Cross-Laminated Timber in Canada

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Wood Building Systems

- Light Wood Frame
- Mass Timber Frames
- Mass Timber Plates
- Hybrid

CLT Structures
Cross-Laminated Timber (CLT)

- CLT is made of three or more layers of wood strips (planks) stacked crosswise on top of each & bonded with structural adhesive
- Panels are available in a range of sizes & can be customized to fit specific applications/needs
  - thickness up to 609 mm
  - width up to 3.0 m
  - lengths up to 18 m
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)
Status of CLT in Canada

- CLT introduced to Canada in 2006
- Canadian-made CLT is commercially available (2 manufacturers + 1 coming soon)
- Over 100 projects that utilizes CLT, either designed or built across Canada
- Extensive research conducted by FPI, Universities (NEWBuildS), NRC and Industry Associations (CWC)
- Strong support from Federal and Provincial governments
- Strong interest in CLT among designers, building officials, governments & developers
CLT in NA Codes and Standards

ANSI/APA PRG 320 - Standard for Performance-Rated Cross-Laminated Timber

- Bi-national product standard for CLT (Canada and the US)

- Scope
  - CLT dimensions and tolerances
  - Component requirements
  - Qualification
  - Quality assurance
  - Annex: Design properties (mandatory)

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CLT in NA Codes and Standards

ANSI/APA PRG 320 - Standard for Performance-Rated Cross-Laminated Timber

- CLT Layups:
  - E1: 1950f-1.7E SPF MSR (II) & No. 3 SPF lumber (⊥)
  - E2: 1650f-1.5E DFL MSR (II) & No. 3 DFL (⊥)
  - E3: 1200f-1.2E Northern Species MSR (II) & No. 3 Northern Species (⊥)
  - E4: 1950f-1.7E SYP MSR (II) & No. 3 SYP lumber (⊥)
  - V1: No. 2 DFL (II) & No. 3 DFL (⊥)
  - V2: No. 1/No. 2 SPF (II) & No. 3 SPF (⊥)
  - V3: No. 2 SYP (II) & No. 3 SYP (⊥)

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## CLT in NA Codes and Standards

### ANSI/APA PRG 320 - Standard for Performance-Rated Cross-Laminated Timber

<table>
<thead>
<tr>
<th>CLT Grades</th>
<th>$f_{b,0}$ (MPa)</th>
<th>$E_0$ (MPa)</th>
<th>$f_{t,0}$ (MPa)</th>
<th>$f_{c,0}$ (MPa)</th>
<th>$f_{v,0}$ (MPa)</th>
<th>$f_{s,0}$ (MPa)</th>
<th>$f_{b,90}$ (MPa)</th>
<th>$E_{90}$ (MPa)</th>
<th>$f_{v,90}$ (MPa)</th>
<th>$f_{s,90}$ (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>E1</td>
<td>28.2</td>
<td>11,700</td>
<td>15.4</td>
<td>19.3</td>
<td>1.5</td>
<td>0.50</td>
<td>7.0</td>
<td>9,000</td>
<td>1.5</td>
<td>0.50</td>
</tr>
<tr>
<td>E2</td>
<td>23.9</td>
<td>10,300</td>
<td>11.4</td>
<td>18.1</td>
<td>1.9</td>
<td>0.63</td>
<td>4.6</td>
<td>10,000</td>
<td>1.9</td>
<td>0.63</td>
</tr>
<tr>
<td>E3</td>
<td>17.4</td>
<td>8,300</td>
<td>6.7</td>
<td>15.1</td>
<td>1.3</td>
<td>0.43</td>
<td>4.5</td>
<td>6,500</td>
<td>1.3</td>
<td>0.43</td>
</tr>
<tr>
<td>V1</td>
<td>10.0</td>
<td>11,000</td>
<td>5.8</td>
<td>14.0</td>
<td>1.9</td>
<td>0.63</td>
<td>4.6</td>
<td>10,000</td>
<td>1.9</td>
<td>0.63</td>
</tr>
<tr>
<td>V2</td>
<td>11.8</td>
<td>9,500</td>
<td>5.5</td>
<td>11.5</td>
<td>1.5</td>
<td>0.50</td>
<td>7.0</td>
<td>9,000</td>
<td>1.5</td>
<td>0.50</td>
</tr>
</tbody>
</table>

For SI: 1 MPa = 145 psi

(a) See Section 4 for symbols.

(b) Tabulated values are Limit States design values and not permitted to be increased for the lumber size adjustment factor in accordance with CSA O86. The design values shall be used in conjunction with the section properties provided by the CLT manufacturer based on the actual layup used in manufacturing the CLT panel (see Table A4).

(c) Custom CLT grades that are not listed in this table shall be permitted in accordance with Section 7.2.1.
CLT in NA Codes and Standards

CSA O86: Canadian Timber Design Standard

- Design provisions proposed at CSA O86 (public review ended Oct. 28)
- Targetting the 2016 Supplement of CSA O86
- Comprehensive proposal that covers provisions for:
  - Bending and shear resistance
  - Serviceability (i.e., deflection and vibration)
  - Connections
  - Lateral load resisting system
  - Fire resistance
CLT in NA Codes and Standards

Quebec’s Guide for Mass Timber Construction up to 12 Storeys

- Released in August, 2015
- Quebec: 1st jurisdiction in NA to officially support the construction of tall mass timber buildings
- “Pre-approved” Alternative Solution to facilitate the design & approval process
- Covers CLT, hybrid and other types of mass timber
- Great interest in the Guide by other jurisdictions in Canada and overseas
CLT Handbook

- State-of-the-art peer-reviewed technical source for CLT
- Provide guidance to designers that facilitates use of CLT as alternative solution
- Support CLT code implementation in Canada and the US
Structural Design

Rolling Shear Modulus and Strength

- Shear Modulus Perpendicular to Grain
  - Rolling Shear Modulus $G_R$

- Shear Strength Perpendicular to Grain
  - Rolling Shear Strength $F_{v,R}$
Structural Design

Rolling Shear Modulus and Strength

- **Rolling Shear Modulus (G<sub>R</sub>)**
  - Generally assumed to be 10% of the shear modulus parallel to the grain of the boards (G)
  - \( G_R \approx G/10 = (E/16)/10 = E/160 \) for softwood species

- **Rolling Shear Strength (F<sub>v,R</sub>)**
  - Rolling shear strength varies between 18% to 28% of parallel-to-grain shear values (\( \approx 0.3 \) to 0.6 MPa)
  - \( \approx \) Tension Perpendicular to Grain Strength
Structural Design

Floor and Roof System

- Mechanically Jointed Beams Theory (Gamma Method)
  - Bending Stiffness
  - Bending Strength
  - Shear Strength

- Composite Theory (k Method)
  - Bending Stiffness
  - Bending Strength

- Shear Analogy (Kreuzinger)
  - Bending Stiffness and Shear Stiffness
Structural Design

Floor and Roof System - CSA O86

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

\[(GA)_{eff} = \left( h - \frac{t_1 - t_n}{2} \right)^2 \]

\[M_r = \phi \cdot F_b \cdot \frac{(EI)_{eff}}{E_1} \cdot \frac{1}{0.5h_{tot}}\]

\[\Delta_{max} = \frac{5}{384} \cdot \frac{wL^4}{(EI)_{eff}} + \frac{1}{8} \cdot \frac{wL^2k}{(GA)_{eff}}\]
Structural Design

Wall System - CSA O86

The slenderness ratio $C_c$ for rectangular CLT walls can be calculated as:

$$C_c = \frac{H}{d} = \frac{H}{2\sqrt{3} \cdot r_{eff}}$$

$$r_{eff} = \sqrt{\frac{I_{eff}}{A_{eff}}}$$

$$A_{eff} = b \cdot h_{eff} = b \cdot \sum_{i} h_i$$

account for only the layers with laminations oriented parallel to the axial load,
Connection

Panel-to-Panel Connection Details

- Single surface spline
  - Plywood or LVL → Screws
  - CLT

- Half-lapped
  - Plywood or LVL → Screws
  - CLT

- Internal spline
  - Plywood or LVL
  - CLT

- Double surface spline
  - Plywood or LVL
  - CLT
Connection

Wall-to-Foundation Connection Details

- CLT Wall
- EWP
- Screws
- Metal bracket
- Anchor bolt
- Concrete footing
Connection

Wall-to-Wall Connection Details

CLT Wall → CLT Wall

Self-tapping screws →
Connection

Wall-to-Floor/Roof Connection Details

CLT Wall

Screws

Metal bracket

Screws

Self-tapping screws

CLT Floor

CLT Wall
Connection

Design of CLT Connections

- Establish the embedment strength equations for each type of fasteners in CLT (in plane & on edge) – Empirically.
- Min. spacing, edge and end distances are specified to minimize brittle failure mode in CLT
Seismic Design
Seismic Design

Observations of CLT Wall Performance

- CLT wall panels behaved almost as rigid bodies during the testing.
- Although slight shear deformations in the panels were measured, most of the panel deflections occurred as a result of the yielding deformation in the joints connecting the walls to the foundation.
- Deformation is a combination of rocking and sliding.
- In case of multi-panel walls, deformations in the half-lap joints also had significant contribution to the overall wall deflection.
Seismic Design

Shear Resistance and Deflection of CLT Walls

- Calculations should be based on principles of engineering mechanics or derived from testing
- Current approach takes only shear resistance of the connections and do not take into account uplift resistance of brackets
- Develop new methods that take into account the bidirectional contribution of each connector as a result of combination of rocking and sliding
Seismic Design

Models With Bidirectional Loading

- Model D4 has circular shear-uplift interaction domain
- Model D5 has triangular shear-uplift interaction domain
- Hold-downs resist uplift forces only
Seismic Design

Force Modification Factors (R-factors)

- 2010 NBCC has two R-factors
  - Ro-factor related to system over-strength
  - Rd-factor related to the system ductility

- Analytical study was undertaken with Colorado State University (CSU) and Colorado School of Mines (CSM) to quantify preliminary R-factors for symmetric platform type CLT structures
Seismic Design

Force Modification Factors (R-factors)

- 44 bi-axial Nonlinear Time History analyses for each of the 60 buildings
- FEMA P-695 ground motions scaled at initial building period

<table>
<thead>
<tr>
<th>Performance Targets</th>
<th>6 Storey</th>
<th>10 Storey</th>
<th>15 Storey</th>
</tr>
</thead>
<tbody>
<tr>
<td>Storey Drift [%] with PNE [%]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.5% with 50% PNE</td>
<td>2.5</td>
<td>3.5</td>
<td>4.0</td>
</tr>
<tr>
<td>2.0% with 80% PNE</td>
<td>2.0</td>
<td>3.0</td>
<td>4.0</td>
</tr>
<tr>
<td>2.5% with 80% PNE</td>
<td>2.5</td>
<td>3.5</td>
<td>4.0</td>
</tr>
<tr>
<td>4.0% with 80% PNE</td>
<td>2.5</td>
<td>4.0</td>
<td>4.0</td>
</tr>
</tbody>
</table>
Fire Safety

- Large size wood members have the inherent ability to provide fire resistance because of the unique charring properties of wood.
  - Burn slowly and forms char layer
  - Non-charred wood retains significant strength
  - Wood is dimensionally stable under fire conditions
Fire Safety

FPInnovations/NRCC Fire Test Program

- Eight (8) full-scale fire tests conducted following ULC S101 time-temperature curve
  - Conducted at NRC facility in Ottawa (Ont.)
  - Joint FPInnovations/NRCC Test report and TechNote available

- Objectives
  - Quantify the charring rate
  - Evaluate the fire resistance of CLT assemblies
  - Develop a simple analytical model to predict CLT fire resistance
## Fire Safety

### FPIInnovations/NRCC Fire Test Program

<table>
<thead>
<tr>
<th># of Plies</th>
<th><strong>Lumber Grade in Major Strength Direction</strong></th>
<th>Thickness in (mm)</th>
<th>Gypsum Board Protection in (mm)</th>
<th>Superimposed Load</th>
<th>Load Ratio (ASD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wall</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>MSR 1650f&lt;sub&gt;b&lt;/sub&gt;-1.5E</td>
<td>4.49 (114)</td>
<td>2 x ½ (12.7)</td>
<td>22818 lbf/ft (333 kN/m)</td>
<td>58%</td>
</tr>
<tr>
<td>5</td>
<td>MSR 1950f&lt;sub&gt;b&lt;/sub&gt;-1.7E</td>
<td>6.89 (175)</td>
<td>Unprotected</td>
<td>22818 lbf/ft (333 kN/m)</td>
<td>29%</td>
</tr>
<tr>
<td>5</td>
<td>No.1/No.2</td>
<td>4.13 (105)</td>
<td>Unprotected</td>
<td>4934 lbf/ft (72 kN/m)</td>
<td>23%</td>
</tr>
<tr>
<td>Floor</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>MSR 1650f&lt;sub&gt;b&lt;/sub&gt;-1.5E</td>
<td>4.49 (114)</td>
<td>2 x ½ (12.7)</td>
<td>56 psf (2.7 kPa)</td>
<td>46%</td>
</tr>
<tr>
<td>5</td>
<td>MSR 1950f&lt;sub&gt;b&lt;/sub&gt;-1.7E</td>
<td>6.89 (175)</td>
<td>Unprotected</td>
<td>246 psf (11.8 kPa)</td>
<td>75%</td>
</tr>
<tr>
<td>3</td>
<td>No.1/No.2</td>
<td>4.13 (105)</td>
<td>1 x ⅜ (15.9)</td>
<td>50 psf (2.4 kPa)</td>
<td>90%</td>
</tr>
<tr>
<td>5</td>
<td>No.1/No.2</td>
<td>6.89 (175)</td>
<td>1 x ⅜ (15.9)</td>
<td>169 psf (8.1 kPa)</td>
<td>120%</td>
</tr>
<tr>
<td>7</td>
<td>No.1/No.2</td>
<td>9.65 (245)</td>
<td>Unprotected</td>
<td>305 psf (14.6 kPa)</td>
<td>119%</td>
</tr>
</tbody>
</table>
Fire Safety

FPInnovations/NRCC Fire Test Program

- Small pieces of the charred layer were observed to fall off during the fire-resistance tests when the glue lamination interface reached ±550°F (300°C)
- Thermal protection from the charred layer no longer in place, thus accelerating the effective charring rate when approaching the glue laminations
- Thinner laminations (< 1 3/8”) seem to char faster (±10%)
- Use of Type X gypsum board (directly attached to CLT) can allow increasing the fire-resistance by:
  - 30 minutes when 1 layer of 5/8” Type X is used
  - 60 minutes when 2 layers of 5/8” Type X are used
Fire Safety

- **Step 1a**: Calculation of lamination fall-off time \((t_{fo})\)
- **Step 1b**: Calculate number of layers that may fall-off \((n_{lam})\)
- **Step 2**: Calculation of the effective char depth

\[
a_{\text{char}} = 1.2 \left[ n_{\text{lam}} \cdot h_{\text{lam}} + \beta_n \left( t - (n_{\text{lam}} \cdot t_{fo}) \right)^{0.813} \right]
\]

- **Step 3**: Determination of effective residual cross-section

\[
h_{\text{fire}} = h - a_{\text{char}}
\]
Durability and Building Envelope

CLT does not change basic enclosure design principles

- Must consider impact of (outdoor/indoor) climate
- Provide a good environmental separation
  - Prevent rain penetration
  - Provide thermal insulation
  - Control air movement
  - Control vapour flow
  - ...
- Ensure durability, thermal efficiency, occupant comfort
Durability and Building Envelope

CLT does not change wood durability principles

- Keep wood dry wherever possible
  - Minimize wetting during shipping, storage & construction
  - Prevent wetting in service
  - Allow drying in case wetting occurs

- If persistent wet conditions or termites anticipated, use
  - Preservative-treated wood
  - Naturally durable wood (e.g., yellow cedar)
Durability and Building Envelope

Thermal insulation

- Exterior mineral insulation recommended to keep wood warm

Vapour barrier

- No additional vapour barrier required in a hot and humid climate barrier itself
Noise Control

NBC Requirements

- Minimum requirements for wall/floor-ceiling assemblies

<table>
<thead>
<tr>
<th>Assembly</th>
<th>Airborne Sound</th>
<th>Impact Sound</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wall</td>
<td>ASTC (Dwelling Units*)</td>
<td>47</td>
</tr>
<tr>
<td></td>
<td>STC (Dwelling - Elevator shaft/Refuse chute)</td>
<td>55</td>
</tr>
<tr>
<td>Floor</td>
<td>IIC (bare floors without carpet)</td>
<td>55**</td>
</tr>
</tbody>
</table>

* Separation between dwelling units and other spaces in building
** Recommended rating

Source Table: 2015 NBCC
Noise Control

Three Defence Approach for Noise Control

1. Control noise at the source
   • Contain airborne noise in source room (use low porosity materials)
   • Use resilient layer under flooring to absorb footstep impact and reduce (floor) vibration

2. Control vibrations with mass and stiffness
   • The greater the weight, the better the sound insulation
   • The stiffer the assembly, the better the sound insulation

3. Control vibrations by decoupling elements
   • Prevent transmission of wall/floor vibration to adjacent element
   • Use multiple layers with an air space between elements
# Noise Control

## CLT Wall Design Example

<table>
<thead>
<tr>
<th>Cross Section</th>
<th>Details</th>
<th>STC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3-layer CLT (3 ³/₄ - 4 ½ in)</td>
<td>32 - 34</td>
</tr>
</tbody>
</table>
| ![Diagram](image1.jpg) | 1. 5/8” gypsum board (directly attached to CLT on 1 side)  
2. 3-layer CLT (3 ³/₄ - 4 ½ in) | 36 - 38 |
| ![Diagram](image2.jpg) | 1. & 3. 3-layer CLT (3 ³/₄ - 4 ½ in)  
2. Sound insulation material (mineral wool) about 1.2 in  
With 5/8” gypsum board (both sides) | 50 - 55 |

# Noise Control

## CLT Wall Design Example

<table>
<thead>
<tr>
<th>Cross Section</th>
<th>Details</th>
<th>STC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1. &amp; 6. 5/8” gypsum board</td>
<td>≥ 55</td>
</tr>
<tr>
<td></td>
<td>2. &amp; 5. 3-layer CLT (3 ¾ - 4 ½ in)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3. &amp; 4. 1.2” Sound insulation material (mineral wool)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5/8” gypsum board</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2x3 wood studs at 16” o.c.</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td>2-1/2” mineral wool in the wall cavity</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1/2” air gap</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3-layer CLT (4 ½ in)</td>
<td></td>
</tr>
</tbody>
</table>

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# Noise Control

## CLT Floor Design Example

<table>
<thead>
<tr>
<th>Cross Section</th>
<th>Details</th>
</tr>
</thead>
</table>
| **FSTC >50, FIIC >50** | 1. 2/5” laminated or engineered wood flooring  
2. 1/8” resilient underlayment (0.16 to 0.37 lb/ft$^2$)  
3. 5-layer CLT (6-7/8”)  
4. 4” Sound Isolation Clip  
5. Metal hat channel at 16” o.c.  
6. 4” sound absorption materials (e.g. glass fibre)  
7. 1/2” gypsum board  
8. 5/8” gypsum board |

| **FSTC >53, FIIC >53** | 1. Hardwood flooring attached to plywood  
2. 3/4” plywood  
3. 2/5” resilient underlayment (0.16 to 0.37 lb/ft$^2$)  
4. 5-layer CLT (6-7/8”)  
5. 4” sound isolation clips  
6. Metal hat channel  
7. 4” sound insulation material (e.g. glass fibre)  
8. 1/2” gypsum board  
9. 5/8” gypsum board |
Ronald McDonald House, Vancouver, BC

- 2-storey CLT building
- 73 units for children and their families when treated at BC Children’s Hospital
Community Center, Elkford, BC

Courtesy of Structurlam Products LP
UBC Okanagan Fitness Centre, Kelowna, BC

- CLT to create the main curved structural frames (cut with CNC equipment)
- HSK mesh to create moment connection
- Purlins and roof deck were mainly 3-ply CLT

Courtesy of Structurlam Products LP
Fort McMurray Airport: Largest Building In North America that uses CLT

- 1.2 m wide CLT panels spaced a distance to allow for mechanical service lines
- Douglas fir glulam beams & columns for the main structural supports

Courtesy of Structurlam Products LP
ESB Building, UBC
Wood Innovation & Design Centre (WIDC), UNBC

- 6-storey (6 stories of wood plus a mezzanine floor) mass timber building
- 29.5 m tall
- CLT core and floor panels, Glulam columns and beams

Courtesy of Structurlam Products LP
NRCan’s Tall Wood Demo Buildings Initiative (2013)

- A request for EOI issued by CWC for design teams to use innovative design and build high-rise wood demo projects
- To support the initiative, a “Technical Guide for the Design and Construction of Tall Buildings in Canada” was developed by FPI
- Provinces & industry partnered with NRCan
- A few projects were selected and detailed design & approval by AHJs is underway
NRCan’s Tall Wood Demo Buildings Initiative

Origine: Quebec City/Canada

- 13-storey mass timber (12 + 1 concrete podium)
- 800 m² floor area, 40 m tall
- Incorporates a CLT core
NRCan’s Tall Wood Demo Buildings Initiative

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 posts
- 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
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