New Canadian Design Provisions for CLT in CSA O86

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ATLANTIC WOOD SOLUTIONS FAIR

Halifax, NS

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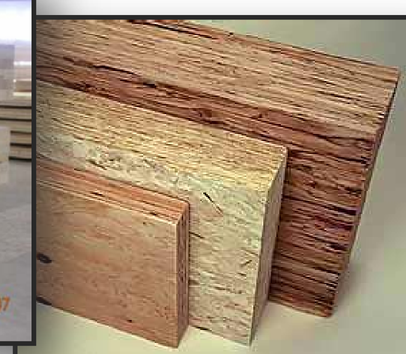
Recent Trends/Opportunities

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 such as CLT, connection systems & design tools
  - Recent changes to building codes
  - Environmental concerns (i.e., climatic changes)- favors wood



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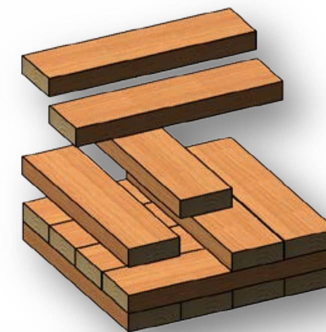
What is Possible to Build with Wood?!

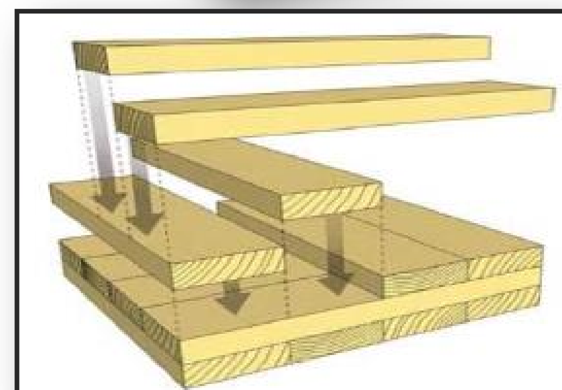
- LWF Construction (up to 6 storeys)
- Mass Timber Frame (e.g. P&B glulam)
- Massive Timber Plates (e.g., CLT, LVL, etc.)
- Hybrid Systems



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



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

- Produced with precision CNC machines
- 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

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

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

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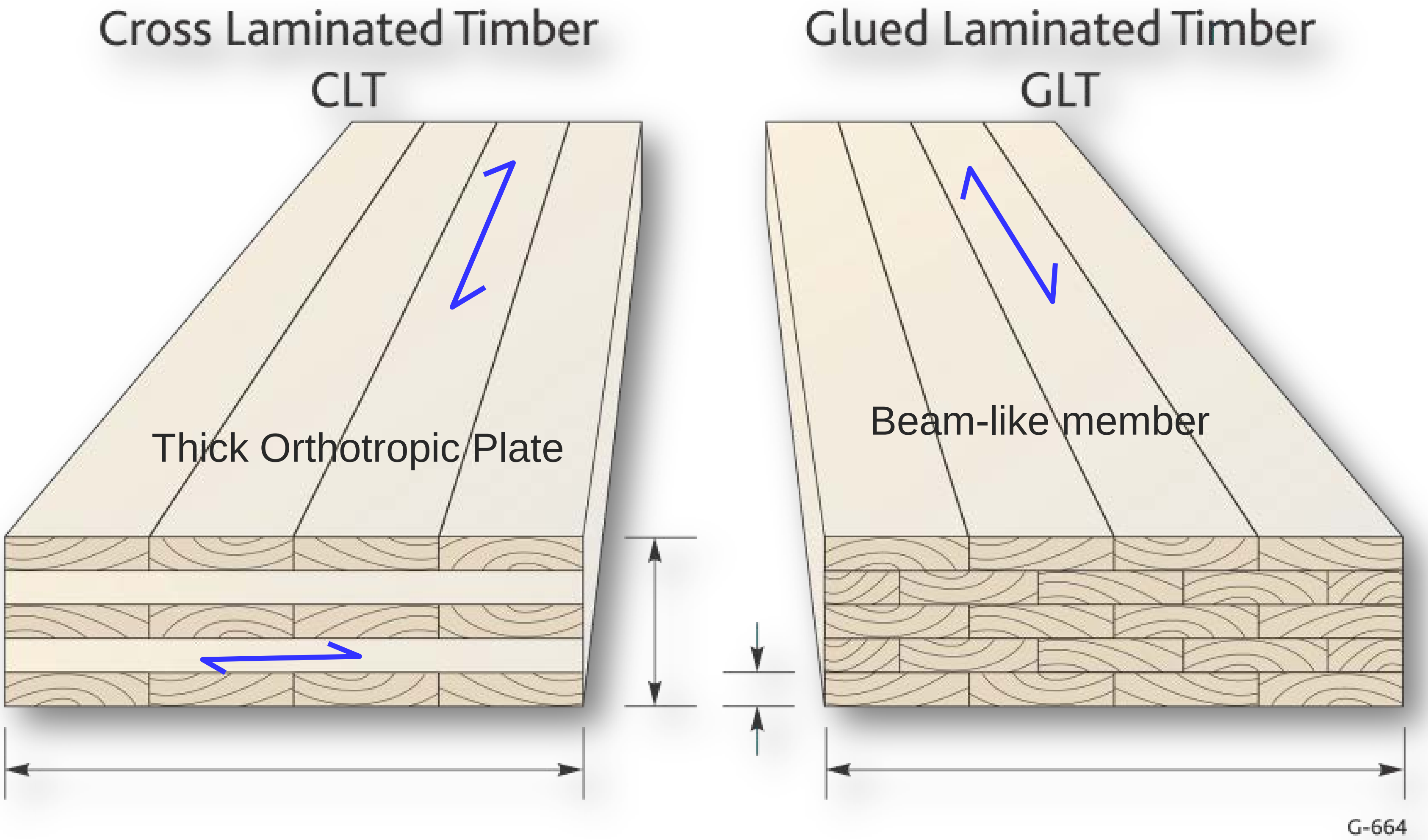
Why CLT is Different than Glulam?!



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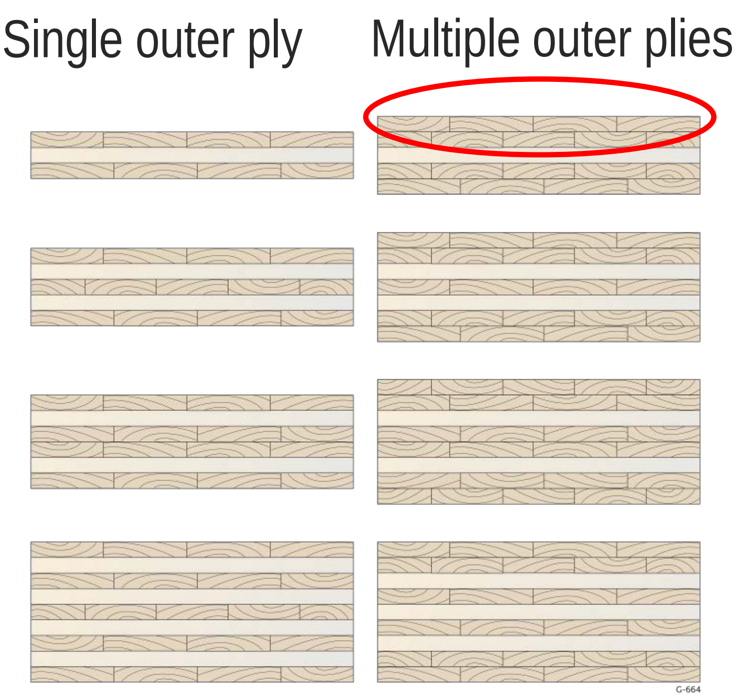
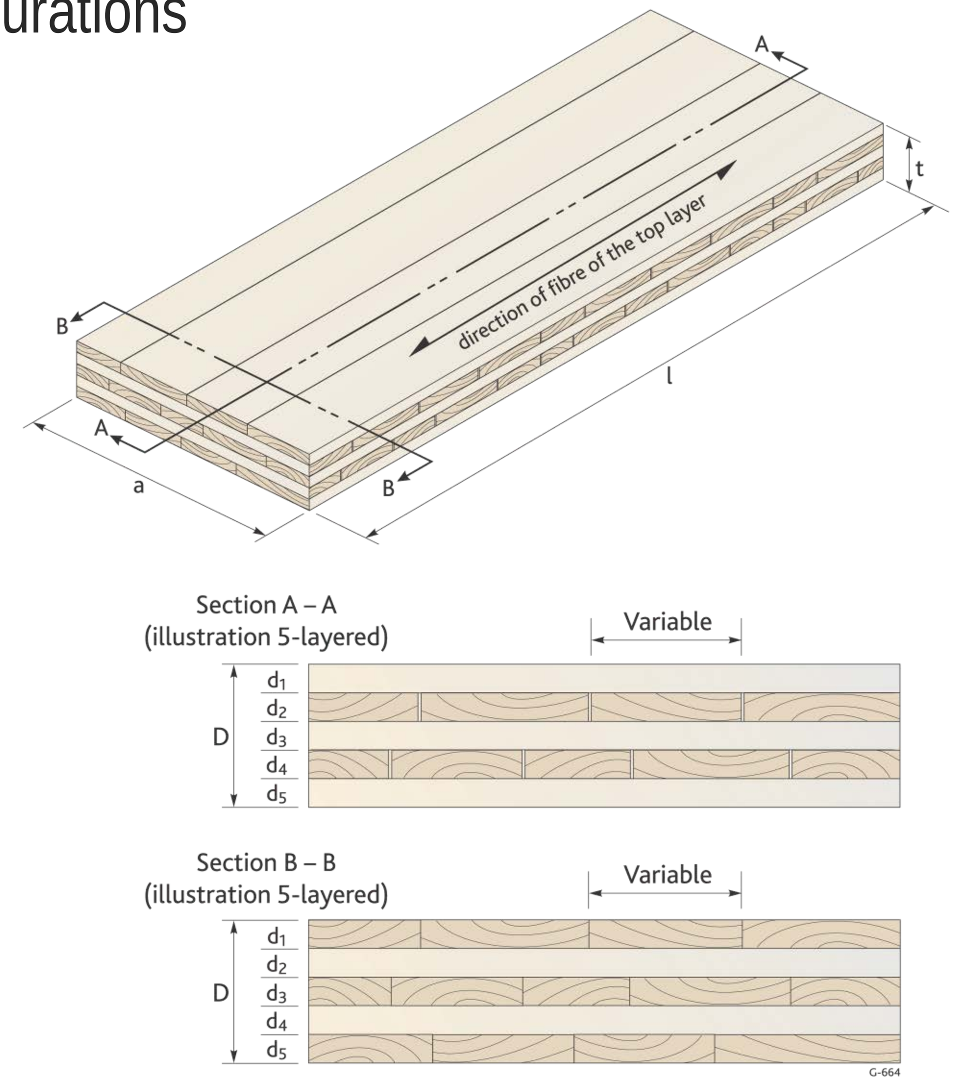
Configurations

Some possible configurations





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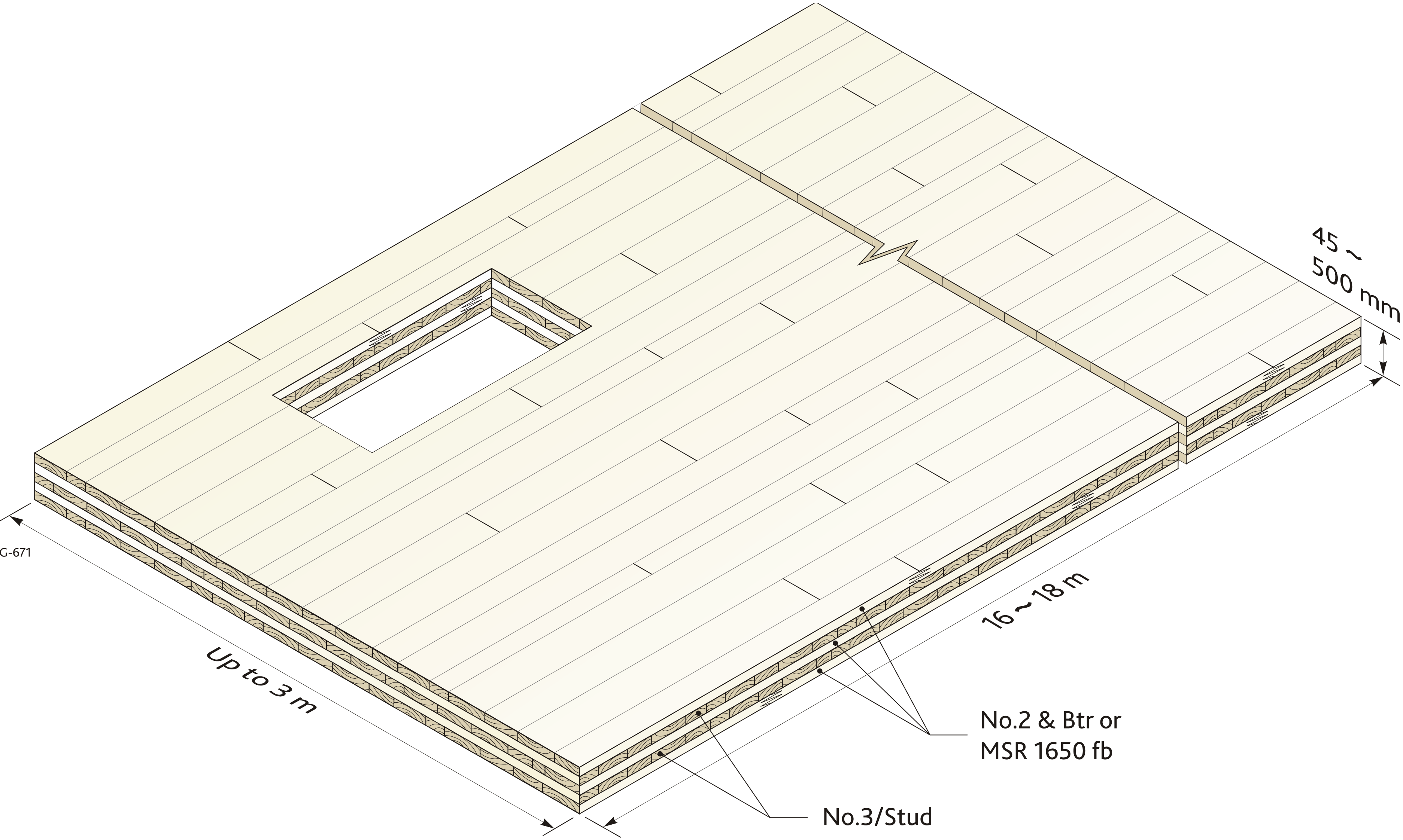

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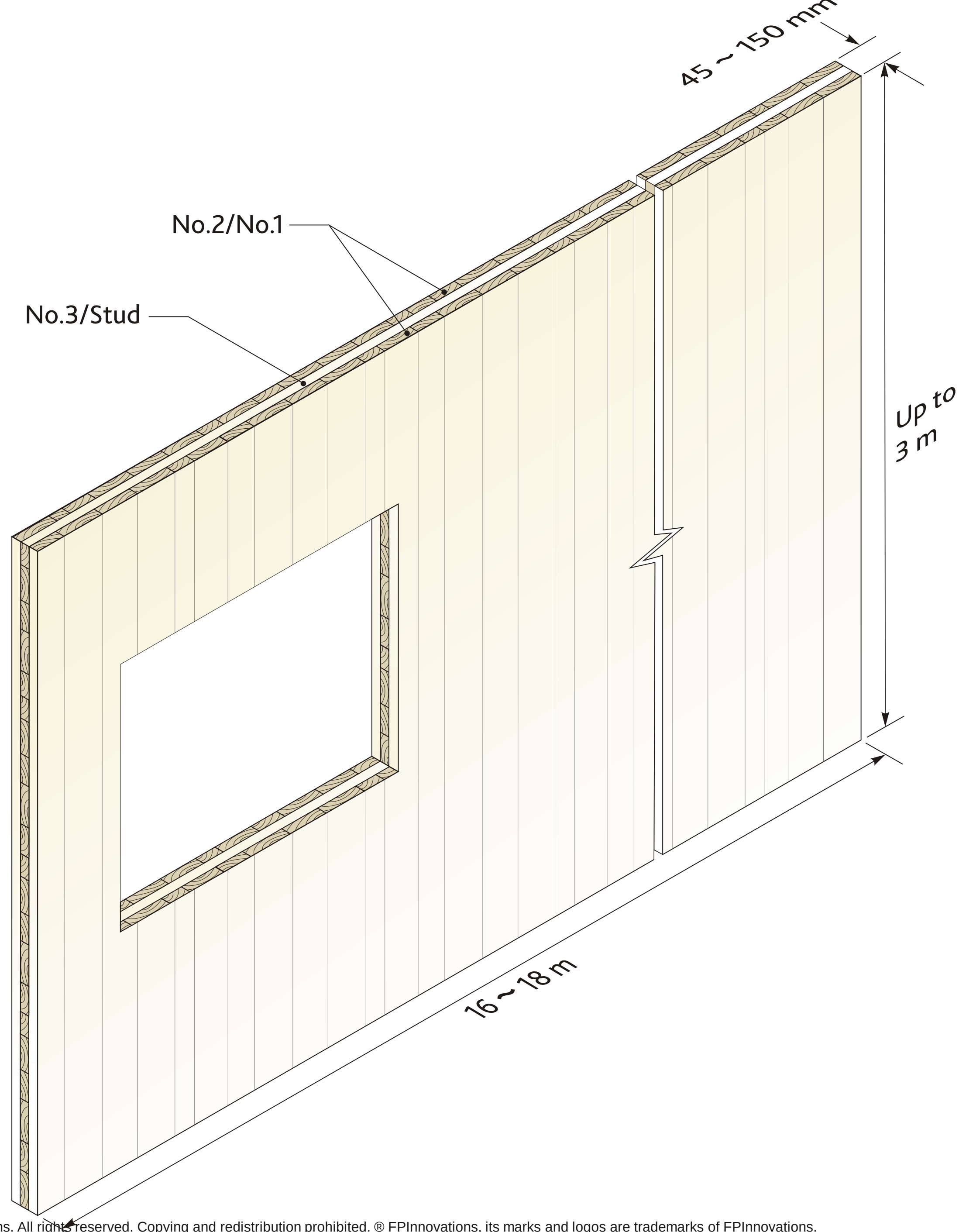

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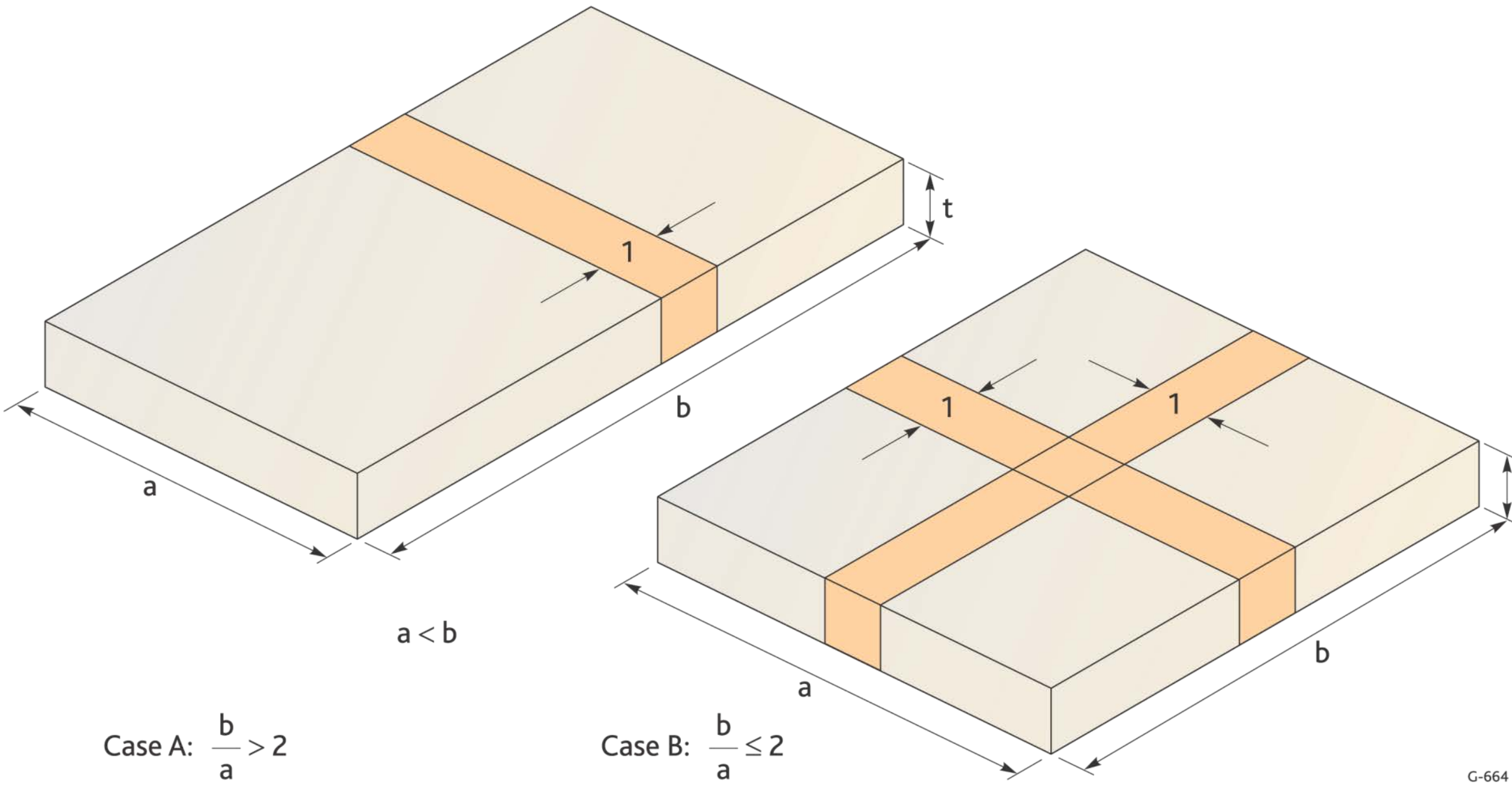
One-Way or Two-Way Slab Action

≈Two way action capability as concrete slab



CLT System in Mid-Rise

Non-residential Applications

CLT Roof on Top of Concrete/Steel Building, Quebec

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CLT in Hybrid Construction

- CLT with concrete stairwells

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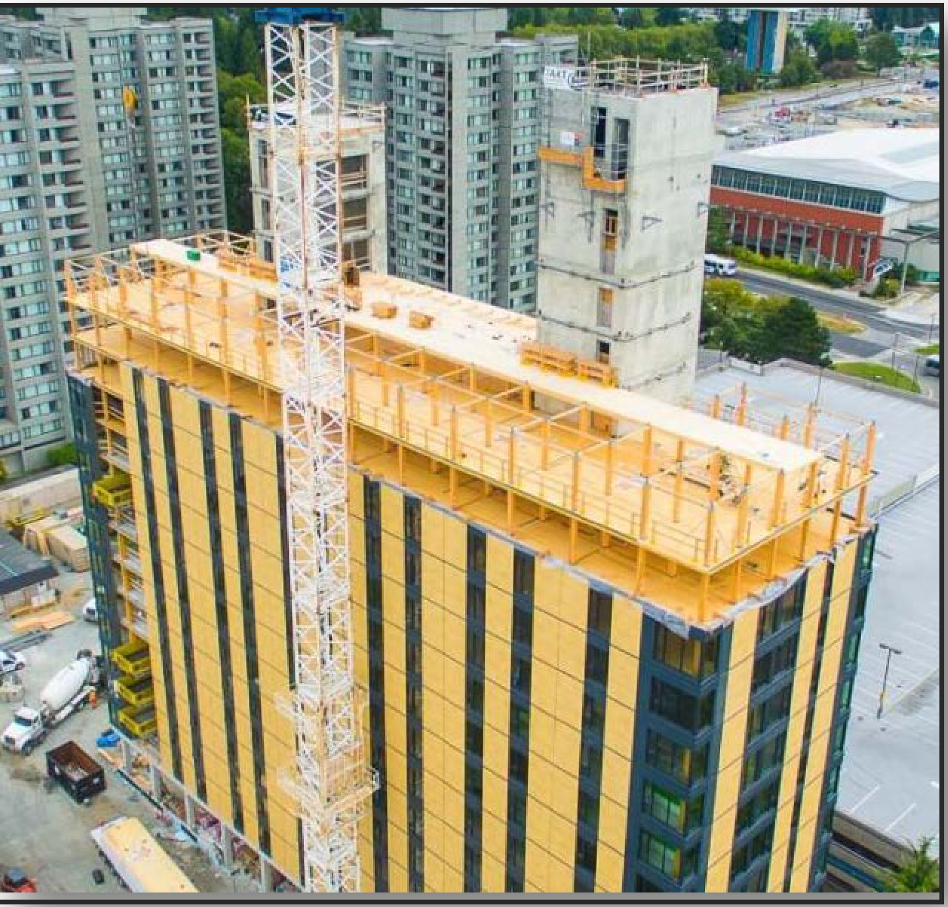
CLT in Hybrid Construction (Parking Garage)

Courtesy of UBC/FII

CLT in Modern Timber Bridges in Canada


Courtesy of Nordic Engineered Wood

CLT in Tall Buildings



Courtesy of UBC/FII

Courtesy of MGA

Courtesy of CWC

NRCan's TWB Demo Initiative

Courtesy of UBC/FII

UBC BC, Vancouver
18 storeys hybrid CLT/glulam


Courtesy of CWC

Nordic's Origine, Quebec City
13 storeys CLT/glulam

Supporting Research (Design & Approval)

- Fire testing (fire resistance, fire stops, shaft demo fire, flammability)
- Structural (shearwalls, diaphragms)
- Acoustics
- Building envelope
- Mitigating construction risks

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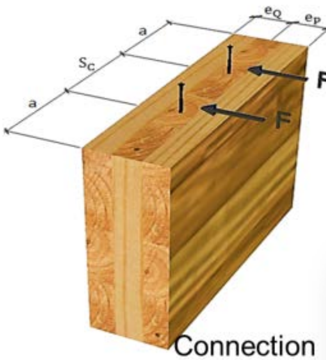
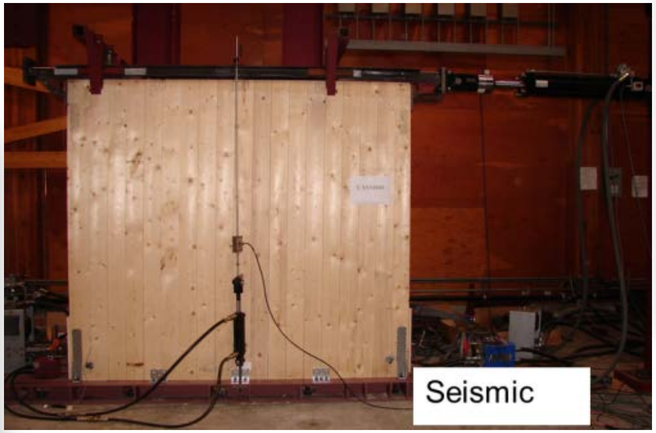
CLT Research and Development in Canada

- 2009-2016: Extensive research on CLT conducted by FPI, NRC, universities (NEWBuildS) and industry
- 2011-16: FPI, CWC/WWs, NEWBuildS held several workshops targeting engineers, architects and other stake holders across Canada to share research findings





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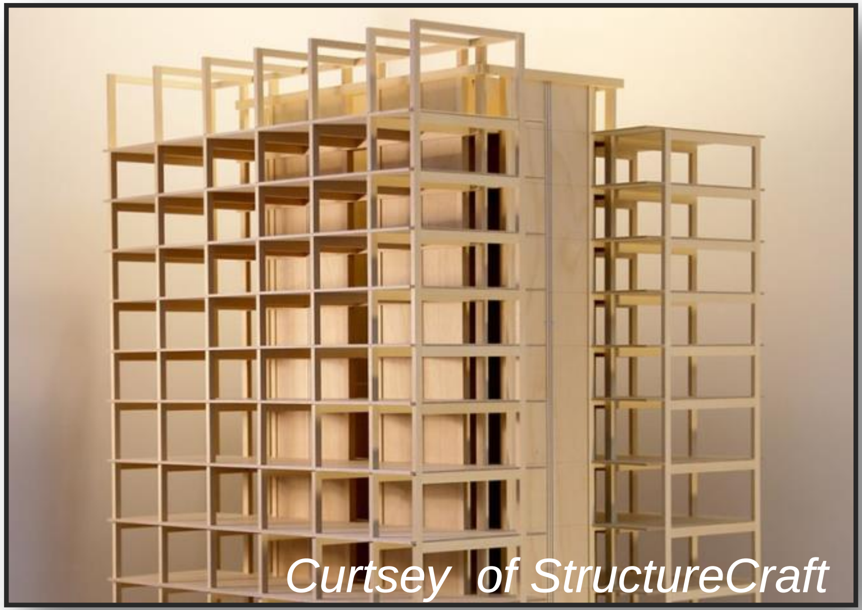
World’s Largest Residential Project in CLT, Montreal

- 597,560 ft^2
- Condos and townhouses
- Completion by fall 2017
- Glulam posts/beams and CLT

US TWB Prize Competition: Winning Building (USDA and SLB)

Framework, a 12 storeys, Portland, Oregon
Curtsey SLB



- Fire & structural testing is underway to support the design/approval
- Use PT technology (IP with FPI)
- Construction is expected to start **January 2018**

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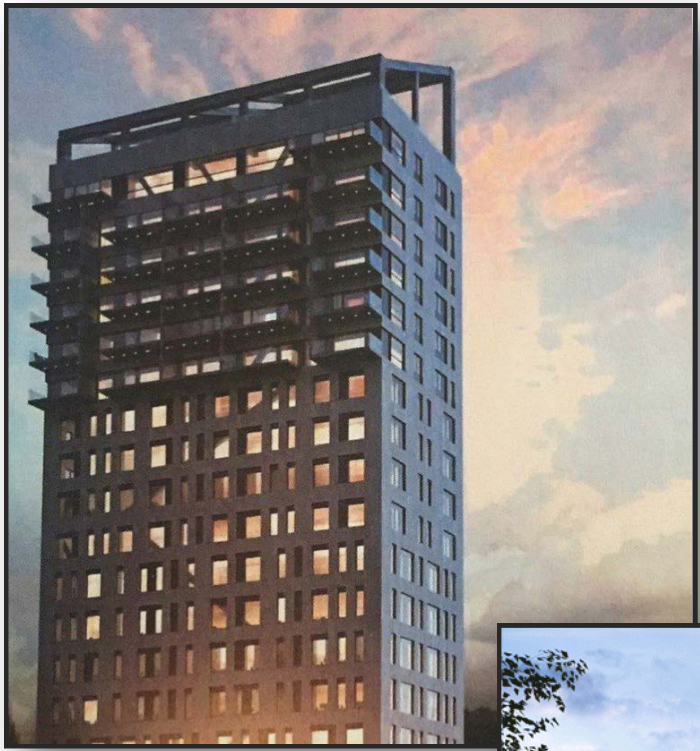
Inspiring Modern Tall Wood Buildings in Europe



Mjøstårnet
18 storeys, Norway
Currently under construction

Cultural Center
Skellefteå, Sweden
16 storeys
Design stage

HOHo, Vienna
24 storeys
Austria
Currently under construction

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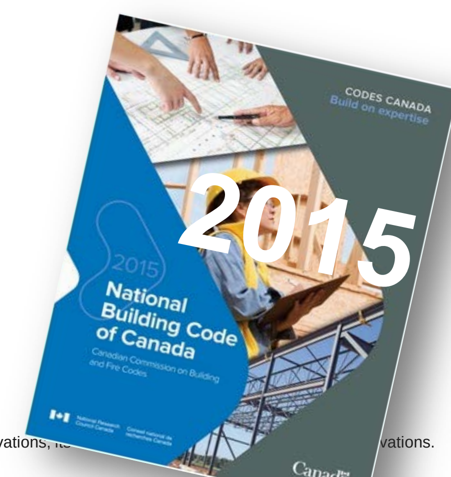
Status of CLT in Canada

- Introduced to Canada in 2006
- Canadian-made CLT is commercially available
- Over 150 projects that utilizes CLT across Canada
- Extensive research by FPInnovations, Universities, NRC & industry
- Mostly funded by NRCan, industry (BSLC) and provinces (QC, BC/FII)
- Strong interest in CLT among designers, developers, etc.

Courtesy of FII/UBC

CLT in Canadian Codes and Standards

- CLT manufacturing standard developed for Canada and US (ANSI/APA PRG 320-12)
- Design provisions implemented in the 2016 Supplement to CSA O86
- Proposal on CLT as a LLRS targeting 2020 edition of the NBCC
- Quebec's "Pre-approved" Alternative Solution Guide for mass timber including CLT for up to 12 storeys
- Request for code change for the implementation of "*Encapsulated Mass Timber*" in the 2020 NBCC for up to 12 storeys
- ON MNRF is developing a TWB Reference Guide



Developing Design Guidelines
CLT Handbook & TWB Guide

- FPI's CLT handbooks have been instrumental in providing guidance to designers under AS provisons & in supporting CLT code change proposals in Canada and the US
- Critical until CLT design provisions are widely accepted in codes and standards in Canada and the US

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The ANSI / APA PRG 320 Standard

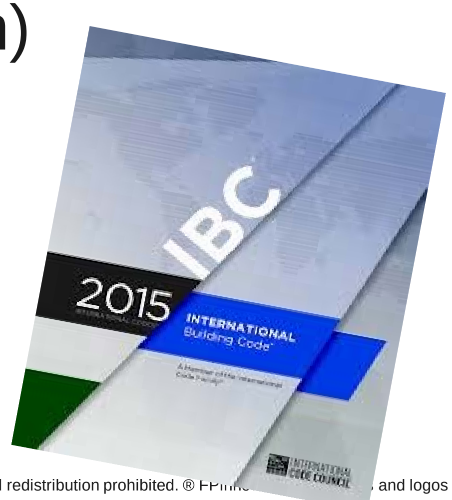
- Product manufacturing standard for CLT developed by APA
- Harmonized NA standard (Canada and the US)
- Scope
  - CLT dimensions and tolerances
  - Component requirements
  - Qualification testing
  - Quality assurance
  - Annex: Design properties (mandatory)

- Currently under revision to update the 2012 edition
- Download www.apawood.org

Introducing CLT Design Provisions in CSA O86

US: Implementation of CLT was Relatively Faster…

- Provisions for CLT were introduced in the 2015 editions of the International Building Code (IBC) for use as "Type IV"-Heavy Timber construction and in the NDS
- Provisions in NDS cover design for gravity loads including connections and fire resistance of CLT
- Seismic design provisions in the US are still under development (ongoing research)



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CLT Design Provisions in CSA O86

2014

- CSA O86 voted to have a “place holder” for CLT in the 2014 edition targeting detailed provisions in the 2016 Supplement
- **This is what we ended up with in CSA O86-14 edition!!!**

O86-14 *© 2014 CSA Group*

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.*

2016

CSA O86-14: 2016 Supplement

- January 2016: CSA O86 approved the adoption of CLT in the 2016 Supplement
- June 2016: 2016 Supplement published by CSA

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CLT Design Provisions in CSA O86-14

- Provisions cover the following:
  - Definition, materials, stress grades
  - Bending stiffness and resistance
  - Shear stiffness and resistance
  - Compressive resistance parallel and perp. to panels
  - Connections in CLT
  - CLT as a lateral load resisting system (LLRS)
  - Serviceability (i.e., deflections, vibrations)
  - Structural fire resistance

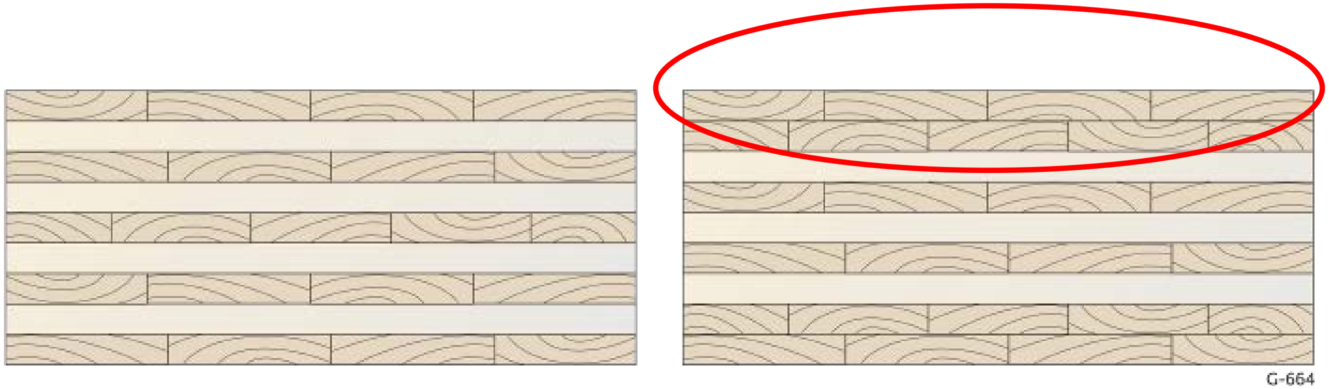
CLT Definition and Layups

- Made of at least 3 layers of **<u>sawn lumber</u>** laminated with structural adhesives manufactured as per ANSI/APA PRG 320 standard

- Balanced combination of orthogonal layers

CLT Definition and Layups

- Laminations oriented in the same direction to be made of lumber of the same grade and species combination
- Stress grades as per APA/PRG 320
- Panels may be designed with adjacent layers oriented in the same direction



Single outer ply

Multiple outer plies

Primary CLT Stress Grades for Canada

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

**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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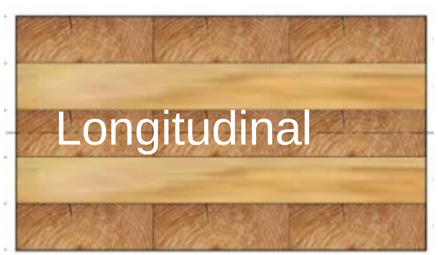
Specified Strengths and MOE of CLT Laminations [MPa]

Stress grade	Longitudinal Layers						Transverse Layers					
	f_b	E	f_t	f_c	f_s	f_{cp}	f_b	E	f_t	f_c	f_s	f_{cp}
E1	*28.2*	*11700*	*15.4*	*19.3*	*0.50*	*5.3*	*7.0*	*9000*	*3.2*	*9.0*	*0.50*	*5.3*
E2	*23.9*	*10300*	*11.4*	*18.1*	*0.63*	*7.0*	*4.6*	*10000*	*2.1*	*7.3*	*0.63*	*7.0*
E3	*17.4*	*8300*	*6.7*	*15.1*	*0.43*	*3.5*	*4.5*	*6500*	*2.0*	*5.2*	*0.43*	*3.5*
V1	*10.0*	*11000*	*5.8*	*14.0*	*0.63*	*7.0*	*4.6*	*10000*	*2.1*	*7.3*	*0.63*	*7.0*
V2	*11.8*	*9500*	*5.5*	*11.5*	*0.50*	*5.3*	*7.0*	*9000*	*3.2*	*9.0*	*0.50*	*5.3*

Notes: (a) Values for dry service conditions
(b) Standard-term DOL applies



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Strength Modification Factors

- Load duration factor, K_D =1.0 (same as lumber/glulam)
- Service condition factor, K_S=1.0 (Dry” service conditions ONLY)
- Treatment factor, K_T
  - 1.0 for no treatment
  - CLT treated with strength-reducing chemicals, strength & stiffness capacities adjustment as per Clause 3.3.2. in CSA O86
- System factor, K_H =1.0 shall be used

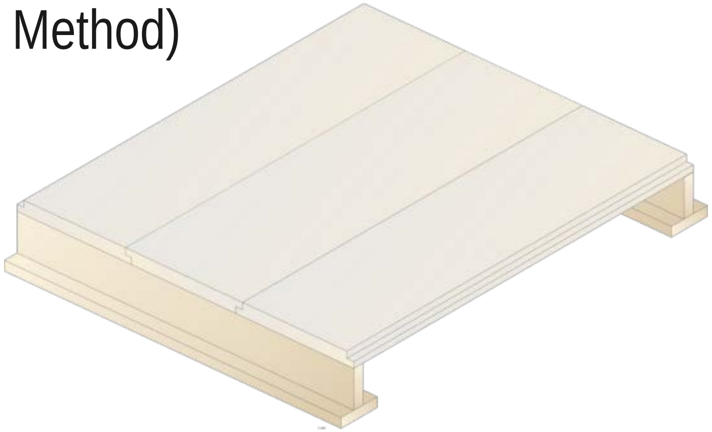
Proposed Analytical Design Methods for CLT Elements used in Floor and Roof Systems

- 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



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Bending Resistance - Major Direction

$$M_{r,y} = \phi \cdot F_b \cdot S_{eff,y} \cdot K_{rb,y}$$

$$\phi = 0.9$$

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

f_b = specified bending strength in the major direction

Effective Section Modulus

$$S_{eff,y} = \frac{(EI)_{eff,y}}{E_1} \cdot \frac{2}{h}$$ If $E_1 \neq E_2 \neq E_3$, etc.

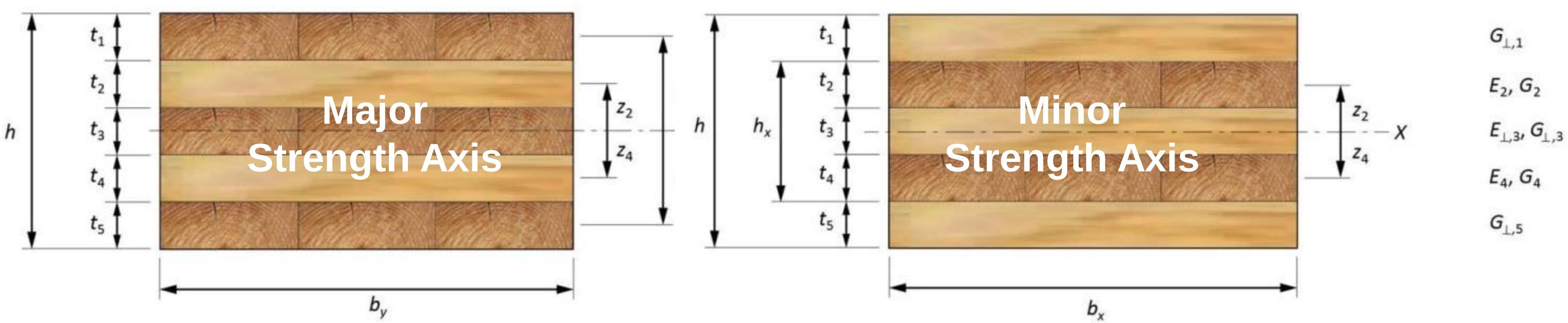
$$S_{eff,y} = \frac{I_{eff,y} \cdot 2}{h}$$ If $E_1 = E_2 = E_3$, etc.

$K_{rb,y}$ = 0.85 Calibration factor

Effective Bending Stiffness and In-plane Shear Rigidity: Major/Minor Strength Axis

$(EI)_{eff\ y,x}$ ~ Effective bending stiffness in the major or minor strength axis

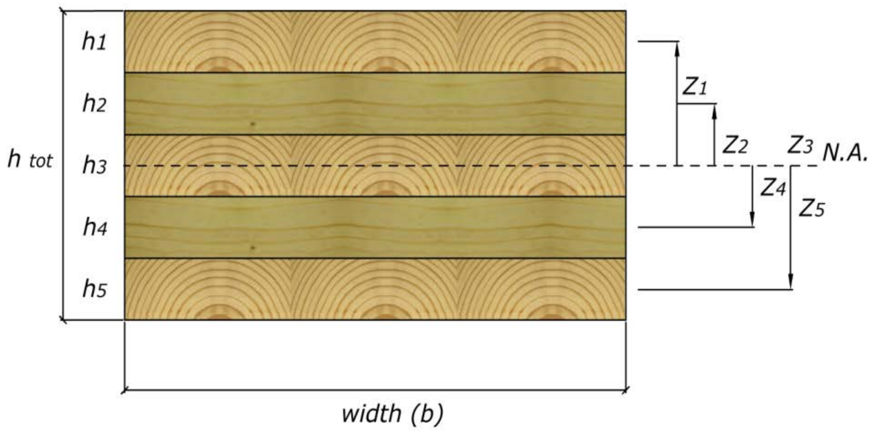
$(GA)_{eff\ zy,zx}$ ~ Effective shear rigidity in the major or minor strength axis



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 $(GA)_{eff}$

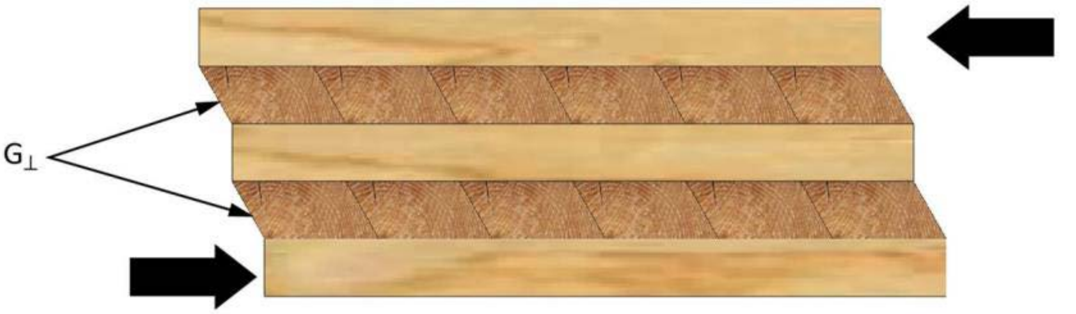
$$(GA)_{eff} = \frac{a^2}{\left[\left(\frac{h_1}{2 \cdot G_1 \cdot b}\right) + \left(\sum_{i=2}^{n-1} \frac{h_i}{G_i \cdot b_i}\right) + \left(\frac{h_n}{2 \cdot G_n \cdot b}\right)\right]}$$

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

Shear Resistance

- In both directions

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



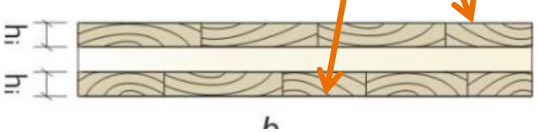
$$\phi = 0.9$$

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

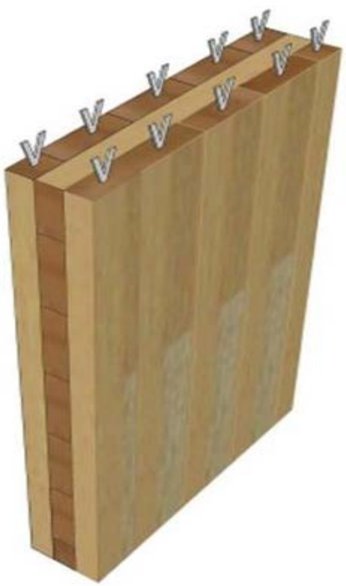
Rolling shear will govern the design!

Compressive Resistance

- Compressive resistance under <u>axial load</u>
  - Only layers with laminations oriented parallel to the applied axial load assumed to carry the load
  - CLT panels designed with outer layers oriented parallel to applied axial loads
  - Resistance to combined bending and axial load



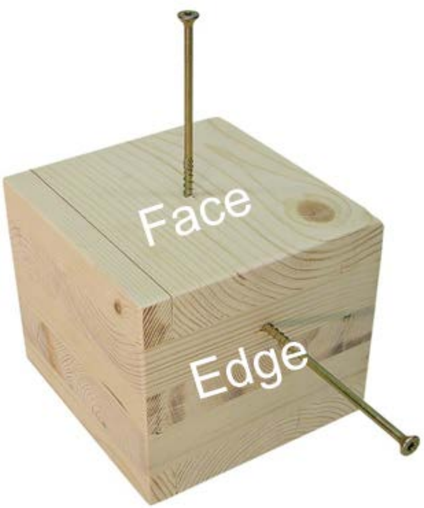
$$\frac{P_f}{P_r} + \frac{M_f}{M_r}\left[\frac{1}{1-\frac{P_f}{P_{E,v}}}\right] \leq 1$$



- Compressive resistance perp. to grain (bearing)
- Effect of load near support

Connections in CLT

- Design equations provided for connections with:
  - Bolts & dowels
  - Lag screws
  - Wood screws
  - Nails & spikes



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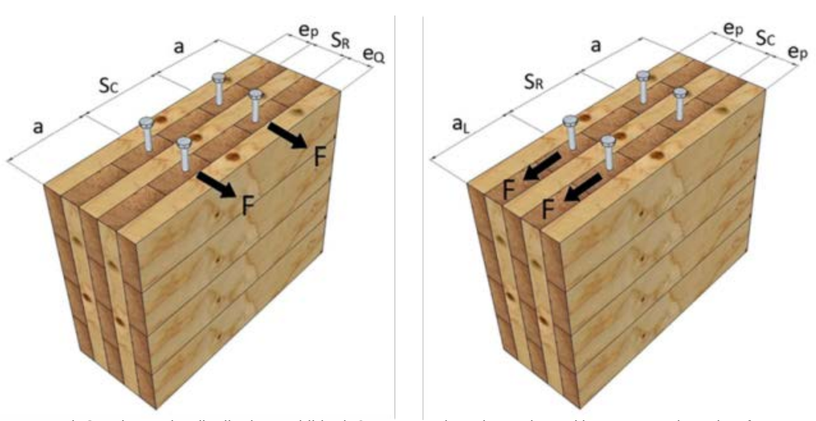
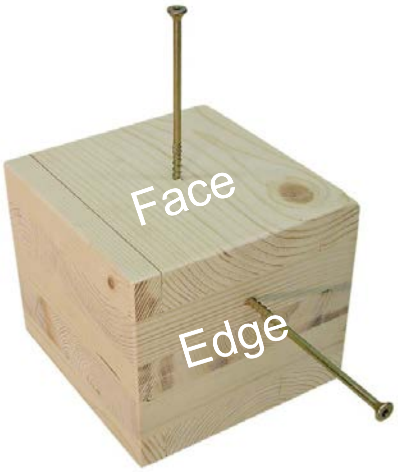
Connections in CLT

- Introduce a “**CLT factor**” for lateral & withdrawal resistances (J_x)
- Spacing between fasteners as for glulam/lumber for fastening on face
- New spacing for fasteners in the panel edge





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Connections in CLT

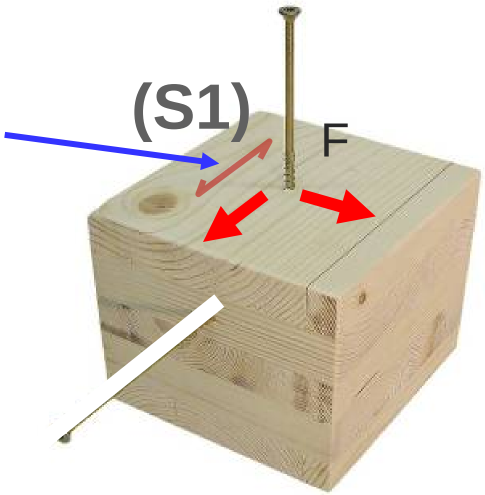
Lateral Resistance in CLT

Dowels, bolts & lag screws installed in the **plane side** of the panel (i.e., perpendicular to the panel)

- Load // to major strength direction (i.e., outer layer)

$$f_{iP} = 50\, G\, (1 - 0.01 d_F)\, J_X$$

J_X = adjustment factor for connections in CLT
= 0.9 for CLT



- Load perp. to major strength direction

$$f_{iQ} = 22\ G(1 - 0.01 d_F) \quad (N/mm^2)$$

Connections in CLT

Lateral Resistance in CLT

- **Dowels, bolts & lag screws** installed in the **narrow side** of the panel (i.e., on edge)

$$f_{iQ} = 0.67 * 22\ G(1 - 0.01 d_F) \quad (N / mm^2)$$

- *0.67 accounts for bolts, dowels & lag screws installed in end grain* *(conservative)*
- *Less conservative: Use Jx=0.9 if precautions are taken to ensure dowels are driven in side grain*

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Connections in CLT

Lateral Resistance in CLT

Timber Rivets: **Beyond Scope**

Could determine capacity based on exterior ply penetration ONLY!

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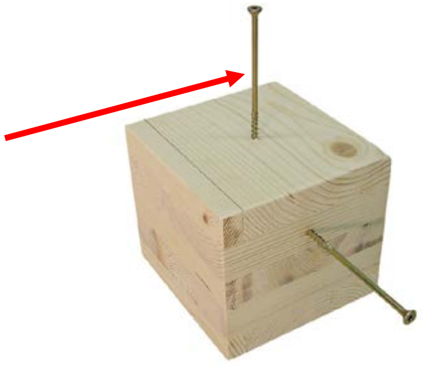
Withdrawal Resistance in CLT

- **Lag screws driven per. to the CLT panel**
  - Use current Eq. for withdrawal for lumber & glulam for **face** with an adjustment factor for CLT (J_X =*0.9*)

$$y_w = 59\, d_F\, 0.82\;\; G^{1.77}\, J_X\;\; N/mm$$



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Withdrawal Resistance in CLT

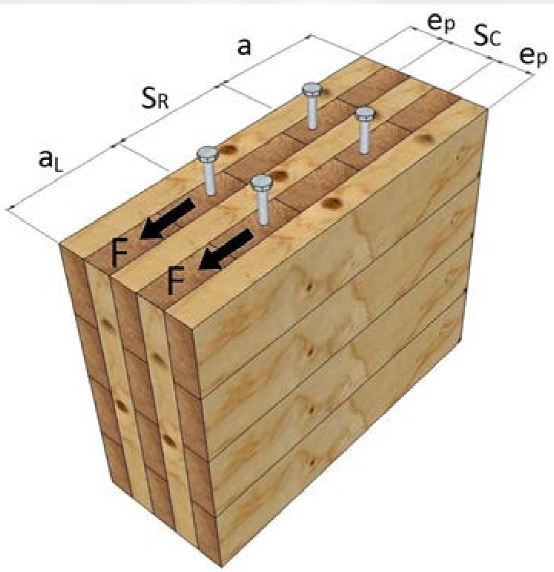
- **Lag screws driven in <u>edge of CLT panel</u>**
  - Use current Eq. for withdrawal for lumber & glulam for **<u>face</u>** with an adjustment factor for CLT (J_X =*0.9*) <u>& end grain factor (J_E = 0.67)</u>

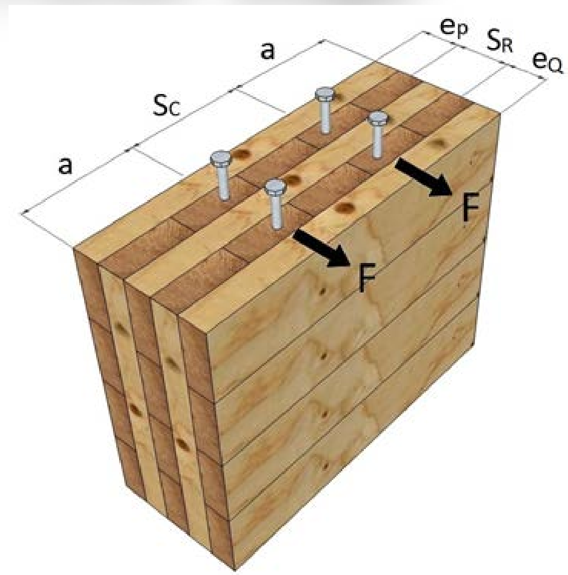
$$y_w = 59\, d_F\, 0.82\ G^{1.77} J_X\ N/mm$$

<u>Conservative:</u> Use 0.67 end grain factor for withdrawal from panel edge
<u>Less conservative</u>: Use same equation for lags screws driven perp. to panel but ensure side grain penetration occurs

Fastenings Capacity in CLT

Placement of Fasteners in Panel Edge





Fastener	S_R	S_C	a_L	a	e_Q	e_P
Nails/ Screws	10d	4d	12d	7d	6d	3d
Bolts	4d	3d	5d/50mm	4d/50mm	5d	1.5d

CLT as a LLRS

CLT shearwalls and diaphragms

- Applies ONLY to platform-type constructions with <u>height not exceeding 30 m</u>
- For <u>high seismic zones</u> ($I_E F_a S_a(0.2) > 0.75$), the height is limited to 20 m
- Factored shear resistance of CLT shearwalls is governed by connections (i.e., panel-to-panel and panel-to-foundations or floors), assuming each individual panel acts as a rigid body

General Seismic Design Considerations

- Rd ≤ 2.0 and Ro = 1.5 where the energy is dissipated through connections (i.e., capacity design principles) assuming wall panels act in rocking or in combination of rocking and sliding
- In-plane and out of plane irregularities not allowed
- CLT wall panels with aspect ratios less than 1:1 or acting in sliding only shall be designed with Rd Ro = 1.3

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Serviceability Design Provisions

- Calculate the maximum deflection of CLT floors
  - Equations account for creep and effect of rolling shear in CLT

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

- Vibration-controlled span limit

  (Based on extensive FPI's floor vibration research program)

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

Fire Resistance of CLT (Annex B)

- Design methodology to develop fire resistance ratings for mass timber
- Design charring rate for CLT
- Facilitates development of “*Alternative Solutions*” designs (i.e., alternate to testing)
- Annex B is “non-mandatory”

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Thank you

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Deflection of CLT slabs

- **Uniformly distributed load, ω**

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

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

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

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

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.

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.*