Chapter 9 Design of CLT Structures

CIVE480 Timber Structures
2019

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9.1 Introduction of CLT (cross-laminated timber)

1) History

- CLT was first developed in **Europe**
- In the mid **1990s**, industry-academia joint research (Austria) → modern CLT
- In early **2000s**, construction in CLT increased significantly (*driven by green building movement*…)

2) In Canada

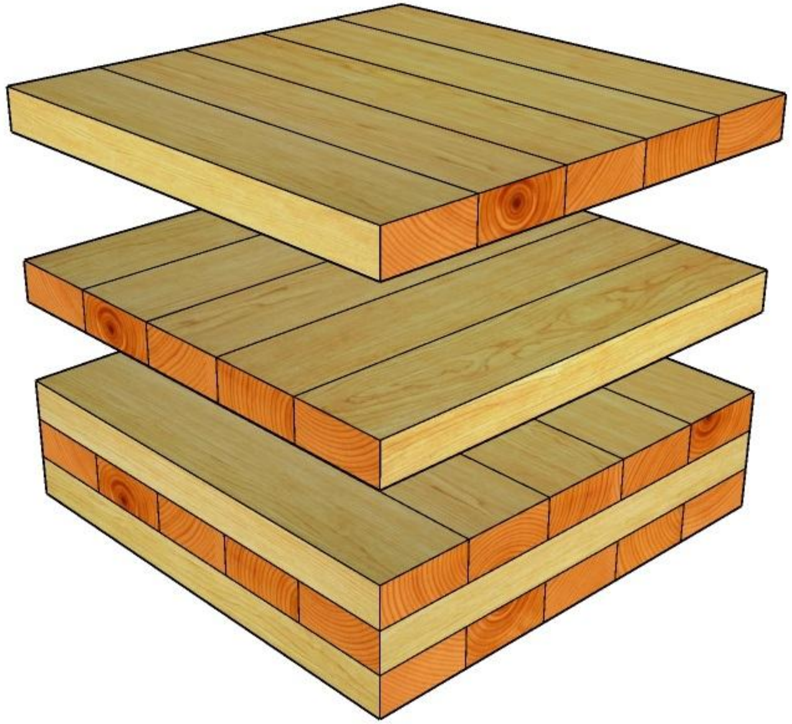
- In 2005, FPInnovations launched a CLT research program,

  → Prepared **CLT Handbook** (2011)
- NSERC Network — NEWBuildS (CLT is one of its four themes) (2010-2015)

→ CLT was introduced into the **CSA O86-14** “Engineering design in wood” **2014 edition update 1** (May 2016)

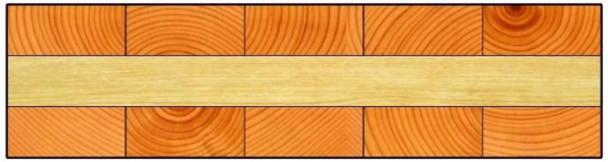
3) Definition

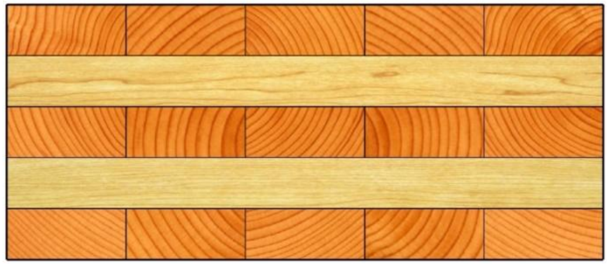
- CLT panels consist of several layers of boards stacked crosswise (typically at 90 degrees) and **glued** together on their **wide faces** and, sometimes, on the narrow faces as well.

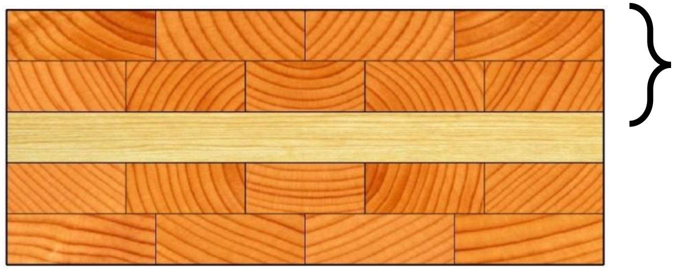


4) Cross section

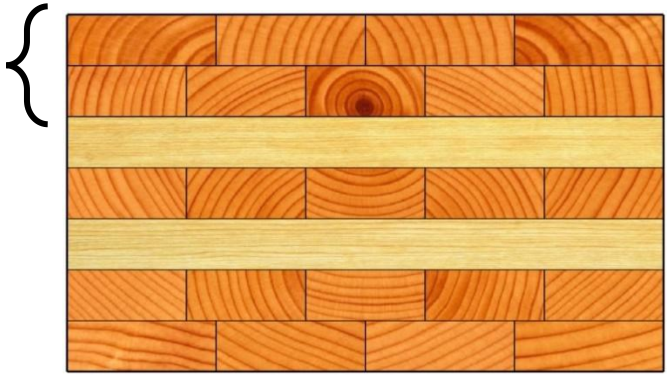
- Typically consist of **3 to 9** alternating layers
- **Same grade and species** of sawn lumber in one lamination
- Consecutive layers may be placed in the same direction





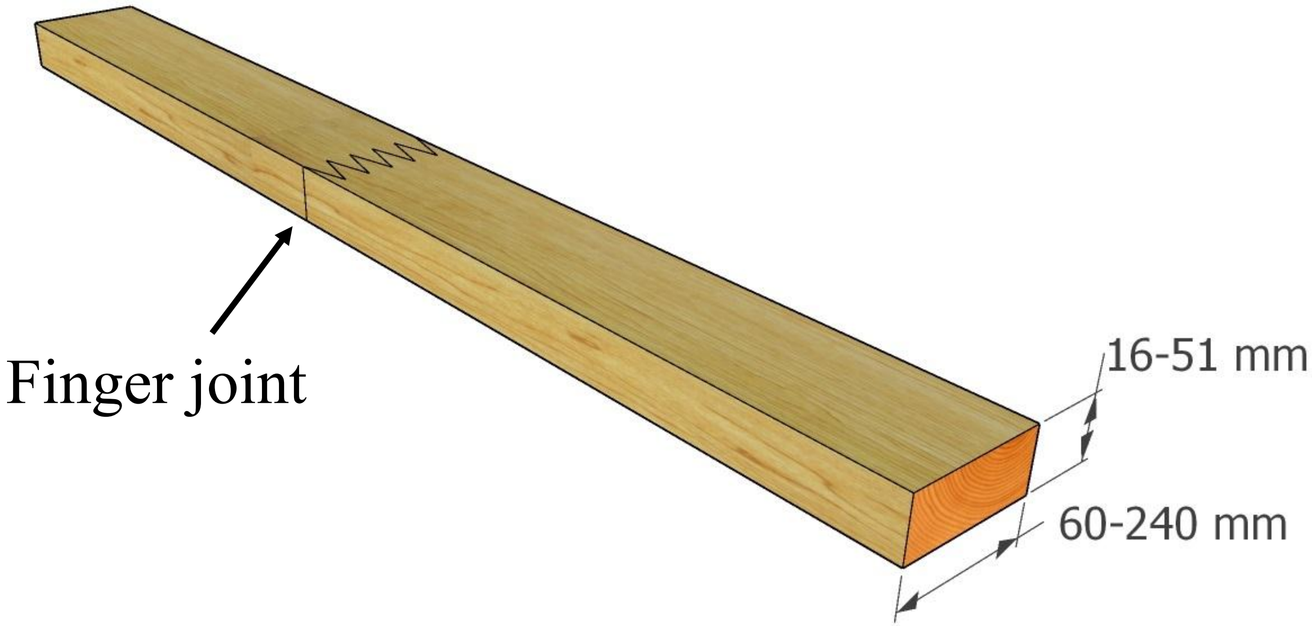


Consecutive layers



5) Individual board

- Size: **16-51 mm** thick, **60-240 mm** wide
- Finger joint using structural adhesive, kiln dried



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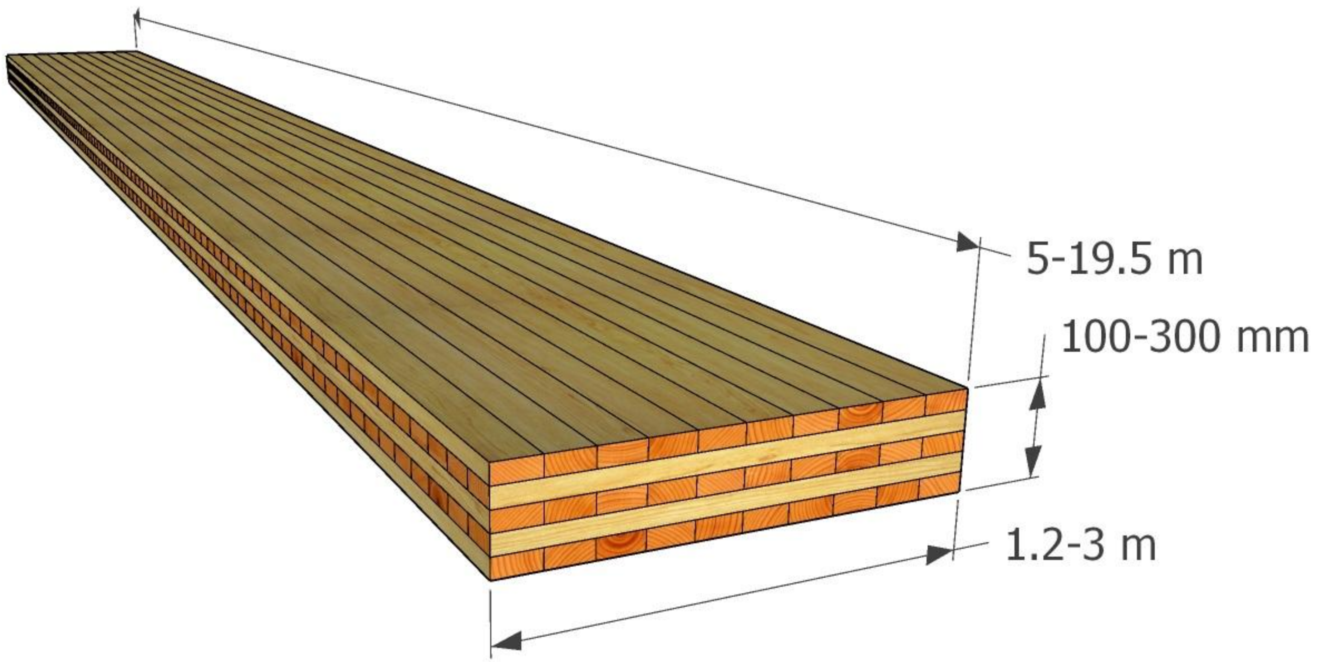
6) CLT panel

- Size: width (**1.2 m to 3 m**), length (**5 m to 19.5 m**), thickness (**100 mm to 300 mm**)
- Limited by the size of manufacturer's press and transportation regulations



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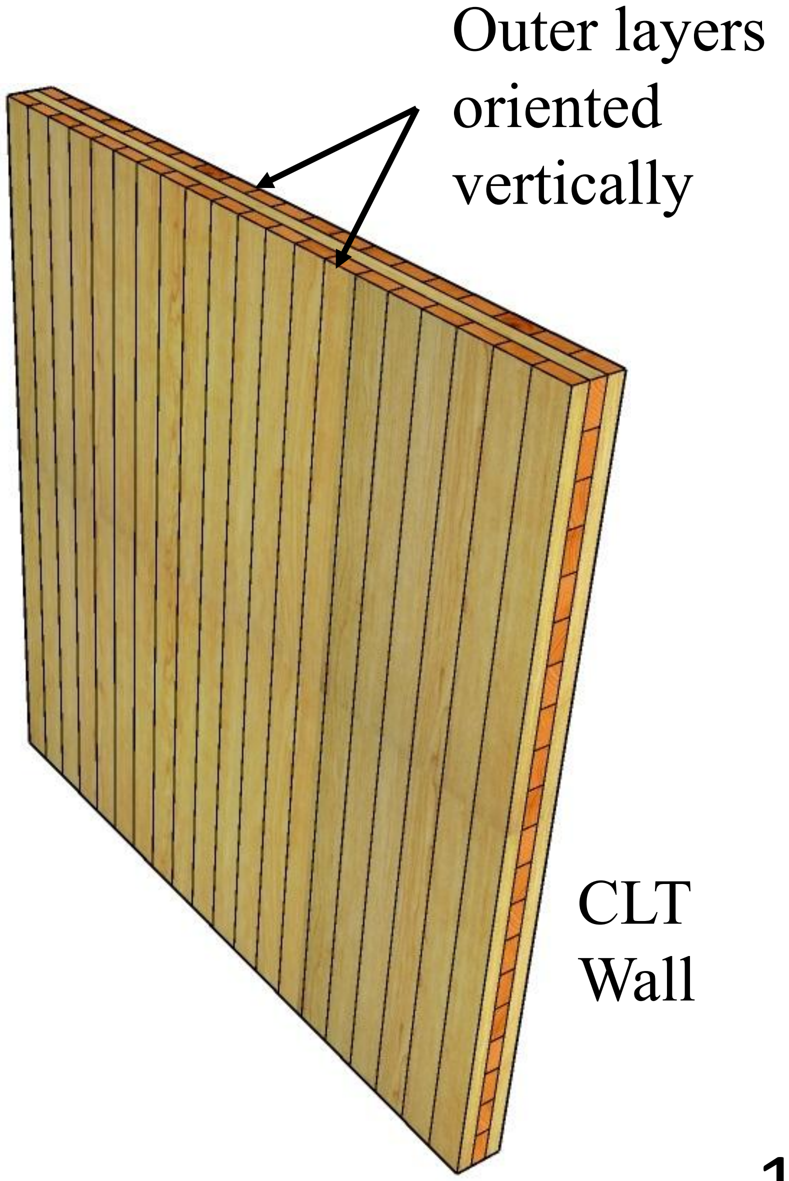
7) Stress grades

- Five primary CLT stress grades (E1, E2, E3, V1, and V2)
  "E" — machine stress rated (MSR, or E-rated)
  "V" — visually graded lumber
- Lumber strength in longitudinal direction strength > transverse direction (*Table 8.2.3 of CSA O86*)

	Longitudinal layers	**Transverse layers**
E1, E2, E3	MSR	Visually graded
V1, V2	Visually graded	Visually graded

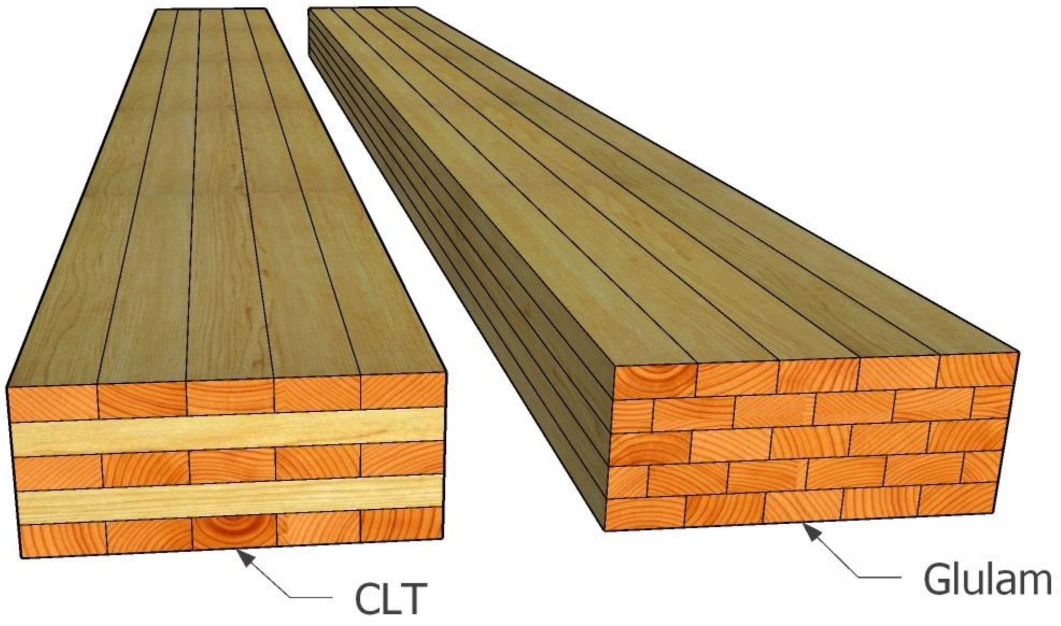
8) Advantages (walls and floors/roofs)

- Improved dimensional stability (wide and long walls and floors)
- Increase splitting resistance of some CLT connections



9) Benefits of cross laminating

- Two-way action capability of floors



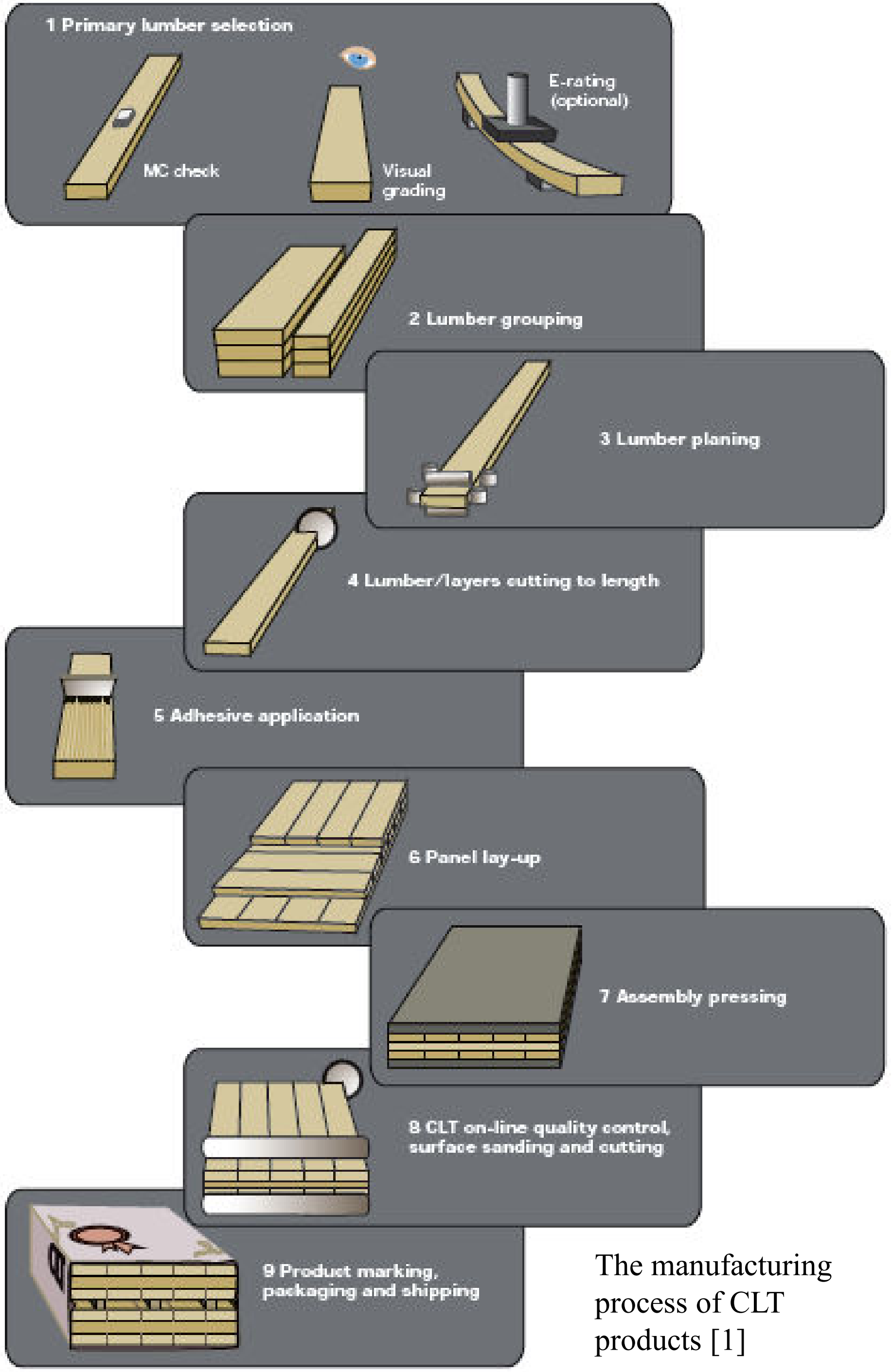
CLT panel vs Glued-laminated timber

10) Other advantages

- Easy handling in construction
- High level of prefabrication
- Good thermal insulation
- Good sound insulation
- A fairly good performance under fire conditions

11) Manufacturing process

- Lumber selection (quality consistency)
- Lumber grouping and planning
- Adhesive application (adhesive bond quality control)
- Panel lay-up and pressing
- Product cutting
- Marking and packaging



The manufacturing process of CLT products [1]

9.2 Structural design and serviceability considerations of CLT

1) Floor/roof elements

- In-plane and out-of-plane bending and shear strength and stiffness
- Short-term and long-term behavior:
  - Instantaneous deflection
  - Long-term strength for permanent loading
  - Long-term deflection (creep deformation)
- <u>Compression perpendicular to grain strength (bearing)</u>
- Fire performance, durability, vibration performance, acoustic performance

2) Wall elements

- In-plane and out-of-plane bending and shear strength and stiffness
- Short-term and long-term behavior:
  - Instantaneous deflection
  - Long-term strength for permanent loading
  - Long-term deflection (creep deformation)
- <u>Loading-bearing capacity (critical)</u>
- Fire performance, durability, ~~vibration performance~~, acoustic performance

3) CLT in Construction

Single-family house in Klagenfurt, Austria (courtesy of KLH) [1]

Multi-family building in London, United Kingdom (courtesy of KLH and Waugh-Thistleton) [1]

3) CLT in Construction

Impulsezentrum, Graz, Austria
(courtesy of KLH) [1]

Brock Common Building at UBC

9.3 Design of CLT panels as flexural members

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1) Design

- Factored moment resistance $M_r \geq$ maximum factored moment M_f
- Factored shear resistance $V_r \geq$ maximum factored shear force V_f

  (loads within a distance from the support equal to the depth of the member may be neglected ?)
- Factored bearing resistance $Q_r \geq$ maximum factored reaction Q_f
- Maximum deflection under specified loads < deflection criteria
- Actual span does not exceed the span determined by vibration criteria

2) Design Factors

- Load duration factor, K_D
- Service condition factors, K_S
- System factor, K_H
- Treatment factor, K_T

3) Load duration factor, K_D

- The specified strengths and capacities in CSA O86 are based on the **standard-term duration** of the specified loads

Load duration	K_D	Explanatory notes
Short term	1.15	Last less than 7 days (e.g. wind, earthquake…)
Standard term	1	Between short and long term (e.g. snow, occupancy, wheel loads…)
Long term	0.65	Subjected to continuous load (e.g. dead loads, fixed machinery…)

(Table 5.3.2.2 of CSA O86)

3) Load duration factor, K_D

- For standard-term loads, P_L is greater than the P_s

$$K_D = 1.0 - 0.5\log(P_L/P_s) \geq 0.65$$

Where:

P_L = specified long-term load

P_s = specified standard-term load based on S and L loads acting alone or in combination
= S, L, S+0.5L, or 0.5S+L, determined using importance factors equal to 1.0

3) Load duration factor, K_D

- For standard-term loads, P_L is greater than the P_s

$$K_D = 1.0 - 0.5\log(P_L/P_s) \geq 0.65$$

K_D		Specified standard-term load Ps (kPa)			
		1.0	1.9	2.0	2.4
Specified long-term load P_L (kPa)	1.5	0.91	**1.00**	**1.00**	**1.00**
	2.0	0.85	0.99	**1.00**	**1.00**
	2.5	0.80	0.94	0.95	0.99

4) Service condition factors, K_S

- Unless specifically permitted by the manufacturers, CLT panels are only used in **dry service conditions** for which

$$K_{Sb} = K_{Sc} = K_{Sp} = K_{St} = K_{Sv} = K_{SE} = 1.0$$

5) System factor, K_H

- K_H is to be taken as 1.0 for all strength properties of CLT panels.

6) Treatment factor, K_T

- CLT shall not be treated with water-borne preservatives after gluing
- For CLT treated with fire-retardant or other potentially strength-reducing chemicals, strength and stiffness is required to be based on documented results of tests.

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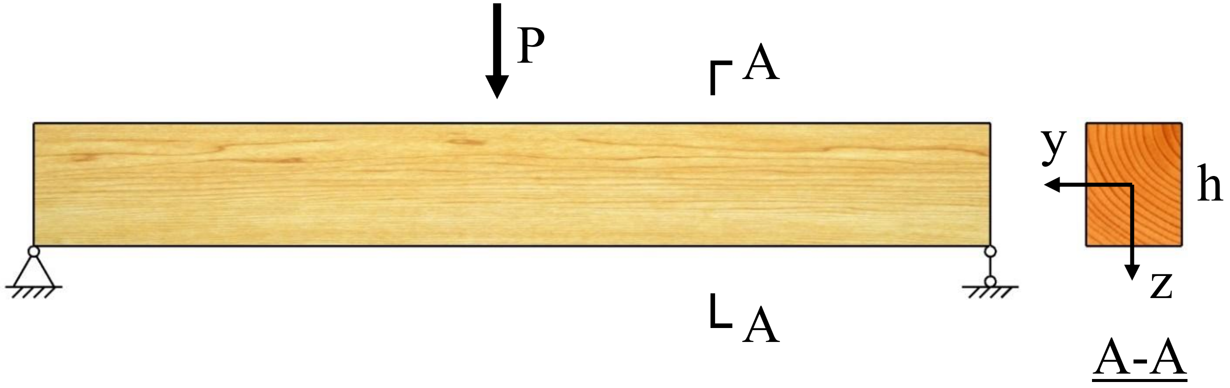
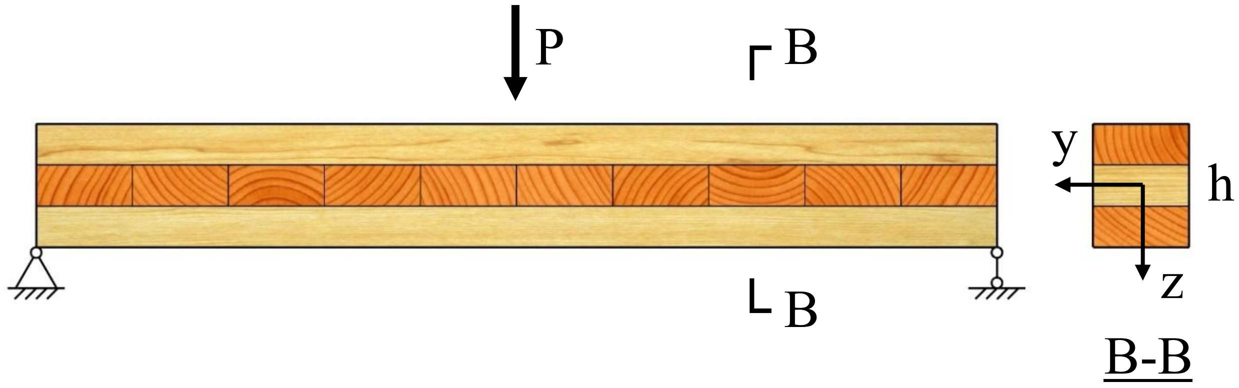
7) CLT under bending





$$M = \sigma I_y \frac{2}{h} = \sigma \frac{\boldsymbol{EI_y}}{E} \frac{2}{h}$$

$$M_{CLT} = \sigma \frac{\boldsymbol{(EI)_{eff,y}}}{E} \frac{2}{h}$$

where σ= bending strength
I_y= moment of inertia
E= Young's modulus
EI_y= bending stiffness of cross section

$(EI)_{eff,y}$= effective bending stiffness of cross section

7) CLT under bending

- The **out-of-plane** factored bending moment resistance:

(a) For the **major** strength axis

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

where $\emptyset = 0.9$

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

where f_b= specified bending strength of **laminations** in the longitudinal layers, MPa

$S_{eff,y} = \frac{(EI)_{eff,y}}{E} \frac{2}{h}$

where $(EI)_{eff,y}$= effective bending stiffness of **the panel** for the major strength axis, N·mm^2

E= specified modulus of elasticity of **laminations** in the longitudinal layers, MPa

h= thickness of **the panel**, mm

$K_{rb,y}$= 0.85

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7) CLT under bending

- The **out-of-plane** factored bending moment resistance:

(b) For the **minor** strength axis

$$M_{r,x} = \emptyset F_b S_{eff,x} K_{rb,x}$$

where $\emptyset = 0.9$

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

where f_b= specified bending strength of **laminations** in the transverse layers, MPa

$S_{eff,x} = \frac{(EI)_{eff,x}}{E} \frac{2}{h_x}$

where $(EI)_{eff,x}$= effective bending stiffness of **the panel** for the minor strength axis, N·mm^2

E= specified modulus of elasticity of **laminations** in the transverse layers, MPa

h_x = thickness of **the panel** <u>without the outer longitudinal layers</u>, mm

$K_{rb,x}$= 1.0

7) CLT under bending

- The factored **shear** resistance:

(a) For the major strength axis $V_{r,zy} = \emptyset F_s \, 2A_{g,zy}/3$

(b) For the minor strength axis $V_{r,zx} = \emptyset F_s \, 2A_{g,zx}/3$

where $\emptyset = 0.9$

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

where f_s= specified strength in **rolling shear of laminations** in the longitudinal layers, MPa

$A_{g,zy}$= gross cross-sectional area of **the panel** for the major strength axis (including all layers), mm^2

$A_{g,zx}$= gross cross-sectional area of **the panel** for the minor strength axis (not including the outer layers), mm^2

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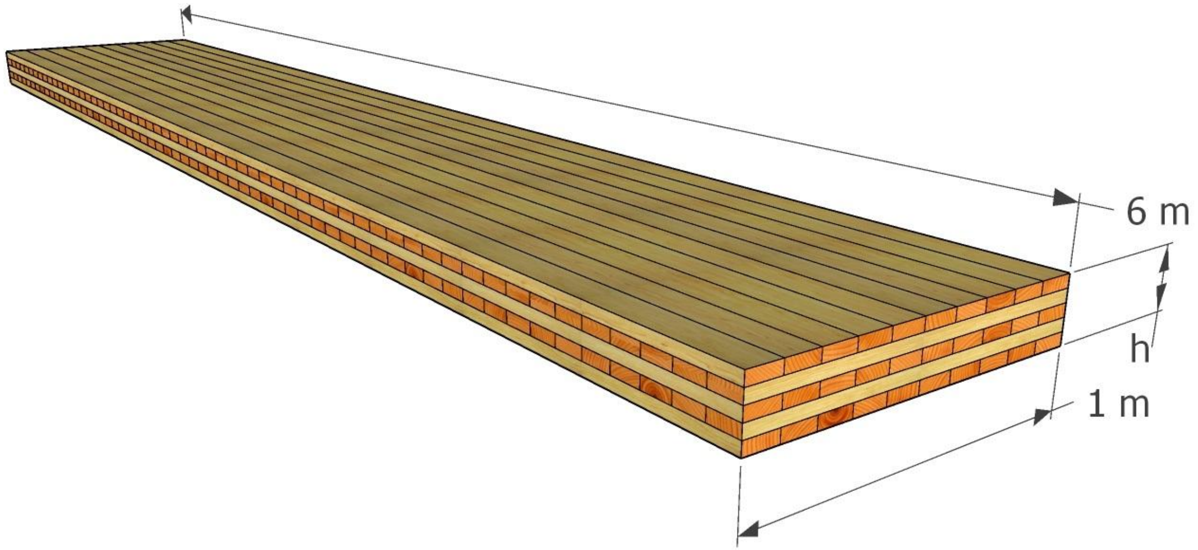
Example 1: CLT floor panel (Strength)

Design single span floor CLT panels

<u>Conditions</u>:

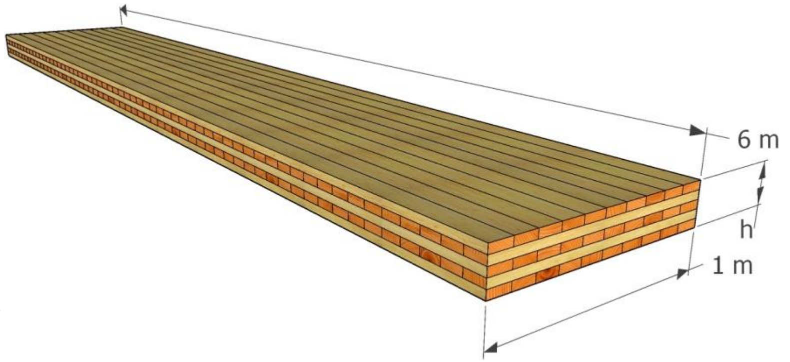
- Panel span = 6 m
- Panel width = 1 m
- Specified dead load = 1.5 kPa
- Specified live load = 2.4 kPa
- Standard load duration
- Dry service condition
- Untreated



Use stress grade V1 oriented about its major strength axis.

The thickness of each ply is 35 mm.

Example 1: CLT floor panel (Strength)



Calculation:

Total factored load = $(1.25 \times 1.5) + (1.5 \times 2.4) = 5.48\ kPa$

$$w_f = 5.48 \times 1m = 5.48\ kN/m$$

$$M_f = \frac{w_f L^2}{8} = \frac{5.48 \times 6.0^2}{8} = 24.6\ kN \cdot m/m$$

$$V_f = \frac{w_f L}{2} = \frac{5.48 \times 6.0}{8} = 16.4\ kN/m$$

From CLT Strength Selection Tables (CWC 2017) try a 5-ply, V1 stress grade (h=175mm)

$M_{r,y} = 31.2\ kN \cdot m/m > 24.6\ kN \cdot m/m$ ***Acceptable***

$V_{r,zy} = 66.2\ kN/m > 16.4\ kN/m$ ***Acceptable***

8) Serviceability check

- Deflection (bending, shear and creep effects)

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

where Δ_{ST}= elastic deflection due to short term and/or standard term loads, without dead load 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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8) Serviceability check

- Deflection under a specified uniformly distributed load, ω

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

where $(EI)_{eff}$= effective bending stiffness
$(GA)_{eff}$= effective in-plane (planar) shear rigidity

- For a concentrated line load, P, in the middle of a single span CLT panel

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

where κ= form factor
= for rectangular cross-sections

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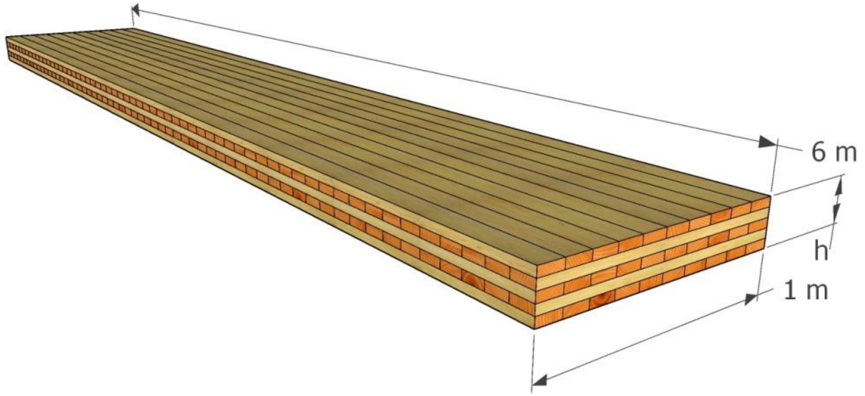
Example 2: CLT floor panel (Serviceability)

For the same cross section and design conditions as in Example 1

Total specified load $= 1.5 + 2.4 = 3.90 kPa$

Total specified live load $= 2.4\ kPa$



<u>Calculation</u>

Considering major strength axis, the live load is L = 2.4 kPa

From CLT Serviceability Selection Tables (CWC 2017) for vibration and deflation, the maximum panel lengths for stress grade V1, 5-ply, are **5.27 m** and **6.63 m**, respectively.

6 m floor span exceeds the vibration span limit.

A different grade or thickness of panel would be required. For example, a 7-ply V1 stress grade panel has a vibration controlled maximum span of **6.58 m**.

9.4 Design of CLT shearwall

1) General

- Platform-type construction, height limit: **30 m**
- High seismic zones ($i.e. I_E F_a S_a(0.2) > 0.75$), height limit: **20 m**
- The factored shear resistance of CLT shearwalls shall be governed by the resistance of the **connections**
- Assuming each individual panel acts as a rigid body (**CSA O86 does not provide the in-plane bending and shear strength and stiffness of CLT panels**)

2) Seismic design consideration (Capacity design principles)

- **Energy dissipative connections**

  (wall-foundation, wall- supporting floor, wall-parallel wall, discrete hold-downs)

- **Non-dissipative connections**

  (continuous steel rods, floor-supporting wall, wall-perpendicular wall

3) Energy-dissipative connections

- **Yielding mode** governs the resistance
- At least **moderately ductile**
- Possess sufficient **deformation capacity** to allow for the CLT panels to develop their assumed deformation behaviour (rocking, sliding)

4) Non-dissipative connections

- **Not to yield** while the energy-dissipative connections reach their ultimate resistance, and to tolerate the **displacement demands** when the energy-dissipative connections reach the target displacement
- The factored resistance of the non-dissipative connections > **strength demand** on them when the energy-dissipative connections reach their **95th percentile of ultimate resistance** under cyclic loading

5) Aspect ratios of CLT shearwalls

- 1:1 and higher, with the maximum 4:1 (ensures the ductility of the structure and desirable rocking mechanism)

  $$R_d = 2.0, R_o = 1.5$$

- Less than 1:1, or acting in sliding only

  $$R_d R_o = 1.3$$

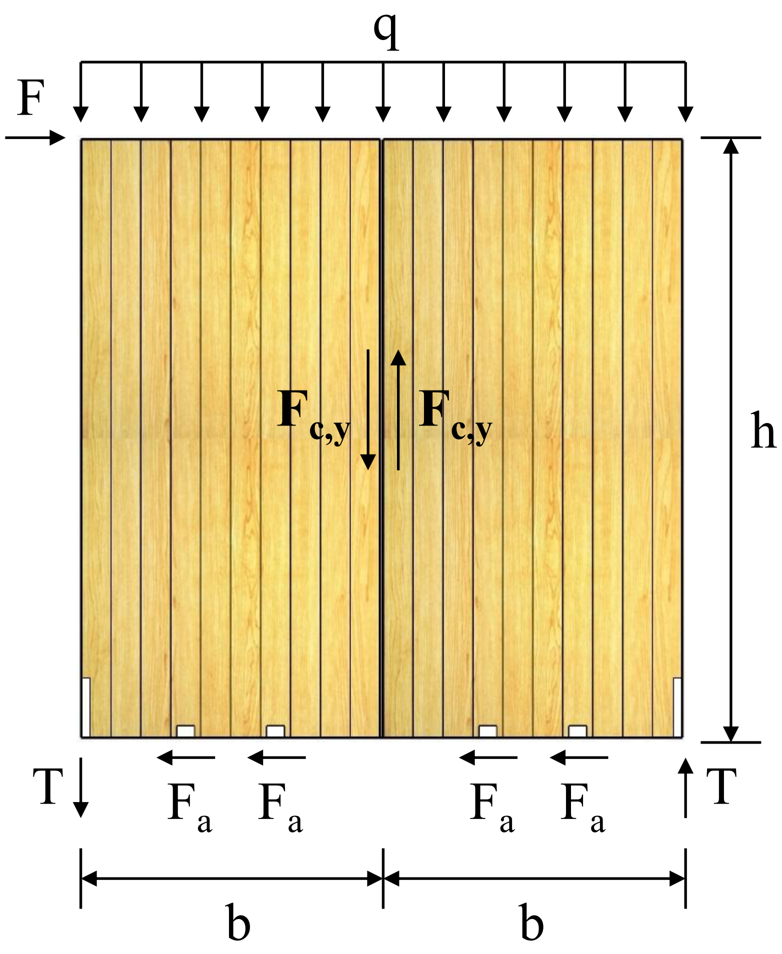
6) Deflections

- In principle, it should account **panel bending**, **shear**, **sliding**, **rocking** and **deformation of supports**
- For simplicity in design situations, the O86 assumes CLT panels act as rigid bodies, and therefore panel **bending and shear** deformation may be ignored

Two-panel CLT shearwall strength

Conditions:

- Hold-down and panel joints are assumed as rigid-plastic
- Rocking motion is assumed
- Hold-down resists the **uplift** caused by overturning
- Angle brackets contribute only to horizontal **shear** resistance (using slotted holes in the uplift direction)
- The shear force at the vertical panel joint is represented by $F_{c,y}$



Couple-panel (CP) kinematic mode

<u>Each panel rotates about its respective point of rotation</u>

The moment about the bottom right corner of the wall

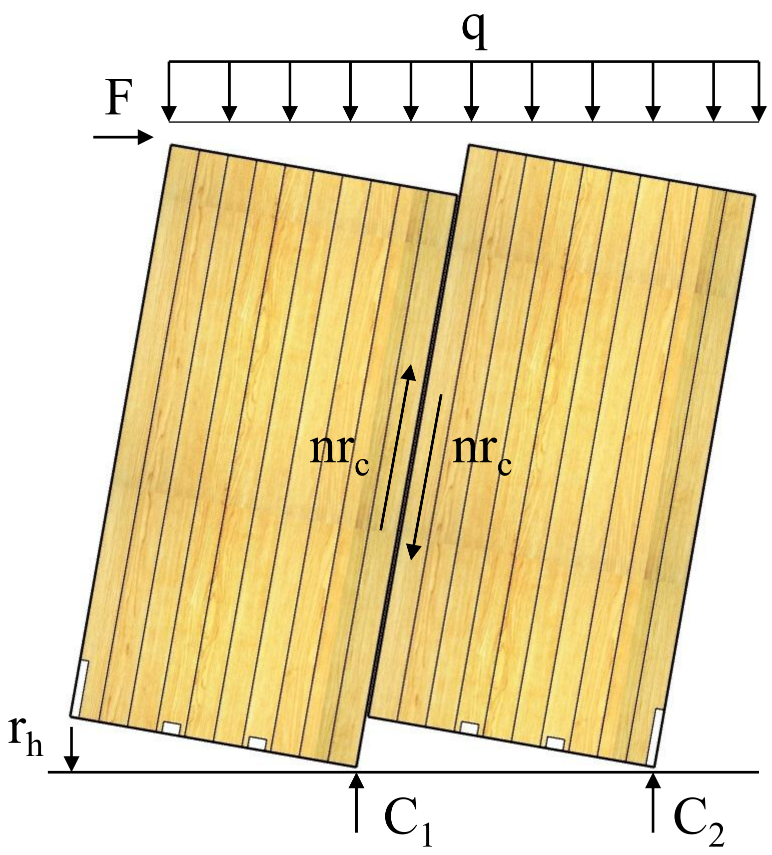
$$\sum M_o = r_h \cdot 2b + q \cdot 2b \cdot b - F \cdot h - C_1 \cdot b = 0$$

Where C_1 and C_2 are reaction forces

$$F = \frac{b}{h}(2r_h + 2qb - C_1)$$

Where C_1 can be found based on equilibrium in the vertical direction for the left-hand side panel

$$\sum F_y = 0 \rightarrow C_1 = qb + r_h - n \cdot r_c$$



The maximum lateral force can be written as a function of the panel joint and hold-down strength:

$$R_w = F = \frac{b}{h}(r_h + qb + n \cdot r_c)$$

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Single-wall (SW) kinematic mode

<u>Two panels rotate about one center of rotation</u>

The moment about the bottom right corner of the wall

$$\sum M_o = r_h \cdot 2b + q \cdot 2b \cdot b - F \cdot h = 0$$

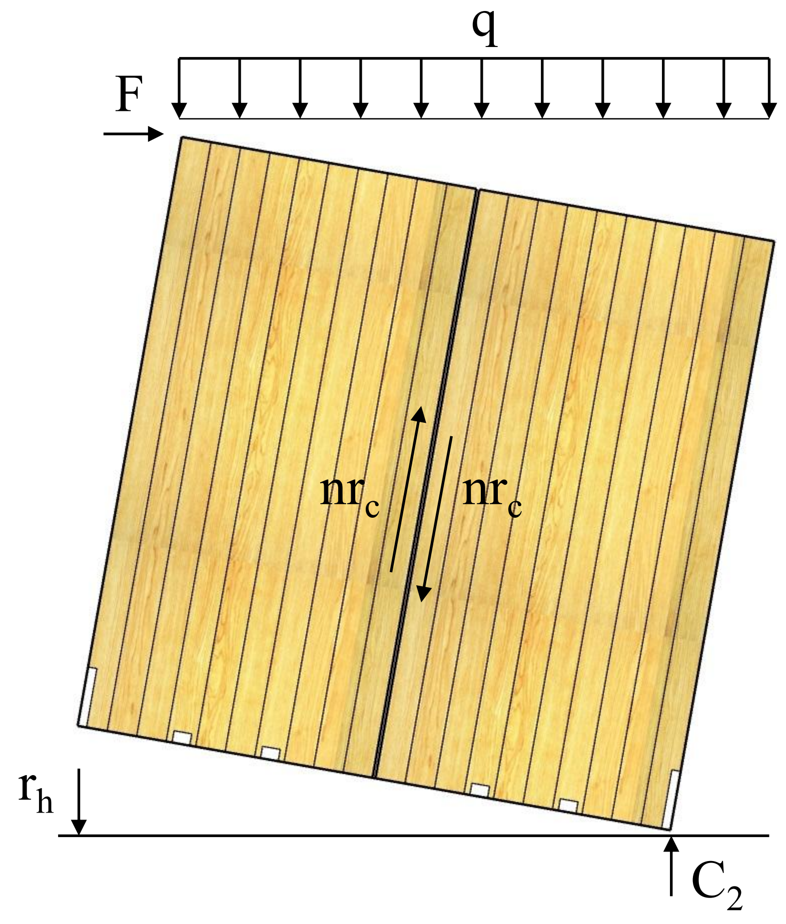
The lateral force acting on the wall can be obtained

$$F = \frac{r_h \cdot 2b}{h} + \frac{q \cdot (2b)^2}{2h}$$

Using small angle approximating, and performing the static equilibrium for a single panel

$$\sum F_y = n \cdot r_c - qb - r_h = 0 \rightarrow n \cdot r_c = qb + r_h$$

$$n \cdot r_c = qb + \frac{F \cdot h}{2b} - \frac{q \cdot 2b}{2} = \frac{F \cdot h}{2b}$$



Single-wall (SW) kinematic mode

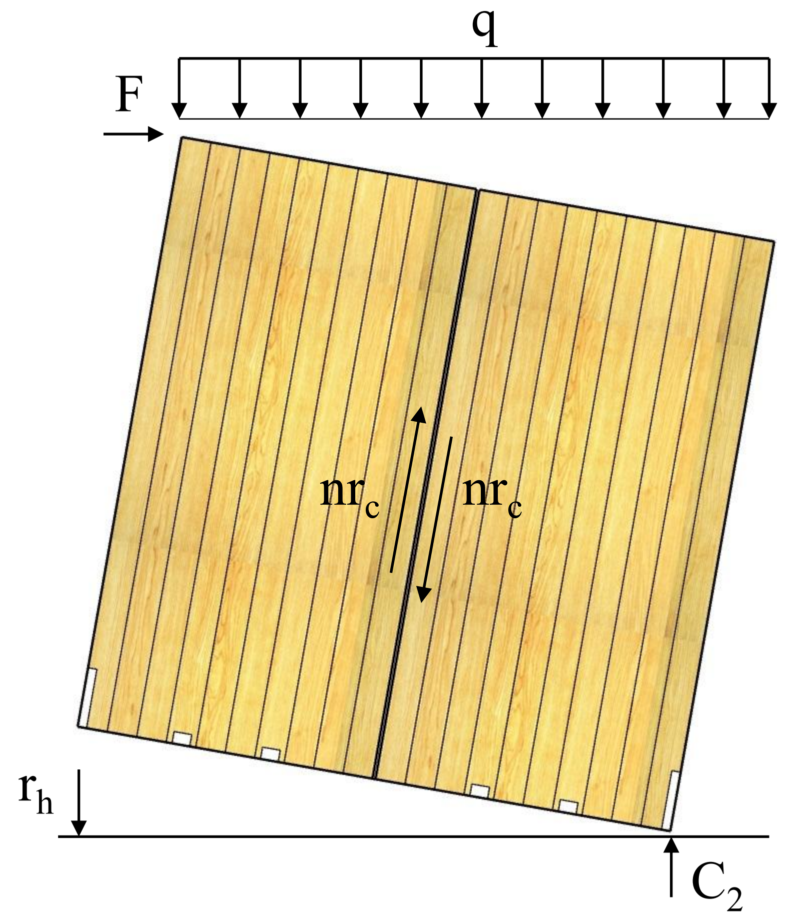
<u>Two panels rotate about one center of rotation</u>

The lateral force, F, can also be expressed as

$$F = \frac{n \cdot r_c \cdot 2b}{h}$$

The lateral force acting on the wall is the minimum of the panel joint strength and the hold-down strength:

$$R_w = Min(\frac{n \cdot r_c \cdot 2b}{h}, \frac{r_h \cdot 2b}{h} + \frac{q \cdot (2b)^2}{2h})$$



Example 3: Two-panel CLT shearwall strength

Calculation

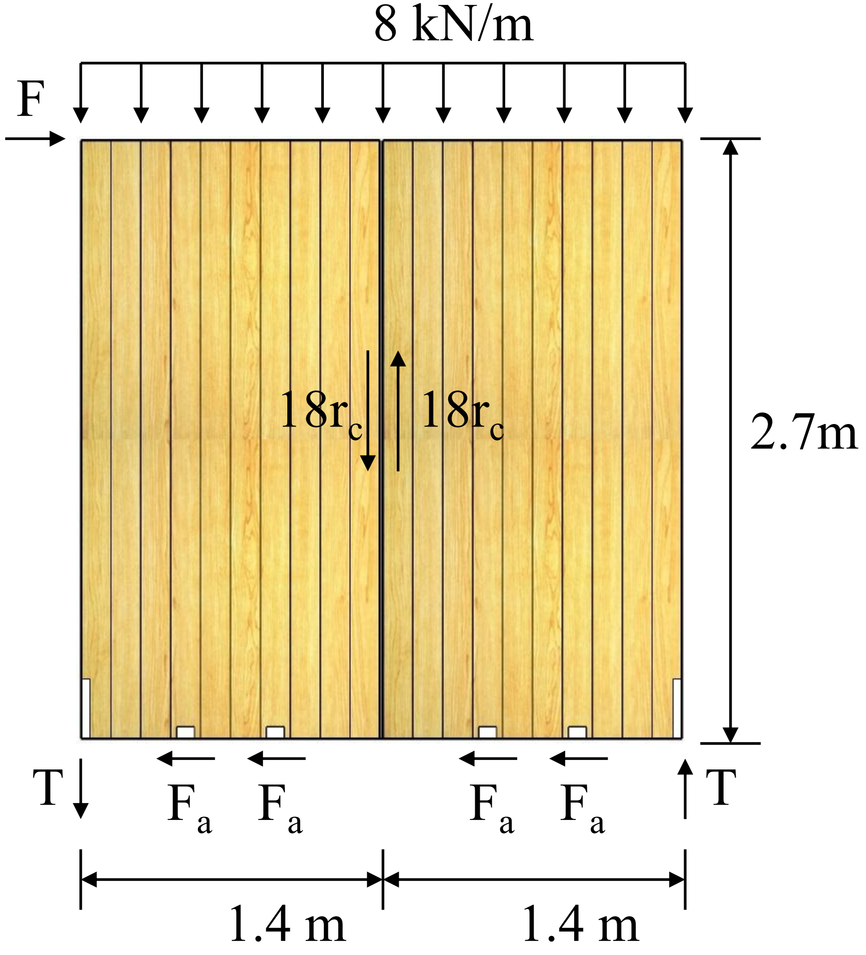
Case A: Strength governed by panel joint

The elastic strength for vertical joint (r_c) and hold-down (r_h) are assumed equal to **2kN** and **100kN**, respectively

CP: $R_w = F = \frac{b}{h}(r_h + qb + n \cdot r_c) = \frac{1.4}{2.7}(100 + 8 \times 1.4 + 18 \times 2) = 76.3kN$

SW: $R_w = Min\left(\frac{n \cdot r_c \cdot 2b}{h}, \frac{r_h \cdot 2b}{h} + \frac{q \cdot (2b)^2}{2h}\right) = Min\left(\frac{18 \times 2 \times 2.8}{2.7}, \frac{100 \times 2.8}{2.7} + \frac{8 \times (2.8)^2}{2 \times 2.7}\right) = Min(37.3, 115.3) = 37.3kN$

The wall strength is taken as the minimum obtained from the two assumptions: **37.3kN**



Example 3: Two-panel CLT shearwall strength

<u>Calculation</u>

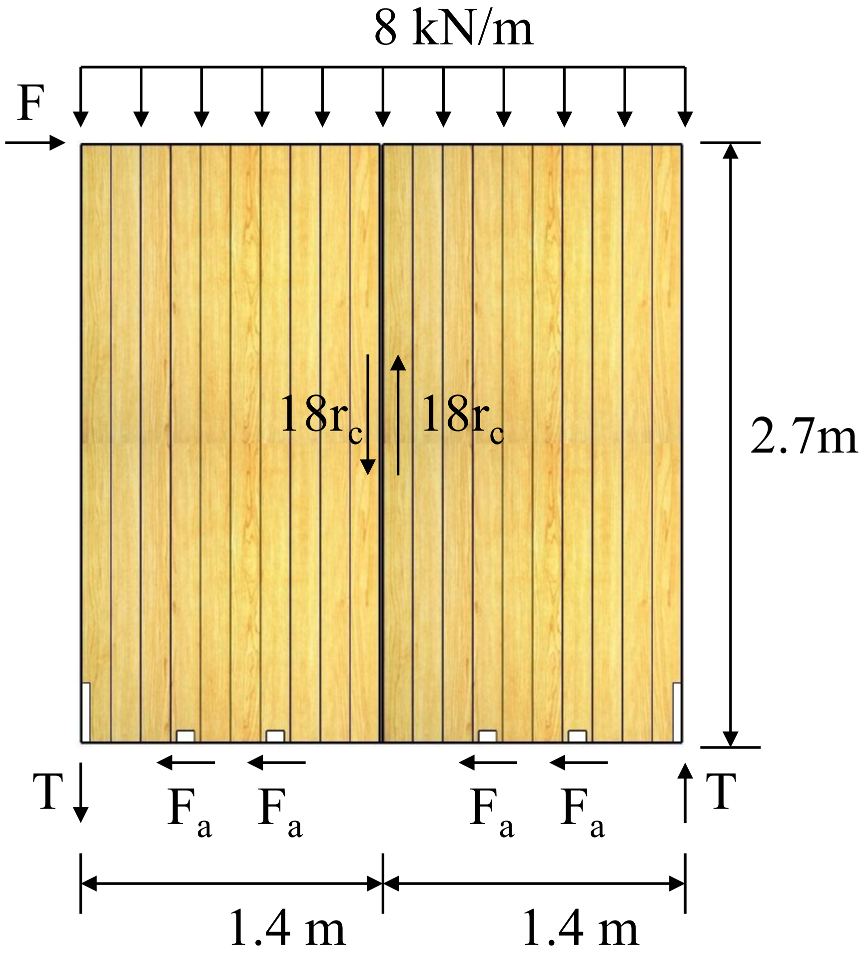
Case B: Strength governed by hold-down

The elastic strength for vertical joint (r_c) and hold-down (r_h) are assumed equal to **5kN** and **50kN**, respectively

CP: $R_w = F = \frac{b}{h}(r_h + qb + n \cdot r_c) = \frac{1.4}{2.7}(50 + 8 \times 1.4 + 18 \times 5) = 78.4kN$

SW: $R_w = Min\left(\frac{n \cdot r_c \cdot 2b}{h}, \frac{r_h \cdot 2b}{h} + \frac{q \cdot (2b)^2}{2h}\right) = Min\left(\frac{18 \times 5 \times 2.8}{2.7}, \frac{50 \times 2.8}{2.7} + \frac{8 \times (2.8)^2}{2 \times 2.7}\right) = Min(93.3, 63.5) = 63.5kN$

The wall strength is taken as the minimum obtained from the two assumptions: 63.5kN



This lecture is developed based on the CLT Handbook [1], Wood Design Manual [2] and CSA O86-2014 [3].

References

[1] FPInnovations. 2011. *CLT Handbook*. Quebec, QC, Canada

[2] Canadian Wood Council (CWC). 2017. *Wood design manual*. Ottawa, ON, Canada.

[3] Canadian Standards Association (CSA). 2017. *Engineering design in wood*. CSA O86-14, Toronto, ON, Canada.