E_1} \cdot \frac{1}{0.5 h_{tot}}$$ If $E_1 \neq E_2 \neq E_3$, etc.

$$S_{eff} = \frac{I_{eff}}{0.5 h_{tot}}$$ If $E_1 = E_2 = E_3$, etc.

K_{rb}= *Calibration factor* for bending *stiffness*
= 0.85 for bending along the major strength direction
= 1.00 for bending along the minor strength direction

Could determine *Mr* in the major or minor strength axis!!

Bending Resistance (ANSI PRG 320-12)

Stress Grade	CLT Thick. (mm)	Lamination Thickness in CLT Layup (mm)							Major Strength Direction			Minor Strength Direction		
									$f_bS_{eff,0}$	$(EI)_{eff,0}$	$(GA)_{eff,0}$	$f_bS_{eff,90}$	$(EI)_{eff,90}$	$(GA)_{eff,90}$
		=	⊥	=	⊥	=	⊥	=	10^6 N-mm/m	10^9 N-mm^2/m	10^6 N/m	10^6 N-mm/m	109 N-mm^2/m	10^6 N/m
E1	105	35	35	35					49	1088	7.3	1.4	32	9.1
	175	35	35	35	35	35			115	4166	15	12	836	18
	245	35	35	35	35	35	35	35	202	10306	22	28	3183	27
E2	105	35	35	35					42	958	8.0	0.94	36	8.2
	175	35	35	35	35	35			98	3674	16	8.1	929	16
	245	35	35	35	35	35	35	35	172	9097	24	19	3537	25
E3	105	35	35	35					31	772	5.3	0.92	23	6.4
	175	35	35	35	35	35			71	2956	11	8.0	604	13
	245	35	35	35	35	35	35	35	125	7313	16	18	2299	19
V1	105	35	35	35					18	1023	8.0	0.94	36	8.7
	175	35	35	35	35	35			41	3922	16	8.1	929	17
	245	35	35	35	35	35	35	35	72	9708	24	19	3537	26
V2	105	35	35	35					21	884	7.2	1.4	32	7.5
	175	35	35	35	35	35			48	3388	14	12	836	15
	245	35	35	35	35	35	35	35	85	8388	22	28	3183	23

(1)Table represents one of many possibilities by varying lamination grades, thicknesses, orientations and the layer arrangements in the lay-up

(2) The capacities are derived analytically using the Shear Analogy Model (Ref. CLT handbook). Other rational and accepted analysis methods could also be used

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Proposed Strength Modification Factors (as per CSA O86)

- **Load duration factor, K_D**

  K_D = 1 (i.e., same as lumber/glulam; **Clause 4.3.2** in CSA O86)

- **Service condition factor, K_S**

  "Dry" service conditions ONLY with K_S =1.0 shall be used

- **Treatment factor, K_T**

  "Dry" service conditions, with no treatment, K_T =1.0

  For CLT treated with strength-reducing chemicals (e.g., FRT), strength & stiffness capacities adjustment as per **Clause 3.3.2**. *in CSA O86*

- **System factor, K_H**

  K_H = 1.0 shall be used in all cases

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Shear Resistance of CLT Slab

Factored Shear Resistance, V_r

$$V_r = \phi\, F_v \frac{2A_{gross}}{3}$$

Where

$\phi = 0.9$

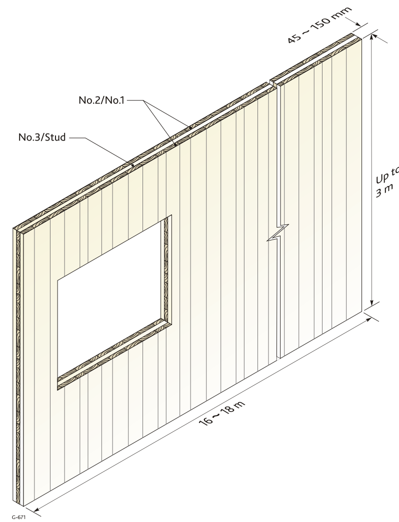
$$F_v = f_s \,(K_D\, K_H\, K_{Sv}\, K_T)$$

f_s = specified strength in interlaminar shear (**rolling shear)** in the major or minor strength direction

Since it is well-established that the rolling shear strength governs the shear resistance of CLT in slab applications, it is not necessary to check the horizontal shear resistance for CLT slab. Other applications may require verification of horizontal shear resistance. In such cases, the minimum of the factored horizontal and rolling shear resistances should be taken

Compressive Resistance // to Major Strength Direction (Wall applications)

$$P_r = \phi \, F_c \; A_{eff} \, K_{Zc} K_C$$



Where

$$\phi = \; 0.8$$

$$F_c = \; f_c \; (K_D K_H K_{Sc} K_T)$$

A_{eff} = *Effective area of the net X-section of the panel* ***accounting for boards oriented parallel to the axial load only,*** *mm*^{2}

$$K_{Zc} = 6.3 \left(2\sqrt{3} \cdot r_{eff} \cdot L\right)^{-0.13} \; \leq \; 1.3$$

For optimum design, CLT panels used as compression members should be designed with outer layers oriented parallel to applied axial loads, especially for 3-layer panels. Only the layers oriented parallel to the axial force should be assumed to carry the load.

Compressive Resistance // to Major Strength Direction (Wall applications)

Slenderness Factor

$$K_C = \left[1.0 + \frac{F_c K_{Zc} C_c{}^3}{35 E_{05} (K_{SE} K_T)}\right]^{-1}$$

$$C_c = \frac{L_e}{\sqrt{12}\, r_{eff}} \qquad r_{eff} = \sqrt{\frac{I_{eff}}{A_{eff}}}$$

$$\frac{L_e}{r_{eff}} \leq 150$$

Compressive Resistance // to Major Strength Direction (Wall applications)

Resistance to combined bending and axial load

Interaction Eq. as per CSA O86

$$\frac{P_f}{P_r} + \frac{M_f}{M_r}\left[\frac{1}{1-\frac{P_f}{P_{E,v}}}\right] \leq 1$$

$$P_{E,v} = \frac{P_E}{1+\frac{\kappa \cdot P_E}{(GA)_{eff}}}$$

P_E = Euler buckling load in the plane of the applied bending moment using I_{eff} and E_{05} of boards parallel to the axial load, kN

κ (kappa) = shear coefficient form factor

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Compressive Resistance Perp. to Grain (Bearing)

- Effect of all applied loads

$$Q_r = \phi F_{cp} A_b K_B K_{Zcp}$$

Where $\phi = 0.80$ $F_{cp} = f_{cp}(K_D K_{Scp} K_T)$

- Effect of loads applied near a support

$$Q'_r = (2/3)\, \phi F_{cp} A'_b K_B K_{Zcp}$$

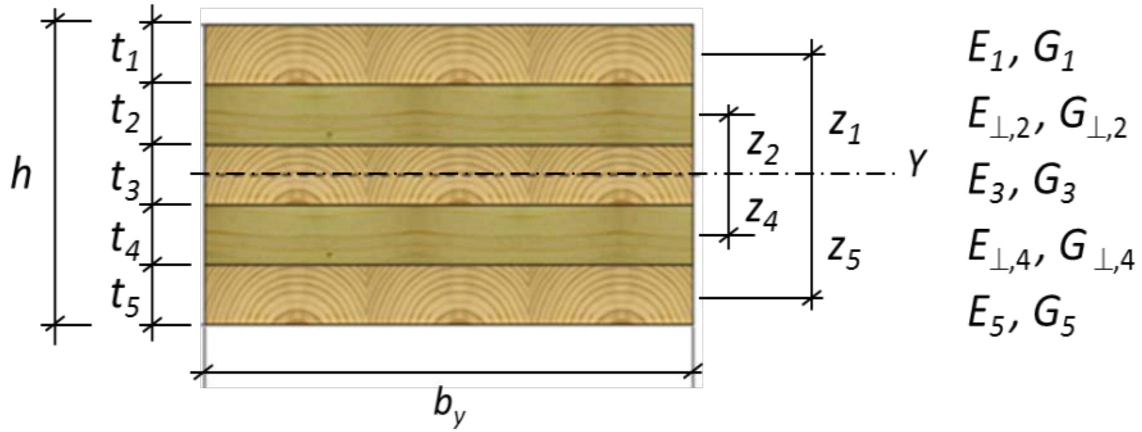
- Unequal bearing area on opposite faces of a slab

$$A'_b = b\left(\frac{L_{b1} + L_{b2}}{2}\right), but \le 1.5b(L_{b1})$$

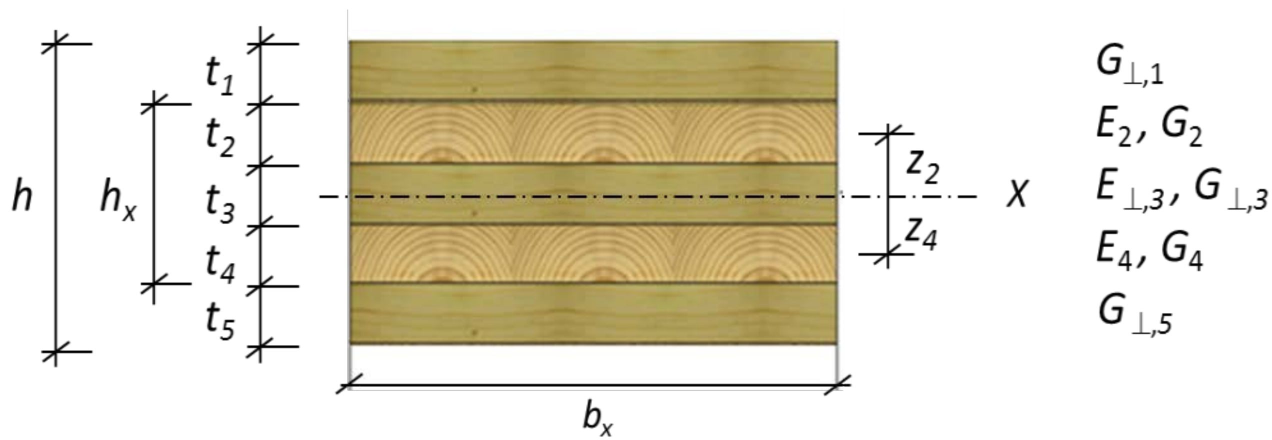
- Compressive resistance at an angle to grain

Effective Bending Stiffness $(EI)_{eff}$ and Shear Rigidity $(GA)_{eff}$

Properties for the major strength axis
$(EI)_{eff,0}$, $(GA)_{eff,0}$



Properties for the minor strength axis
$(EI)_{eff,90}$,$(GA)_{eff,90}$



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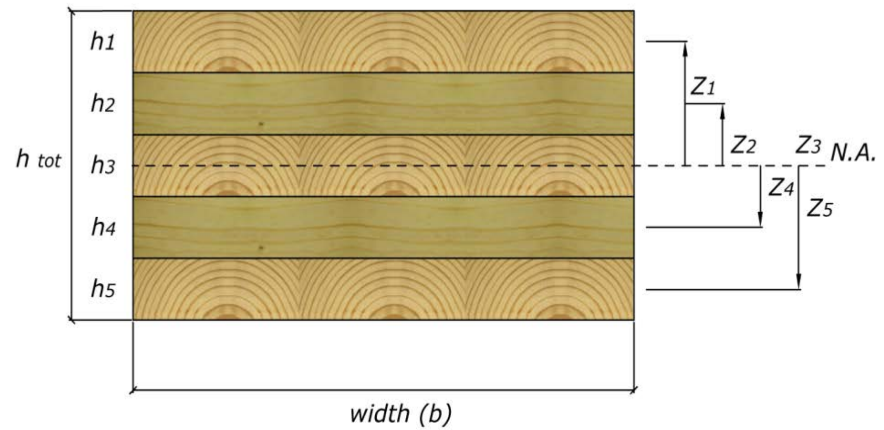
Effective Bending Stiffness $(EI)_{eff}$ and Shear Rigidity $(GA)_{eff}$

(1) Effective bending stiffness $(EI)_{eff}$

$$(EI)_{eff} = \sum_{i=1}^{n} E_i \cdot b_i \cdot \frac{h_i^3}{12} + \sum_{i=1}^{n} E_i \cdot A_i \cdot z_i^2$$



(2) Effective shear stiffness $(GA)_{eff}$

$$(GA)_{eff} = \frac{a^2}{\left[\left(\frac{h_1}{2 \cdot G_1 \cdot b}\right) + \left(\sum_{i=2}^{n-1} \frac{h_i}{G_i \cdot b_i}\right) + \left(\frac{h_n}{2 \cdot G_n \cdot b}\right)\right]}$$

$$a = h_{tot} - \frac{h_1}{2} - \frac{h_n}{2}$$

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Serviceability Limit States

Deflection of CLT Floors

$$\Delta_{max} = \Delta_{ST} + \Delta_{LT} \cdot K_{creep}$$

Δ_{ST} = elastic deflection due to short term or standard term loads (without dead loads in combination)

Δ_{LT} = instantaneous elastic deflection due to long term loads

K_{creep} = creep adjustment factor

= 2.0 for dry service condition

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Deflection of CLT slabs

- **Uniformly distributed load, ω**

$$\Delta = \frac{5}{384}\frac{\omega L^4}{(EI)_{eff}} + \frac{1}{8}\frac{\omega L^2 \kappa}{(GA)_{eff}} \boxed{k_{RS}}$$

- **Mid-span concentrated load, P**

$$\Delta = \frac{1}{48}\frac{PL^3}{(EI)_{eff}} + \frac{1}{4}\frac{PL\kappa}{(GA)_{eff}} \boxed{k_{RS}}$$

Max. deflection under the load combinations for serviceability limit states <u>shall not exceed L/180 of the span.</u>

k_{RS} = adjustment factor to shear stiffness to account for rolling shear effect
= 1.33 for elastic deflection under short term or standard term loads (Δ_{ST})
= 1.0 for instantaneous elastic deflection under long term loads (Δ_{LT})

κ (kappa) = shear coefficient form factor equals to 1.2 for a single span. For continuous spans, relevant values shall be used.

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Serviceability Limit States

Vibration Performance of CLT Floors

$$l \leq 0.11 \frac{\left(\frac{(EI)_{eff}}{10^6}\right)^{0.29}}{m^{0.12}}$$

l = vibration controlled span, m

$(EI)_{eff}$ = apparent stiffness in the span direction for 1 m wide panel, N-mm^2

m = linear mass of CLT for 1 m wide panel, kg/m

Note: *Increase span by up to 20% (≤ 8.0m) for multiple-span floors with a non-structural element that is considered to provide enhanced vibration effect, e.g. internal partition, finishes and ceiling.*