Seismic performance of cross-laminated-timber shear walls and recent research on hold-downs

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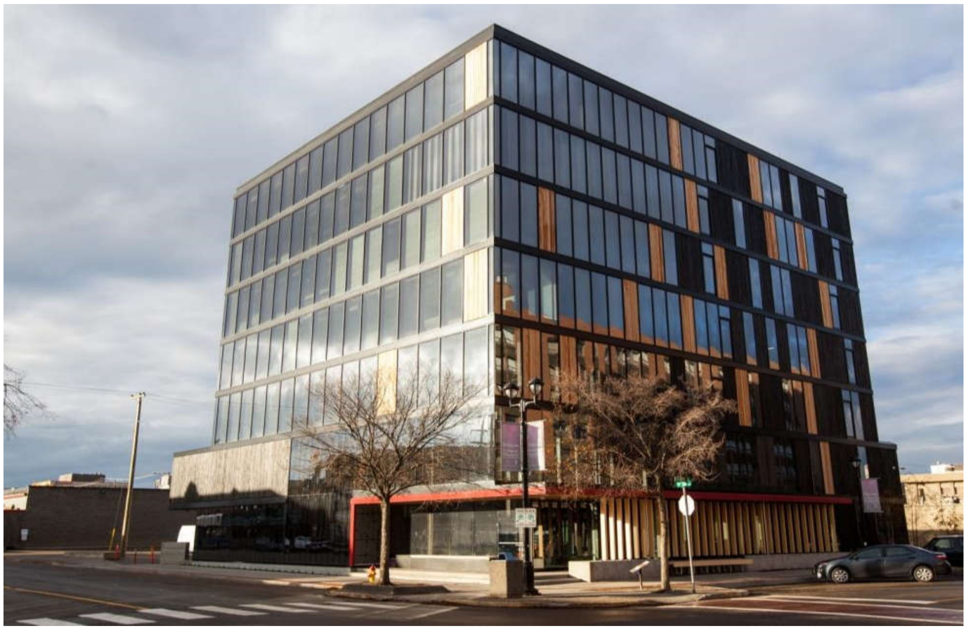
Summary

- Mass-timber construction worldwide is on the rise, and Canada is contributing to the developments
- Several novel solutions for hold-downs are available for mass-timber shear walls to meet high seismic demands

UNBC's Wood Engineering program is housed in the 24.5m tall Wood Innovation Design Centre

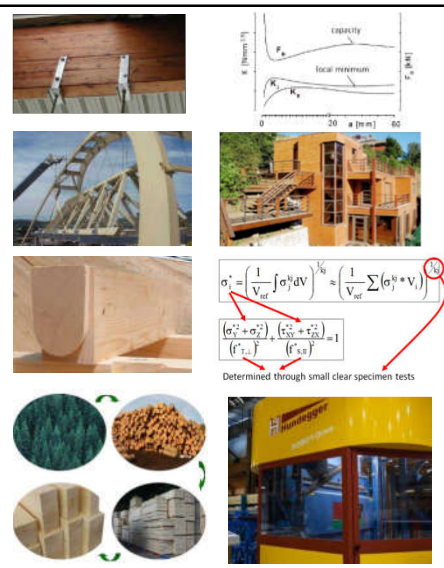


UNBC offers an MEng in Integrated Wood Design

Our research is conducted in the Passive-house certified Wood Innovation Research Lab, NA’s most airtight industrial building

Presenter's Bio

- Dipl.Ing. Bauhaus-University Weimar, Germany
- MASc Wood Technology, Universidad Bio Bio, Chile
- PhD Timber Engineering, UBC Vancouver
- Associate, Bern University of Applied Sciences, Switzerland
- Associate Chair Wood Building Design, UBC Vancouver



Content

- **Mass-timber construction in Canada**
- Lateral load resisting systems
- Design of CLT shear walls according to CSA-O86
- Hold-downs for mass-timber shear walls

Early tall timber buildings

Leckie Building, Vancouver, 1908

Early tall timber buildings

Butler Square, Minneapolis, 1906, 44m tall

Objective-Based Building Code since 2005

6-storey light-frame wood construction since 2009

British Columbia Wood First Act in 2009

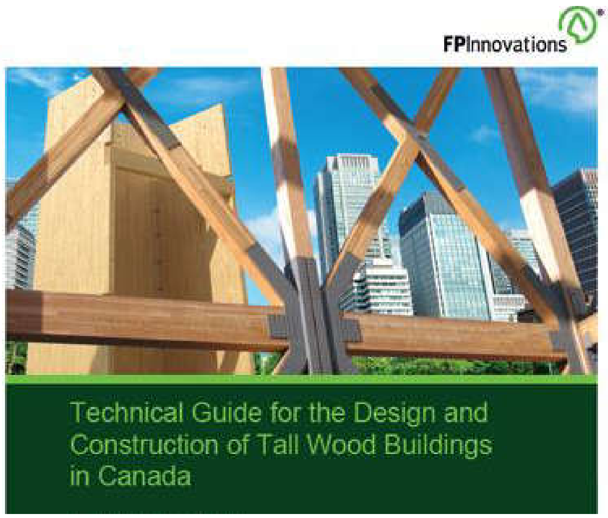
Introduction of Cross-Laminated Timber in Canada

FPInnovations' CLT Handbook:

"Tall Wood" initiative starting around 2011

TALL WOOD

"Tall Wood" initiative



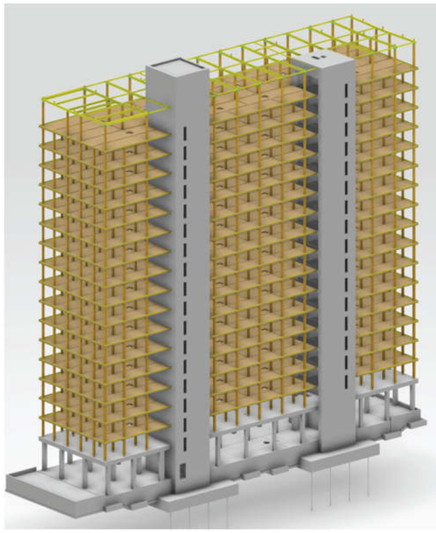
CLT included in CSA-O86 IN 2014

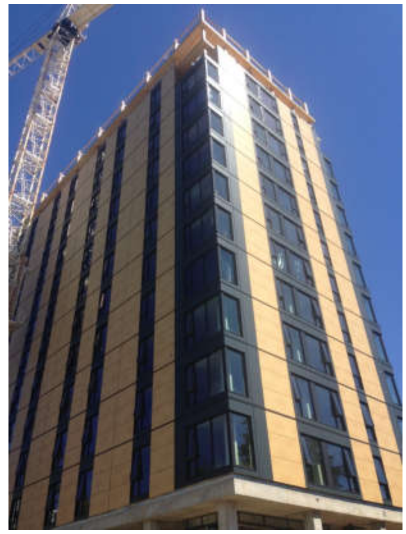
O86-14 - Engineering design in wood

Publication Year: 2014
Total Pages: 280

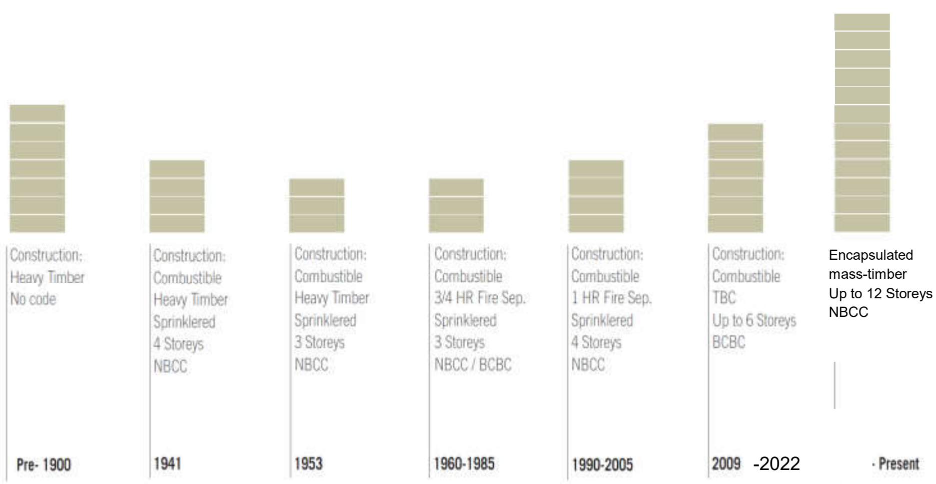
Clause 11.9 has been added for the design of CLT shearwalls and diaphragms for platform-type construction

UBC Brock Commons student residence 2016





Height restrictions of wooden buildings



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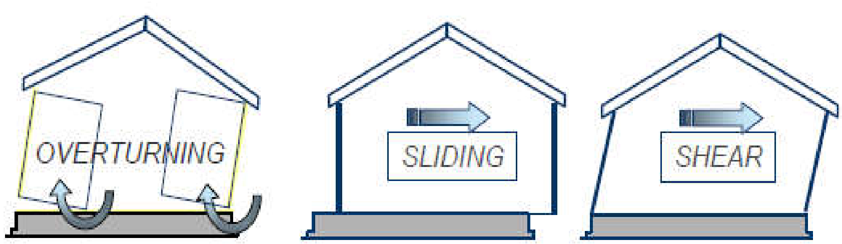
Load path need to be provided to resist



Lateral load-resisting systems

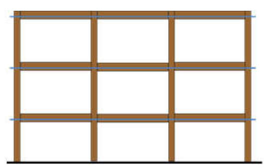
Light-frame wood shear walls

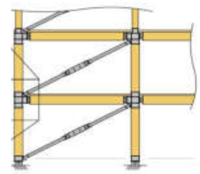
Cross-laminated timber shear walls

Braced frames

Moment frames

Post-tensioned frames





Hybrid systems

Platform vs balloon framing

CLT handbook

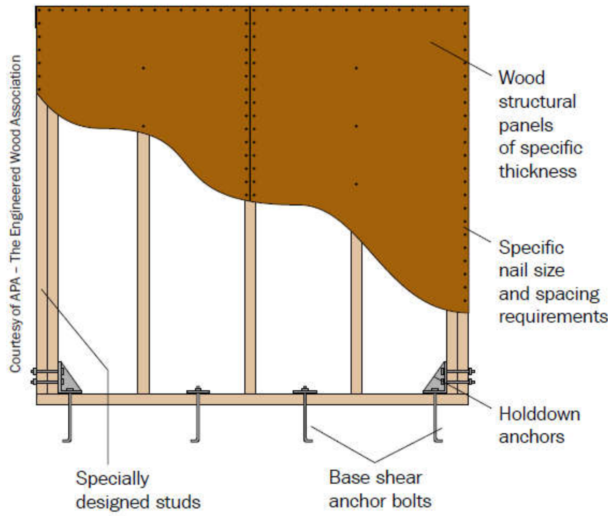
Seismic ductility reduction factors in NBCC 2020

Structural type	DCM	Overstr.
CLT shear wall system (platform-frame)	2.0	1.3
Light-Frame buildings	3.0	1.7
CLT Vertical cantilever (balloon-frame)	1.0	1.3?
Concrete coupled ductile shear walls	3.5	1.7

Behaviour factors for systems in pre EN 1995

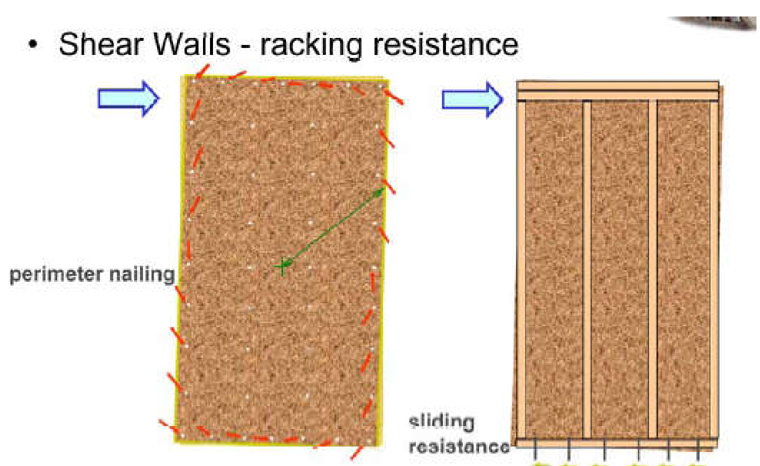
Structural type	DCM	DCH	Overstr.
CLT shearwall system (platform-frame)	2,0	3,0	1.3
Light-Frame buildings	2,5	4,0	1.3
CLT Vertical cantilever (balloon-frame)	2,0	-	1.6

Light-frame wood shear walls



Connections typically the critical element!

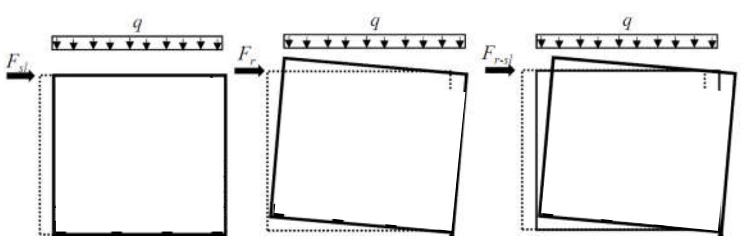
Light-frame wood shear walls



Source: APA DES130: Lateral loads

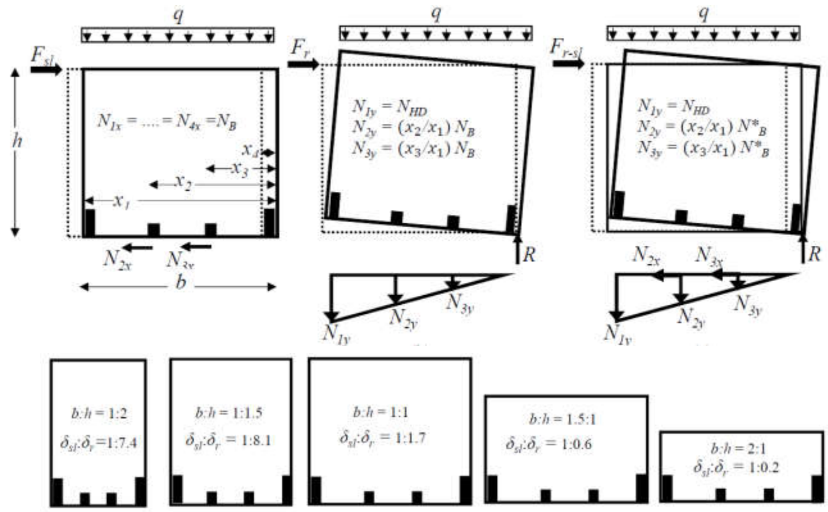
CLT shearwalls

CLT shearwalls: possible kinematic motions



sliding　rocking　combination sliding/rocking

Impact of wall aspect ratio on wall kinematic



Shahnewaz et al

Coupled vs. single wall kinematic behaviour

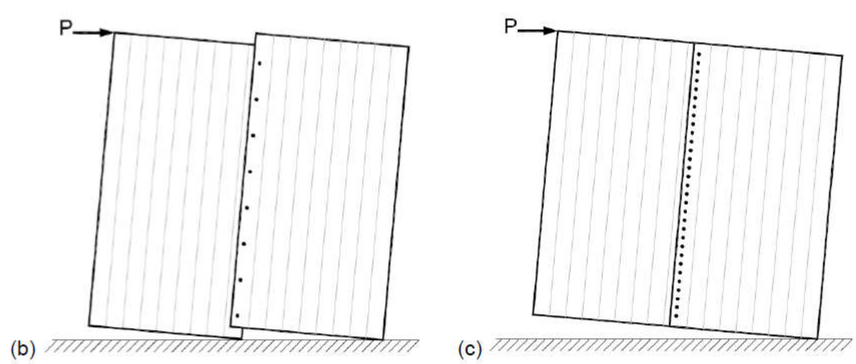


Figure 4 (a) **CLT shear wall made of two vertical panels connected to each other with a half-lap joint; (b) shear wall panels acting as two segments; and (c) shear wall panels behaving as one segment (a rigid connection)**

CLT handbook

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CSA-O86 2016 supplement

11.9 Design of CLT shearwalls and diaphragms

Note: *The provisions in this Clause should be used in conjunction with the CWC* Commentary on CSA O86.

11.9.1 General

11.9.1.1

Clause 11.9 shall apply to platform-type constructions not exceeding 30 m in height. For high seismic zones (i.e., $I_E\ F_a\ S_a(0.2) > 0.75$), the height shall be limited to 20 m. Alternative systems shall be designed in accordance with Clause 4.3.2 of this Standard and *NBC* subsection 4.1.8.

11.9.1.2

The factored shear resistance of CLT shearwalls shall be governed by the resistance of connections between the shearwalls and the foundations or floors, and connections between the individual panels, calculated using methods of mechanics, assuming each individual panel acts as a rigid body.

11.9.1.3

The factored shear resistance of the diaphragms shall be governed by the resistance of the connections between the diaphragms and the supporting structure and the connections between the individual panels, calculated using methods of mechanics, assuming each individual panel acts as a rigid body.

CSA-O86 2016 supplement

11.9.2 Seismic design considerations for CLT structures

11.9.2.1 General

Factors $R_d \leq$ 2.0 and R_o = 1.5 shall apply to platform-type CLT structures where the energy is dissipated through connections as specified in Clause 11.9.2.2 following the capacity design principles given in Clause 11.9.2.4, and wall panels act in rocking or in combination of rocking and sliding. Type 4 or 5 irregularities as defined in the *NBC* shall not be allowed. Other types of irregularities shall be dealt with in accordance with the *NBC*. CLT structures with wall panels with aspect ratios (height-to-length) less than 1:1 or acting in sliding only shall be designed with $R_d R_o$ = 1.3.

Note: *See the CWC* Commentary on CSA O86 *for further information.*

H/L ≥ 1.0	H/L < 1.0
$R_d R_0$ = 3.0	$R_d R_0$ = 1.3

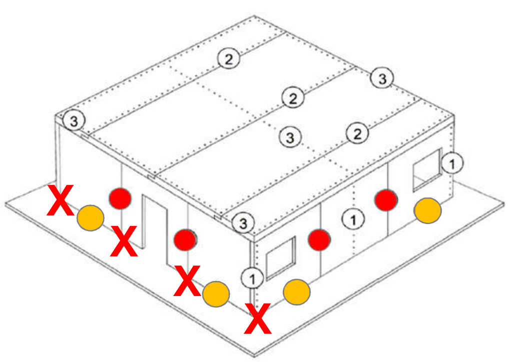
CSA-O86 2019 design provisions

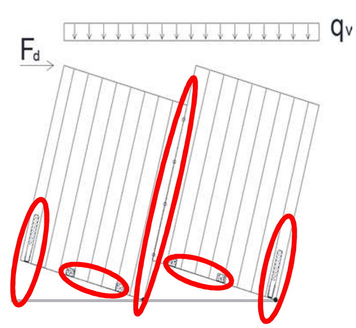
11.9.3.4.1 Energy-dissipative connections

Energy-dissipative connections shall be designed in accordance with the requirements in Clause 11.9.3.3.1 to ensure that all principle inelastic deformations and principle energy dissipation occurs in

a) connections between vertical joints of adjacent shearwall segments; and

b) shear connections of shearwalls to foundations, and shearwalls to floors beneath, in uplift only.





CSA-O86 2016 supplement

11.9.2.2 Energy dissipative connections

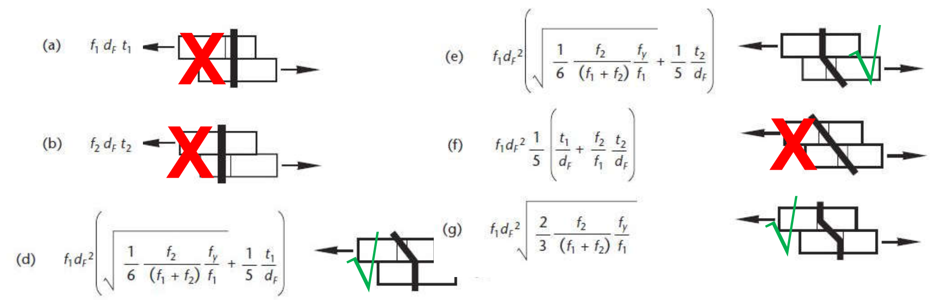
Energy dissipative connections of CLT structures shall satisfy all of the following requirements:

(a) connections shall be designed so that a yielding mode governs the resistance;

(b) connections shall be at least moderately ductile in the directions of the assumed rigid body motions of CLT panels; and

(c) connections shall possess sufficient deformation capacity to allow for the CLT panels to develop their assumed deformation behaviour, such as rocking, sliding, or combination thereof.

Note: *For further information on moderately ductile connections, see the CWC* Commentary on CSA O86.



CSA-O86 2016 supplement

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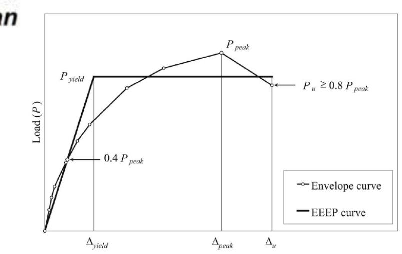
Note: *For further information on moderately ductile connections, see the CWC* Commentary on CSA O86.

- The ***ductility ratio should be calculated*** (ASTM E2126) ***using the EEEP curve***
- The ***strength reduction during the first and the third cycle*** of testing should be ***less than 20%*** (method B)
- Moderately ductile connection $\mu \geq 3.0$



CSA-O86 2016 supplement

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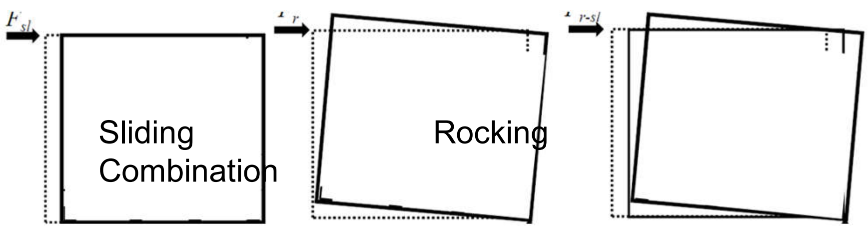
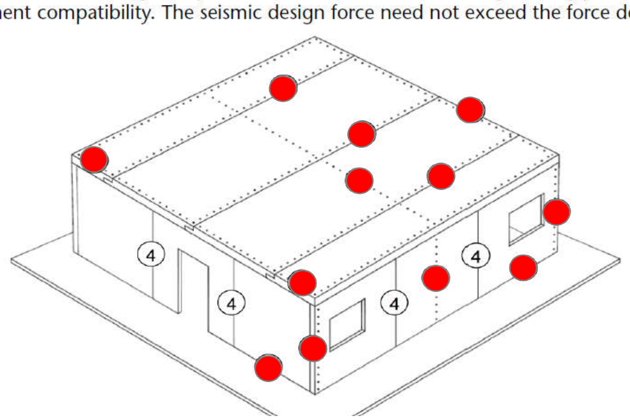


CSA-O86 2016 supplement

11.9.2.3 Non-dissipative connections

Non-dissipative connections shall be designed to remain elastic under the force and displacement demands that are induced in them when the energy-dissipative connections reach the 95th percentile of their ultimate resistance or target displacement, in accordance with engineering principles of equilibrium and displacement compatibility. The seismic design force need not exceed the force determined using $R_d R_o = 1.3$.



CSA-O86 2019 provisions

The NBC subcommittee on earthquake design requested several changes to clause 11.9 of CSA-O86!

11.9.1.1 Standard systems

Clause 11.9 shall apply to platform-type CLT construction where

a) the lateral-load-resisting system consists of CLT shearwalls; and

b) CLT walls are placed on
   - i) a platform of CLT floor panels; or
   - ii) a concrete podium or concrete foundation at the lowest level.

11.9.1.2 Alternative systems

Alternative systems shall be designed in accordance with Clause 4.3.2 of this Standard

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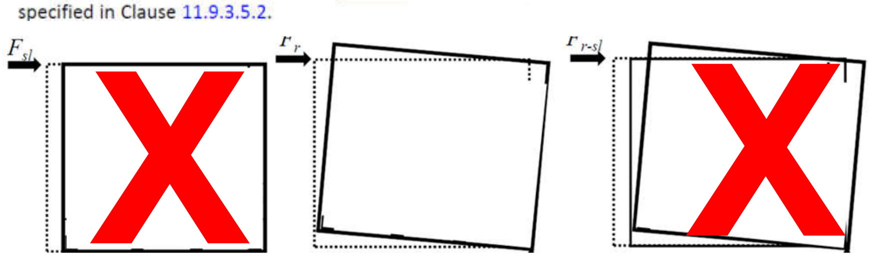
CSA-O86 2019 design provisions

11.9.3.1 General

Except as specified in Clause 11.9.3.2.2, a SFRS consisting of moderately ductile CLT shearwalls, platform-type construction, as defined in the *National Building Code*, shall be designed to resist forces calculated using R_d = 2.0 and R_o = 1.5, where energy is dissipated in rocking motion of shearwall segments through designated connections in accordance with Clause 11.9.3.3.1 following the capacity design principles described in Clause 11.9.3.4. Shearwall segments shall have an aspect ratio as specified in Clause 11.9.3.5.2.



Rocking Only!

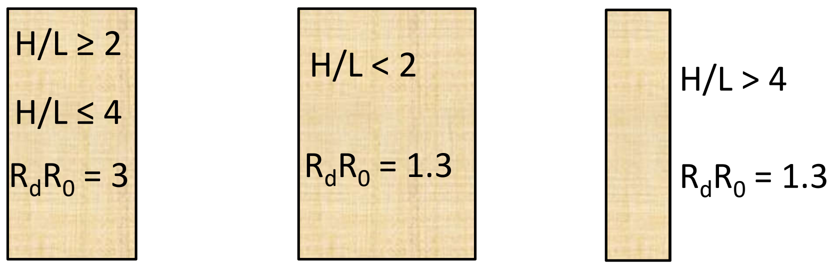
CSA-O86 2019 design provisions

11.9.3.5.1 Minimum shearwall thickness

CLT shearwalls shall have a minimum thickness of 87 mm.

11.9.3.5.2 Permitted aspect ratio of shearwall segments

Except as permitted in Clause 11.9.3.2.2, all CLT shearwall segments considered part of the SFRS shall have an aspect ratio of not less than 2:1 and not greater than 4:1.



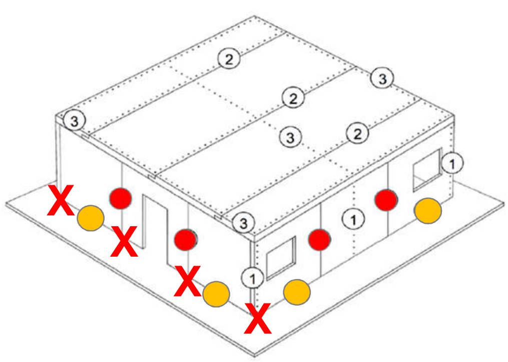
CSA-O86 2019 design provisions

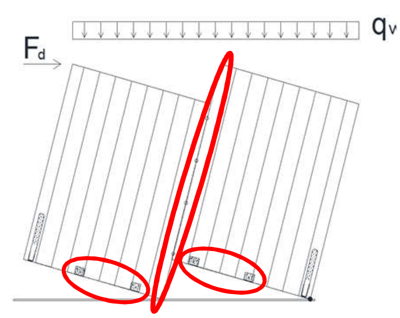
11.9.3.4.1 Energy-dissipative connections

Energy-dissipative connections shall be designed in accordance with the requirements in Clause 11.9.3.3.1 to ensure that all principle inelastic deformations and principle energy dissipation occurs in

a) connections between vertical joints of adjacent shearwall segments; and

b) shear connections of shearwalls to foundations, and shearwalls to floors beneath, in uplift only.





Design proposal Casagrande et al.

Level	Shearwalls	Required failure modes	Dissipative connections	Hierarchy between dissipative connections	Limited ductility connections	Hierarchy between non-dissipative and dissipative components	Eurocode behaviour factors *q*
Level 3	Multi-panel	Rocking (CP)	vertical joints; hold-down;	I. vertical joints (primary) II. hold-down (other)	shear connections	Yes	3
Level 2	Single-panel	Rocking	hold-down;	N/A	shear connections	Yes	2
	Multi-panel	Rocking	hold-down; vertical joints (optional)[1];	No	shear connections	Yes	
Level 1	Single- and Multi- panel	N/A	N/A	N/A	N/A	No	1.5

[1] vertical joints may be assumed either dissipative or non-dissipative

Will partially be adopted in CSA-O86

Challenges in design

CLT panels that are part of the lateral-force-resisting system shall be designed for seismic forces that are developed when energy dissipative connections in shearwalls reach the 95th percentile of their ultimate resistance but need not exceed the force determined using $R_d R_o = 1.3$. The in-plane shear resistance of the CLT panels shall be provided by the product manufacturer. Net section effects and openings shall be accounted for in the design.

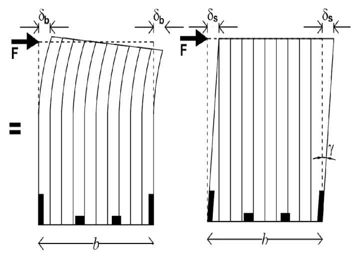
Note: *See the CWC* Commentary on CSA O86 *for further information.*

Table 8 - CrossLam® CLT In-Plane Shear Loading

CrossLam® CLT Series															
87 V	87 E	105 V	105 E	139 V	139 E	175 V	175 E	191 V	191 E	245 V	245 E	243 V	243 E	315 V	315 E
V_r (kN/m1)															
54	54	95	95	108	108	190	190	163	163	285	285	217	217	380	380

Notes:
1. For structural panel properties - see page 18.
2. Table assumes dry service conditions.
3. The following factors were used for calculations: k_{mod} = 0.8; γm = 1.25.
4. Computed values based on "In-Plane Shear Capacity and Verification Methods" by Prof. G. Schickhofer, University of Graz.
5. Specified modulus of Strength: f_v,CLT,k = 5.0 Mpa; f_T,CLT,k = 2.5 Mpa, ref: "BSPhandbuch Holz-Massivbauweise in Brettsperrholz", Technical University of Graz.
6. Minimum width of wood used in layup is 89 mm.
7. Values are for CrossLam® CLT panel only, not for shear connectors.
8. Table values are to be used for preliminary design only.

Challenges in design



$$\delta = \boxed{\delta_b + \delta_s} + \delta_{sl} + \delta_r$$

???

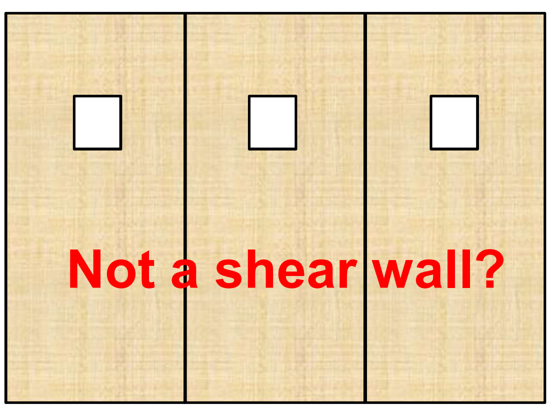
Table 8.2
Specified strengths and moduli of elasticity of laminations in primary CLT grades, MPa
(See Clause 8.2.4.)

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	11 700	15.4	19.3	0.50	5.3	7.0	9000	3.2	9.0	0.50	5.3
E2	23.9	10 300	11.4	18.1	0.63	7.0	4.6	10 000	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	11 000	5.8	14.0	0.63	7.0	4.6	10 000	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

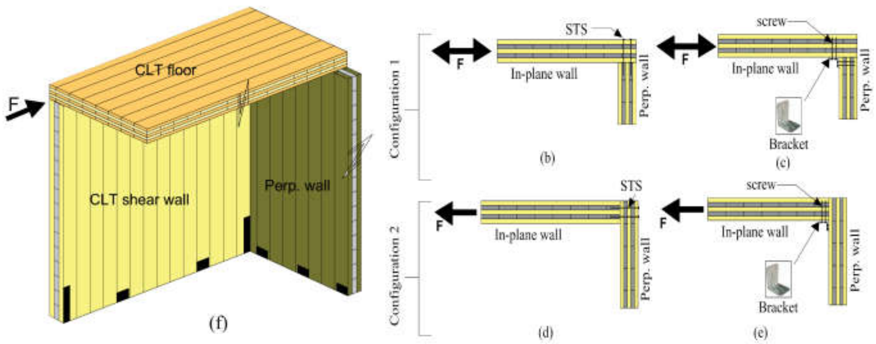
Challenges in design

11.9.3.5.4 Openings in shearwalls

Parts of shearwalls interrupted by openings shall not be considered part of the SFRS.



Challenges in design

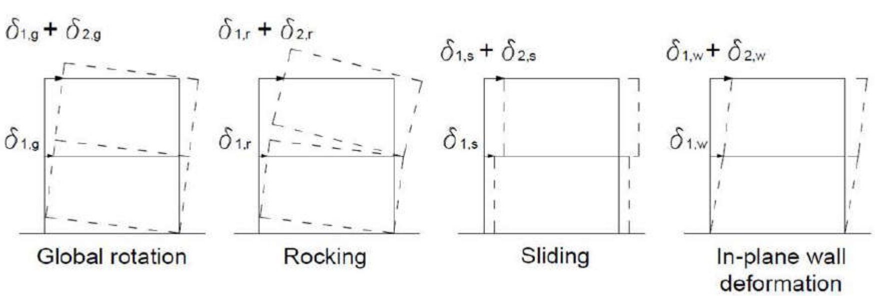


Impact of perpendicular walls?

Shahnewaz et al

Challenges in design

multi-storey deflection



How to limit cumulative bending effect to less than 20%?

CLT handbook

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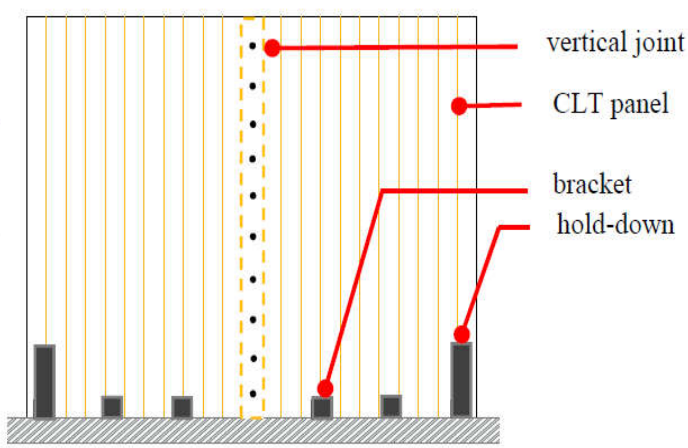
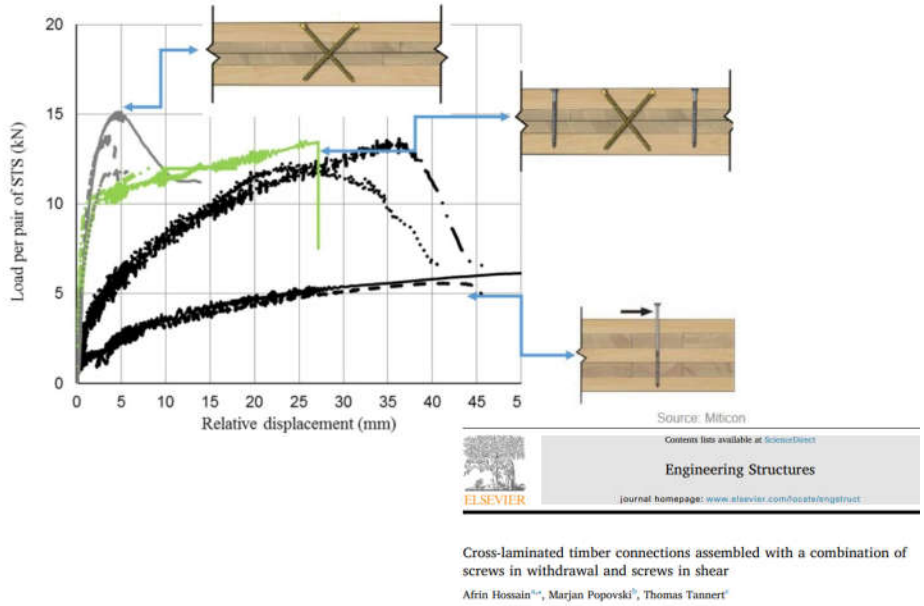
CLT shear wall connections



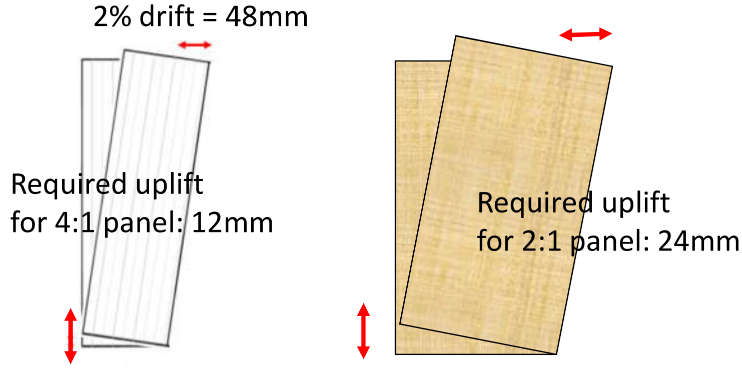
Vertical joints



Deformation compatibility of hold-downs

The factored resistance of discrete hold-downs shall be at least 20% greater than the forces developed in them when the vertical joints reach their nominal resistance.

2% drift = 48mm



“Traditional” Hold-downs

Pull-out failure

Shear failure

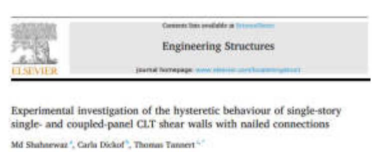
Net tension failure

Edge break out

Wood crushing

Group tear-out

UNBC tests with nail connections


Engineering Structures

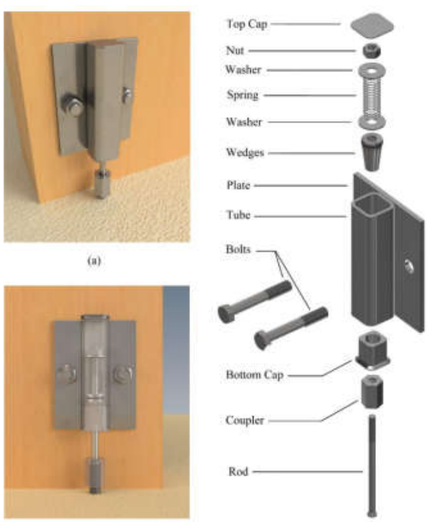
Experimental investigation of the hysteretic behaviour of single-story single- and coupled-panel CLT shear walls with nailed connections

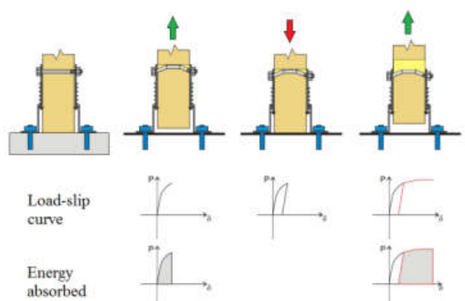
Md Shahnewaz, Carla Dickof, Thomas Tannert

Dowelled slotted-in steel plates

Foto: Fast+Epp

Pinching-free connectors





Source: Thesis Nicholas Chan

Resilient slip friction connection

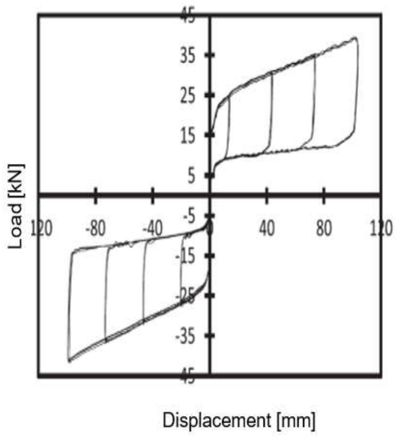
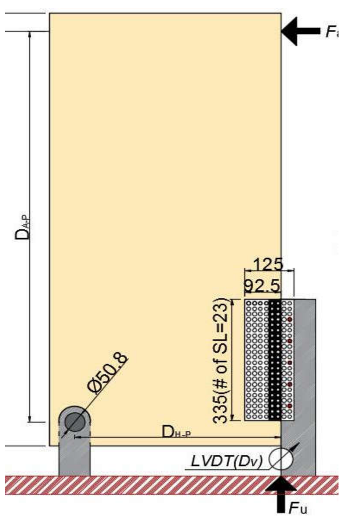
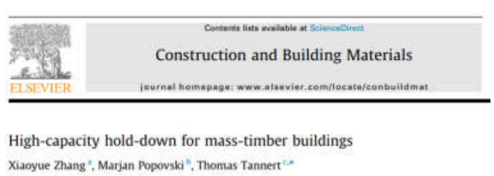


Foto: Fast+Epp

Modified HSK connector




Contents lists available at ScienceDirect

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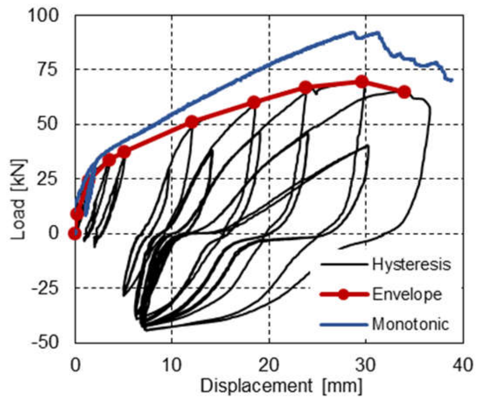
Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

High-capacity hold-down for mass-timber buildings

Xiaoyue Zhang [a], Marjan Popovski [b], Thomas Tannert [c,*]

Perforated internal steel plates



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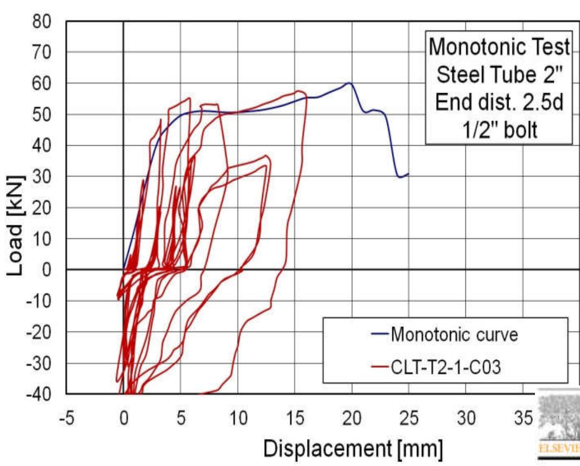
Performance of coupled CLT shear walls with internal perforated steel plates as vertical joints and hold-downs

Selamawit Dires[a], Thomas Tannert[b,*]

Internal steel tube connector



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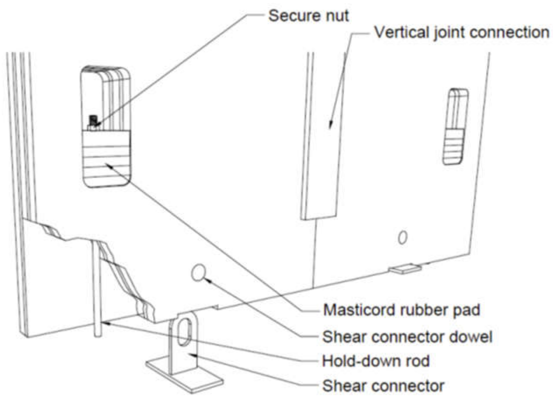
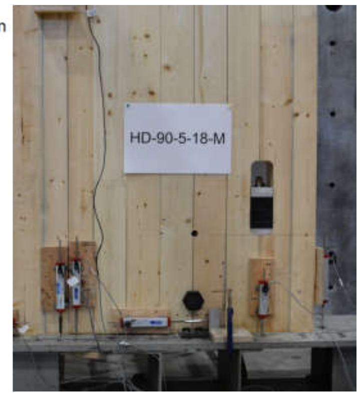
Experimental assessment of a novel steel tube connector in cross-laminated timber

J. Schneider[a,*], T. Tannert[b], S. Tesfamariam[c], S.F. Stiemer[d]

Hyperelastic hold-down



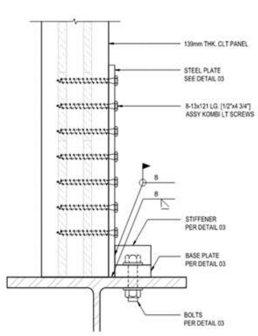


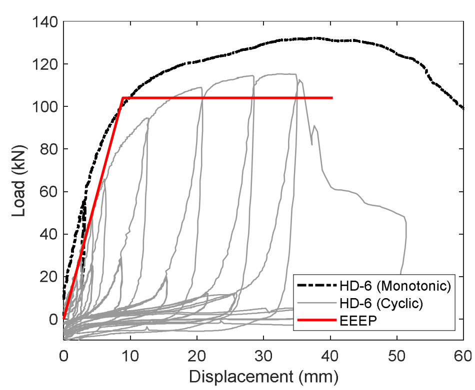
ASCE

Structural Performance of CLT Shear Walls with Hyperelastic Hold Downs

Thomas Tannert, M.ASCE[1]; Oyawoye Abubakar Ajibola[2]; and Marjan Popovski, M.ASCE[3]

UNBC tests with STS hold-downs





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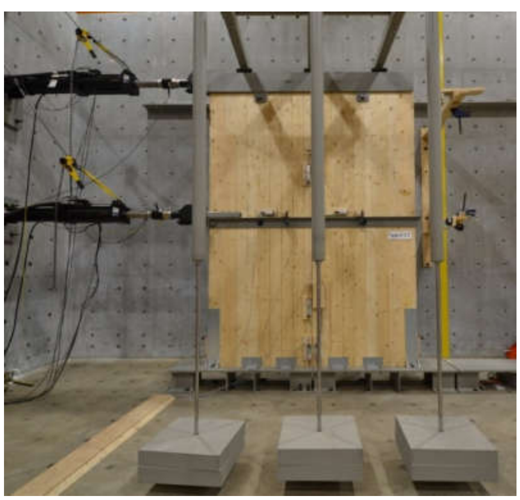
Experimental Parameter Study on CLT Shear Walls with Self-Tapping Screw Connections

Yuxin Pan, A.M.ASCE[1]; Thomas Tefissi[2]; and Thomas Tannert, M.ASCE[3]

Application in full-scale two-story tests

Extension towards balloon-framed CLT shear walls



Seismic Behavior of Balloon Frame CLT Shear Walls with Different Ledgers

Md Shahnewaz[1]; Carla Dickof[2]; and Thomas Tannert, M.ASCE[3]