Course Description

This presentation is intended for designers of building systems seeking to familiarize themselves with the category of products known as mass timber, and specifically cross laminated timber (CLT). Topics will include manufacturing and product performance standards, structural design standards, and recognition of CLT in the International Building Code. Specific attention will be given to the design of CLT in horizontal applications—i.e., as panels of floor and roof systems—and discussion will include how to address important serviceability requirements related to deflection and floor vibration design. Example projects and details will be presented to highlight possible applications of CLT in building structures.
Learning Objectives

1. Discuss product manufacturing and design standards relevant to cross laminated timber (CLT), and identify where these standards are recognized in the International Building Code.
2. Consider the structural design properties of CLT relevant to floor and roof applications.
3. Discover how to design CLT floors to achieve serviceability goals related to deflection and vibration.
4. Examine the use of CLT in example buildings and connection details.

New Class of Wood Products
Mass Timber Framing Options

Nail Laminated Timber (NLT)
Glue Laminated Timber (GLT)
Glulam Beams & Columns
Laminated Veneer Lumber (LVL)
Cross Laminated Timber (CLT)

Images Source: Structurecraft

CLT Composition

Planks in alternating directions
Structural CLT Floor and Roof Construction
Woodwork Webinar

**Structural Flexibility**

Photo Credit: APA

75% Lighter Weight Than Concrete
Pre-fabricated and Precise

Murray Grove, London UK
- 8 stories of CLT over 1 story concrete podium
- 8 stories built in 27 days (~1/2 the time of precast concrete)

Norwich Academy, Norwich UK
- 102,300 ft² 3 story secondary school
- 17 weeks to construct

Reduced Construction Time
**CLT History Timeline**

- **1990**: Austria industry-academia joint research
- **2000**: Significantly increased use in Europe
- **2010**: 1st Production
  - 2010 - 1st Production
  - 2011 - PRG320
  - 2011 - Canadian Handbook
  - 2013 - US Handbook
- **2015**: Recognized in 2015 IBC
  - 0.3 million m$^3$ of built CLT projects
  - 0.6-1 million m$^3$ of built CLT projects

**CLT Product Standardization**

- **ANSI / APA PRG 320**: Standard for Performance Rated Cross-Laminated Timber
US CLT Handbook

1. Introduction  
2. Manufacturing  
3. Structural  
4. Lateral  
5. Connections  
6. DOL and Creep  
7. Vibration  
8. Fire  
9. Sound  
10. Enclosure  
11. Environmental  
12. Lifting

Source of CLT Handbook

www.rethinkwood.com/masstimmer
**Structural Composition of CLT**

**Laminations:** (Per PRG 320-2012)
- 5/8" to 2" thick.
- Machine Stress Rated or Visually Graded Dimensional Lumber or SCL
- Dried to 12% Moisture Content before layup.
- A common NA thickness is 1 3/8" (planed 2x stock)
- PRG 320 provides thickness to width requirements of laminations

**Layers:** (Per PRG 320-2012)
- Oriented in orthogonal arrangement
- Odd number of symmetric layers most common
- Double parallel exterior layers permitted
- Unbalanced layup permitted
- Reference glu-lam adhesive standard (AITC 405)
Structural Composition of CLT

Panels, also known as Billets.
- 20 inch max thickness in PRG 320
- Up to 8 ft or wider per manufacturer and shipping
- Up to 40 ft or longer per manufacturer and shipping
- Major axis: stronger, stiffer, usually long direction
- Minor axis: less strong and stiff, usually short direction

CLT Fabrication Press

Photo Credit: DR Johnson
## CLT Stress Grades

<table>
<thead>
<tr>
<th>Stress Grade</th>
<th>Major Strength Direction</th>
<th>Minor Strength Direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>E1</td>
<td>1950f-1.7E MSR SPF</td>
<td>#3 Spruce Pine Fir</td>
</tr>
<tr>
<td>E2</td>
<td>1650f-1.5E MSR DFL</td>
<td>#3 Doug Fir Larch</td>
</tr>
<tr>
<td>E3</td>
<td>1200f-1.2E MSR Misc</td>
<td>#3 Misc</td>
</tr>
<tr>
<td>E4</td>
<td>1950f-1.7E MSR SP</td>
<td>#3 Southern Pine</td>
</tr>
<tr>
<td>V1</td>
<td>#2 Doug Fir Larch</td>
<td>#3 Doug Fir Larch</td>
</tr>
<tr>
<td>V2</td>
<td>#1/#2 Spruce Pine Fir</td>
<td>#3 Spruce Pine Fir</td>
</tr>
<tr>
<td>V3</td>
<td>#2 Southern Pine</td>
<td>#3 Southern Pine</td>
</tr>
</tbody>
</table>

Non-mandatory in PRG 320. Other stress grades including SCL permitted

## Common CLT Layups

- 3-ply 3-layer
- 5-ply 5-layer
- 7-ply 7-layer
- 9-ply 9-layer
- 7-ply 5-layer
- 9-ply 7-layer
PRG 320 Defined Layups

<table>
<thead>
<tr>
<th>TABLE A1.</th>
<th>THE ALLOWABLE BENDING CAPACITIES* FOR CLT LISTED IN TABLE A1 (FOR USE IN THE U.S.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lamination Thickness (in.) in CLT Layup</td>
<td>Major Strength Direction</td>
</tr>
<tr>
<td></td>
<td>$f_{L2,0}$ (psi)</td>
</tr>
<tr>
<td>0.18</td>
<td>1.59</td>
</tr>
<tr>
<td>0.35</td>
<td>1.59</td>
</tr>
<tr>
<td>0.56</td>
<td>1.59</td>
</tr>
<tr>
<td>0.67</td>
<td>1.59</td>
</tr>
<tr>
<td>0.99</td>
<td>1.59</td>
</tr>
<tr>
<td>1.10</td>
<td>1.59</td>
</tr>
<tr>
<td>0.35</td>
<td>1.59</td>
</tr>
<tr>
<td>0.56</td>
<td>1.59</td>
</tr>
<tr>
<td>0.67</td>
<td>1.59</td>
</tr>
<tr>
<td>0.99</td>
<td>1.59</td>
</tr>
<tr>
<td>0.99</td>
<td>1.59</td>
</tr>
<tr>
<td>1.10</td>
<td>1.59</td>
</tr>
</tbody>
</table>

For SI: 1 in. = 25.4 mm; 1 ft = 304.8 mm; 1 lb = 4.448 N

(a) See Section 4 for symbols.

(b) This table represents one of many possibilities that the CLT could be manufactured by varying lamination grades, thicknesses, orientations, and support arrangements in the layup.

(c) Custom CLT grades that are not listed in the table shall be permitted in accordance with Section 7.2.1.

Product Reports

Structuriam CrossLam
Structuriam Products LP
PR-L314
Issued May 23, 2013

Nordic X-Lam
Nordic Engineered Wood
PR-L306
Revised May 23, 2013
Product Reports

Table 1. Allowable Design Properties\(^{\text{a}}\) for Nordic X-Lam (For use in the U.S.)

<table>
<thead>
<tr>
<th>CLT Grade</th>
<th>F_{90} (psi)</th>
<th>E (10^4 psi)</th>
<th>F_{90} (psi)</th>
<th>E (10^4 psi)</th>
<th>F_{90} (psi)</th>
<th>E (10^4 psi)</th>
<th>F_{90} (psi)</th>
<th>E (10^4 psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>E1</td>
<td>12</td>
<td>1.7</td>
<td>725</td>
<td>1.4</td>
<td>1660</td>
<td>1.3</td>
<td>206</td>
<td>1.2</td>
</tr>
</tbody>
</table>

For SI: 1 psi = 0.000689 MPa

\(^{\text{a}}\) Tabulated values are allowable design values and not permitted to be increased for the lumber size adjustment factor in accordance with the NDS. The design values shall be used in conjunction with the wetted properties provided by the CLT manufacturer based on the actual layers used in manufacturing the CLT panel (see Table 2).

Table 2. The Allowable Bending Capacities\(^{\text{a}}\) for Nordic X-Lam Listed in Table 1 (For use in the U.S.)

<table>
<thead>
<tr>
<th>CLT Grade</th>
<th>Laminate Thickness (in.)</th>
<th>Major Strength Direction</th>
<th>Minor Strength Direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>E1</td>
<td>0.125</td>
<td>1.825</td>
<td>0.845</td>
</tr>
<tr>
<td></td>
<td>0.25</td>
<td>3.65</td>
<td>1.695</td>
</tr>
<tr>
<td></td>
<td>0.375</td>
<td>5.475</td>
<td>2.545</td>
</tr>
</tbody>
</table>

For SI: 1 in. = 25.4 mm; 1 ft = 304.8 mm; 1 lb f = 444N

\(^{\text{a}}\) Tabulated values are allowable design values and not permitted to be increased for the lumber size adjustment factor in accordance with the NDS.

Structural Design Standardization

National Design Specification for Wood Construction
2015 Edition
New Chapter 10 covering Adjustment Factors for CLT
Formatting Similar to Wood Structural Panels

### Table 10.3.1 Applicability of Adjustment Factors for Cross-Laminated Timber

<table>
<thead>
<tr>
<th>Condition</th>
<th>ASRD only</th>
<th>ASRD and LRFD</th>
<th>LRFD only</th>
</tr>
</thead>
<tbody>
<tr>
<td>Local Bending Force</td>
<td>Cu</td>
<td>Cu</td>
<td>Cu</td>
</tr>
<tr>
<td>Local Shear Force</td>
<td>Cu</td>
<td>Cu</td>
<td>Cu</td>
</tr>
<tr>
<td>Local Torsion Force</td>
<td>Cu</td>
<td>Cu</td>
<td>Cu</td>
</tr>
<tr>
<td>Local Stability Factor</td>
<td>Cu</td>
<td>Cu</td>
<td>Cu</td>
</tr>
<tr>
<td>Bearing Macro Factor</td>
<td>Cu</td>
<td>Cu</td>
<td>Cu</td>
</tr>
<tr>
<td>Bearing Micro Factor</td>
<td>Cu</td>
<td>Cu</td>
<td>Cu</td>
</tr>
<tr>
<td>Tension Compressive Force</td>
<td>Cu</td>
<td>Cu</td>
<td>Cu</td>
</tr>
<tr>
<td>Tension Force</td>
<td>Cu</td>
<td>Cu</td>
<td>Cu</td>
</tr>
<tr>
<td>Tensile Force</td>
<td>Cu</td>
<td>Cu</td>
<td>Cu</td>
</tr>
</tbody>
</table>

CLT in NDS 2015

Connectors for CLT in NDS 2015:
Dowel Type Fasteners, e.g. Lag Screws, Wood Screws and Nails
Model Building Code Acceptance

2015 International Building Code

CLT is Defined – 2015 IBC

SECTION 202
DEFINITIONS

CROSS-LAMINATED TIMBER. A prefabricated engineered wood product consisting of at least three layers of solid-sawn lumber or structural composite lumber where the adjacent layers are cross-oriented and bonded with structural adhesive to form a solid wood element.

Add new text as follows:

2303.1.4 Structural glued cross-laminated timber. Cross-laminated timbers shall be manufactured and identified as required in ANSI/APA PRG 320-2011.

Add new standard to Chapter 35 as follows:

ANSI

Highlights of CLT Provisions in IBC 2015

- CLT is generally available for use in Type III, IV and V construction.

- Chapter 6 Defines Dimensions of CLT to qualify as Heavy Timber (Type IV Construction)
  - 6” Walls
  - 4” Floors
  - 3” Roofs
    - non Fire-Retardant Treated CLT allowed in Exterior Walls of Type IV construction in many conditions.

Product Availability

- North American producers of APA 320 certified structural CLT:
  - Nordic Structures in Quebec, Canada
  - Structurlam in British Columbia, Canada
  - DR Johnson Lumber in Riddle, Oregon

- Other companies building manufacturing facilities and working to product certification for building applications to PRG 320
  - SmartLam in Montana

- Non-commodity based product
  - Variety of lumber species and grades
  - Variety of layups
  - Different maximum panel size limitations
**Strength**

Photos Courtesy Structurlam

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**Floors**
Structural Section Properties

Non-homogenous, anisotropic material

Flexural Strength

Design Properties based on Extreme Fiber Model:

Flexural Capacity Check:

\[ M_b \leq (F_b S_{eff})' \]

- \( M_b \) = applied bending moment
- \( (F_b S_{eff})' \) = adjusted bending capacity
- \( S_{eff} \) = effective section modulus
- \( F_b \) = reference bending design value of outer lamination

Reference: NDS 2015
**Flexural Strength**

Design Properties based on Extreme Fiber Model:

**Flexural Capacity Check (ASD)**

\[ (F_b S_{\text{eff}})' = C_D C_M C_t C_L (F_b S_{\text{eff}}) \]

- Bending Stress
- \( M_b \leq C_D (1.0) (F_b S_{\text{eff}}) \)

*Commonly 1.0 From Manufacturer*

*Reference: NDS 2015 & Product Reports*

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**Flexural Strength**

Design Properties based on Extreme Fiber Model:

**Flexural Capacity Check (LRFD)**

\[ (F_b S_{\text{eff}})' = C_M C_t C_L (F_b S_{\text{eff}}) K_f \phi \lambda \]

- Bending Stress
- \( M_b \leq (1.0) (F_b S_{\text{eff}}) (2.54)(0.85) \lambda \)

*Commonly 1.0 From Manufacturer*

*Reference: NDS 2015 & Product Reports*
**Design Example: Flexure**

Select acceptable CLT section

**Given:**

- 16 foot span floor
- 40 psf live load, 40 psf total dead load.

**Assume:**

- one-way spanning action in major axis of CLT

ASD Dead + Live Flexural Demands:

\[ M_b = \frac{w L^2}{8} = \frac{(40+40\text{psf}) \times (16\text{ft})^2}{8} = 2560 \text{ lb-ft/ft} \]

**Design Example: Flexure**

Try 5 ply, (6 7/8 in thick) CLT Grade V2 Section

<table>
<thead>
<tr>
<th>TABLE A2. THE ALLOWABLE BENDING CAPACITIES&lt;sup&gt;min&lt;/sup&gt; FOR CLT LISTED IN TABLE A1 (FOR USE IN THE U.S.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lamination Thickness (in.) in CLT Layup</td>
</tr>
<tr>
<td>CLT Grade</td>
</tr>
<tr>
<td>V1</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>V2</td>
</tr>
<tr>
<td></td>
</tr>
</tbody>
</table>

Reference: ANSI/APA PRG 320-2012
Design Example: Flexure

**ASD Flexural Capacity:**
Dead + Live load, $C_D = 1.0$

$$(F_b S_{eff})' = C_D (1.0) (F_b S_{eff})$$
$$= 1.0 (1.0) (4675 \text{ lb-ft/ft})$$
$$= 4675 \text{ lb-ft/ft}$$

$M_b = 2560 \text{ lb-ft/ft} \leq F_b' S_{eff} = 4675 \text{ lb-ft/ft}$

Flexural Strength OK

Shear Strength

Design Properties based on Extreme Fiber Model:

Shear Capacity Check:

$$V_{\text{planar}} \leq F_s (\text{lb/Q})_{eff}'$$

$V_{\text{planar}} = \text{applied shear}$

$F_s (\text{lb/Q}_{eff})' = \text{adjusted shear strength}$

Reference: NDS 2015
Shear Strength

Design Properties based on Extreme Fiber Model:

Shear Capacity Check (ASD):

\[ F_s (lbQ)_{\text{eff}}' = C_M C_t (F_s (lbQ)_{\text{eff}}) = C_M C_t V_s \]

- Commonly 1.0
- From Manufacturer for Standard Sections

\[ V_{\text{planar}} \leq (1.0) V_s \]

Reference: NDS 2015 & Product Reports

Flexural Stiffness

Shear Analogy Method

\[ EI_{\text{eff}} = \sum_{i=1}^{n} E_i \cdot b_i \cdot \frac{h_i^3}{12} + \sum_{i=1}^{n} E_i \cdot A_i \cdot z_i^2 \]

\[ S_{\text{eff}} = \frac{2EI_{\text{eff}}}{E_i h} \]

\[ (lb/Q)_{\text{eff}} = \frac{EI_{\text{eff}}}{\sum_{i=1}^{n} E_i h_i z_i} \]

Reference: US CLT Handbook Chapter 3
Flexural Stiffness

\[ EI_{eff} = \sum_{i=1}^{n} E_i \cdot b_i \cdot \frac{h_i^3}{12} + \sum_{i=1}^{n} E_i \cdot A_i \cdot z_i^2 \]

\[ GA_{eff} = \frac{a^2}{\left( \frac{h_1}{2 \cdot G_1 \cdot b} \right)^2 \left( \sum \frac{h_i}{2 \cdot G_i \cdot b} \right)^4 \left( \frac{h_n}{2 \cdot G_n \cdot b} \right)^4} \]

Structural Material Assumptions


Given lumber for a lamination with modulus of elasticity for bending in major strength direction, \( E_0 \), assume:

- \( E_{90} = \frac{E_0}{30} \)
- \( G_0 = \frac{E_0}{16} \)
- \( G_{90} = \frac{G_0}{10} = \frac{E_0}{160} \)

Flexural Stiffness

\[ EI_{\text{eff}} = \sum_{i=1}^{n} E_i \cdot b_i \cdot \frac{h_i^3}{12} + \sum_{i=1}^{n} E_i \cdot A_i \cdot z_i^2 \]

Important to develop properties of new CLT Sections. Not to use standard CLT Sections.

\[ GA_{\text{eff}} = \frac{a^2}{\left[ \frac{h_1}{2 \cdot G_1 \cdot b} + \left( \sum_{i=2}^{n} \frac{h_i}{G_i \cdot b} + \frac{h_n}{2 \cdot G_n \cdot b} \right) \right]} \]

Advanced Use: Calculating Structural Capacities under Fire Conditions using NDS 2015 Chapter 16.
Stiffness & Deflection

Major Axis Stiffness

Minor Axis Stiffness

Structural Section Properties

Flexural Strength: \( F_b S_{eff,0} \) \( F_b S_{eff,90} \)
Flexural Stiffness: \( EI_{eff,0} \) \( EI_{eff,90} \)
Shear Strength: \( V_{s,0} \) \( V_{s,90} \)
Shear Stiffness: \( GA_{eff,0} \) \( GA_{eff,90} \)

Values in RED provided by CLT manufacturer

Reference: PRG 320 and CLT Product Reports
Deflection Calculations

General Purpose, 2 Way, Plate Action

- **Flexural Stiffness**
  - $E_{I_{eff,0}}$, $E_{I_{eff,90}}$

- **Shear Stiffness:**
  - $\frac{5}{6} G_{A_{eff,0}}$, $\frac{5}{6} G_{A_{eff,90}}$
  - $\frac{5}{6}$ from $A' = \frac{5}{6} A$ for rectangular sections

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Deflection Calculations

General Purpose: 1 Way, Beam Action

- **Stiffness:**
  - $E_{I_{eff,0}}$, $\frac{5}{6} G_{A_{eff,0}}$

Can model multiple spans, cantilevers, etc.
Example Deflection Calculations

Example Calculation:
Uniform loading on one way slab:
Beam Analysis using
Flexural Stiffness: $E_{l_{eff,0}}$
Shear Stiffness: $5/6 G_{A_{eff,0}}$
Maximum Deflection @ Mid-Span

$$\Delta_{max} = \frac{5}{384} \cdot \frac{wL^4}{E_{l_{eff}}} \cdot \frac{1}{8} \cdot \frac{wL^2}{5/6 G_{A_{eff}}}$$

Design Example:

$= 0.161 \text{ in} + 0.02 \text{ in} = 0.183 \text{ in}$

$= L / 1050$

Deflection Calculations

Simplified Beam Deflections:
Given load pattern and support conditions:

$$\Delta_{max} = \frac{5}{384} \cdot \frac{wL^4}{E_{l_{app}}} \cdot \frac{1}{8} \cdot \frac{wL^2}{5/6 G_{A_{eff}}}$$

Find **Apparent** Flexural Stiffness, $E_{l_{app}}$, such that

$$\Delta_{max} = \frac{5}{384} \cdot \frac{wL^4}{E_{l_{app}}}$$

$$E_{l_{app}} = \frac{E_{l_{eff}}}{1 + \frac{11.5E_{l_{eff}}}{G_{A_{eff}}L^2}}$$

Reference: US CLT Handbook
Deflection Calculations

Simplified Beam Deflections

For single span, simple loading patterns, Apparent Flexural Stiffness, $E_I_{app}$, to determine maximum (mid-span) deflection:

$$E_I_{app} = \frac{E_I_{eff}}{1 + \frac{K_s E_I_{eff}}{G A_{eff} L^2}}$$

US CLT Handbook & NDS 2015 Commentary

$$E_I_{app} = \frac{E_I_{eff}}{1 + \frac{16 K_s E_I_{eff}}{A_{eff} L^2}}$$

NDS 2015

For Major Axis Spans:

$$l_{eff} = \frac{E_I_{eff}}{E_o}$$

$$A_{eff} = G A_{eff}/G_o$$

$$G_o = E_o/16$$


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Deflection Calculations

Simplified Beam Deflections

For single span, simple loading patterns, Apparent Flexural Stiffness, $E_I_{app}$, to determine maximum (mid-span) deflection:

$$E_I_{app} = \frac{E_I_{eff}}{1 + \frac{K_s E_I_{eff}}{G A_{eff} L^2}}$$

$$E_I_{app} = \frac{E_I_{eff}}{1 + \frac{16 K_s E_I_{eff}}{A_{eff} L^2}}$$

Apparent Flexural Stiffness depends on Load Pattern and Support Conditions

<table>
<thead>
<tr>
<th>Loading</th>
<th>End Supports</th>
<th>$K_s$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uniform</td>
<td>Pinned</td>
<td>11.5</td>
</tr>
<tr>
<td></td>
<td>Fixed</td>
<td>57.6</td>
</tr>
<tr>
<td>Midspan Line</td>
<td>Pinned</td>
<td>14.4</td>
</tr>
<tr>
<td></td>
<td>Fixed</td>
<td>57.6</td>
</tr>
</tbody>
</table>

Reference: NDS 2015 Table 10.4.1.1 for additional $K_s$ values
Creep Factor

Deformation to Long Term Loads

\[ \Delta_T = K_{cr} \Delta_{LT} + \Delta_{ST} \]

NDS Eq 3.5-1

\[ \Delta_{ST} \quad \text{Deflection due to short-term loading} \]

\[ \Delta_{LT} \quad \text{Immediate deflection due to long term loading} \]

\[ K_{cr} \quad 2.0 \text{ for CLT in dry service conditions} \]

Reference: NDS 2015

Floor Vibration

Occupant perception of vibration is a highly recommended design consideration.

One approach: CLT Handbook, Chapter 7

Calculated natural frequency of simple span:

\[ f = \frac{2.188}{2L^2} \sqrt{\frac{EI_{\text{app}}}{\rho A}} \]

Where:

\[ EI_{\text{app}} = \text{apparent stiffness for 1 foot strip, pinned supported, uniformly loaded, simple span (} K_s = 11.5 \text{) (lb-in}^2\text{)} \]

\[ \rho = \text{specific gravity of the CLT} \]

\[ A = \text{the cross section area (thickness x 12 inches) (in}^2\text{)} \]

Reference: US CLT Handbook, Chapter 7
**Floor Vibration**

*CLT Handbook, Chapter 7* recommends,

\[
f = \frac{2.188}{2L^2} \sqrt{\frac{EI_{app}}{\rho A}} \geq 9.0 \text{ Hz}
\]

and

\[
\text{Max span } L \leq \frac{1}{12.05} \left( \frac{EI_{app}}{\rho A} \right)^{0.293}
\]

*Reference: US CLT Handbook, Chapter 7*

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**Floor Vibration**

*CLT Handbook, Chapter 7 Recommendations*

**Experimental Verification – Results**

Research by Lin Hu, et al. at

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Floor Vibration

**CLT Handbook, Chapter 7** method:

Natural frequencies above 9 Hz and:

\[
\text{Max span } L \leq \frac{1}{12.05} \left( \frac{E I_{\text{app}}}{\rho A} \right)^{0.293}
\]

\( E I_{\text{app}} \) depends on \( L \), so an iterative calculation required.

Only depends on CLT section properties, so…

Values calculated and provided by CLT Manufactures

16ft span example: V2 Grade 5 ply (6 7/8 in) \( L \max = 16.7 \text{ feet} \).

*Reference: US CLT Handbook, Chapter 7*

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Floor Vibration

Occasional perception of vibration a recommended design consideration

**CLT Handbook, Chapter 7** recommends natural frequencies above 9 Hz and:

\[
\text{Max span } L \leq \frac{1}{12.05} \left( \frac{E I_{\text{app}}}{\rho A} \right)^{0.293}
\]

Limitations:
- Potential advantages of topping slab stiffness not taken into account
- Potential advantages of multiple spans or other restraining details
- For long spans, it may be inefficient to keep natural frequency above 9 Hz.
Alternative Vibration Criteria

Alternative: Use acceptance criteria which address low frequency floors and alternative support configurations.

*Calibration of dynamic modeling with physical testing valuable*

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SOM Timber Tower

Prototype Building

Source: SOM Timber Tower Research Project, May 2013
SOM Timber Tower

24 to 25 ft CLT Floor Spans. 6.5 to 8.5 Hz Range

Alternative Vibration Criteria

Long spans can be designed using **CLT Handbook Criteria:**

- Keep Fundamental Frequency > 9 hz
- Idealized as Single Span, Simply Supported Panels

24 foot spans result in ~12 inch thick or greater CLT floors.
Alternative Vibration Criteria

SOM Timber Tower used:
AISC Design Guide 11, Velocity Criteria (Chapter 6)
Acceptance Criteria selected:
\[ \leq 16,000 \ \mu\text{in/sec} \text{ w/ moderate walking in living areas} \]
\[ \leq 8,000 \ \mu\text{in/sec} \text{ w/ slow walking pace in sleeping areas.} \]
AISC DG 11 suggests approximate velocity limit of human perception
8,000 \ \mu\text{in/sec} at 8 Hz and above.

AISC Design Guide 11 not for dynamic modeling of CLT floors

SOM Timber Tower Resulted in 8” Thick Floor

Alternative Vibration Criteria

A Common European CLT Floor Design Method:
- a) Static deflection to 1 kN point load > 0.25 mm
- b) Keep fundamental frequency > 8 Hz
   OR
   Fundamental frequency > 4.5 Hz
   + additional acceleration investigation and limits

See:
- “Floor Vibrations – New Results” Hamm, Richter & Winter, 2010
- Cross-Laminated Timber Structural Design. Basic design and engineering principles according to Eurocode. proHolz Austria, 2014
- Alternative criteria for varying performance expectations provided
Connection Styles

Floor Panel to Floor Panel

- Single Surface Spline
- Double Surface Spline
- Interior Spline
- Half Lap
Connections

---

**Platform Frame with Only Screws**

**Platform Frame with Double Brackets**

**Platform Frame with Single Brackets**
### Connection Details

Simple connections with:
- Metal angles
- Self-taping Screws

Source: US CLT Handbook

### Connection Styles

**Floor Panel to Wall**
- Self-tapping screws

**Platform Frame with Hidden Bracket**

**Platform Frame with Bracket**

**Balloon Frame With Supporting Ledger**
Proprietary Connector Products

Variety of Self Tapping Screws

Proprietary Products

Table 1: Allowable stress design values – CLT panel connection

<table>
<thead>
<tr>
<th>Model ID</th>
<th>Dimensions (in.)</th>
<th>Fastener Schedule</th>
<th>Allowable Load (kips), Cx = 1.60</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Width</td>
<td>Depth</td>
<td>Length</td>
</tr>
<tr>
<td>ABR1000</td>
<td>14</td>
<td>3/4</td>
<td>12</td>
</tr>
<tr>
<td>ABR1050</td>
<td>15</td>
<td>3/4</td>
<td>12</td>
</tr>
<tr>
<td>AER1050</td>
<td>1.3</td>
<td>3/4</td>
<td>12</td>
</tr>
<tr>
<td>AER1000</td>
<td>1.3</td>
<td>3/4</td>
<td>12</td>
</tr>
</tbody>
</table>

Notes:
1. The allowable loads are based on the use of SPF Studs & Cross Laminated Timber (CLT) structural components as per APA PR-320.
2. The installation and fastener schedule assumes platform framing, i.e., initial vertical leg at bottom edge of CLT and panel, and horizontal leg on CLT floor panel with 1-1/2 in. min. edge distance.
3. Allowable loads have been increased for wind or earthquake loading with no further increase allowed. Reduce for other load durations as required by code.
4. Test results have been increased to account for wood-to-wood panel and panel-to-joist connections.
5. Nominal size 3 1/4 in. x 3 1/2 in. x 3 1/4 in. long 2 x 4 x 2 in. wood screws.
CLT in Lateral Force Resisting Systems

CLT Panels have a very high in-plane shear strength.

<table>
<thead>
<tr>
<th>Panel d (in)</th>
<th>SLT3</th>
<th>SLT5</th>
<th>SLT7</th>
<th>SLT9</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vr (lbs/ft)</td>
<td>2906</td>
<td>5812</td>
<td>8718</td>
<td>11624</td>
</tr>
</tbody>
</table>

Source: The Cross Laminated Timber Design Guide v11 from Structurlam
CLT Seismic Design

CLT Seismic Force Resisting Systems Not addressed In

ASCE/SEI 7-10
SDPWS 2015

CLT as a Seismic LFRS Summary

- Development of seismic parameters for Equivalent Linear Force under current research via FEMA P-695 process
- Innovative high performance systems under current research.
- For the near term, CLT shear wall systems in CA possibly justified via alternative means:
  - Conservative Seismic Design Parameters
  - Performance-Based Design leveraging research or new testing
Hybrid Building Systems

Photos © Nick Lehoux for the Bullitt Center

Bullitt Center, Seattle, WA

Photos © Nick Lehoux for the Bullitt Center
Panel In-Plane Strength:
- Panel strength generally does not govern diaphragm shear strength.
- Reference Design Values
  - Not covered by APA PRG 320-12 product standard
  - Are covered by New ICC AC455 Acceptance Criteria
  - Ask for design values from the Manufacturers

Connection Strength:
- Commodity connectors (e.g. Nails) per NDS 2015
- Proprietary Connectors (Self-Tapping Screws) per Evaluation Reports, Manufacturer’s Information and Engineering Mechanics.
- For seismic design, select connection details so ductile limit states govern capacities.

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**Design Example White Paper**

**CROSS LAMINATED TIMBER**  
Horizontal Diaphragm Design Example

Our aim for this white paper is to provide a practical design method to determine the strength of a Cross Laminated Timber horizontal diaphragm and deflection due to lateral wind or seismic loads.

**CLT HORIZONTAL DIAPHRAGM DESIGN**

The design approach is based on compliance with engineering design of CLT in accordance with the 2015 International Building Code, reference standards, and other published information including manufacturer’s literature.

Applicable Building Code, reference standards, and other information sources:
- ICC, 2015 International Building Code
- IBC/IFC NDS-2012 National Design Specification (NDS) for Wood Construction with Commentary
- ACI 7.5-06 Minimum Design Loads for Buildings and Other Structures
- AWC, ND-10 Load Factors for Structural Steel Buildings
- AIA, Product Data NR-11-17, Cross Laminated Timber Products, LLC
Diaphragm Design Example

- Shows calculations for simple diaphragm following US CLT Handbook Recommendations with many limit states.
- Presented modification of WSP diaphragm deflection calculation for large Panels

\[ \delta_{dia} = \frac{5vL^3}{8EAW} + \frac{vL}{4G_{e}t_{v}} + CL_{w} + \frac{\sum(x\Delta_{c})}{2W} \]

\[ C = \frac{1}{2} \left( \frac{1}{P_{L}} + \frac{1}{P_{W}} \right) \]

- \( P_{L} \) is panel length
- \( P_{W} \) is panel width

Design Example White Paper
**Ideas for Near Term Seismic Diaphragms**

- Possible routes for near term *seismic* project designs under Alternative Means and Methods include:

1) Elastic Design Method
   - Based on lower-bound strength of components
   - Following new ASCE 7-16 alternative diaphragm method to determine elastic seismic diaphragm force demands

2) Capacity-Based Design Method
   - Using designated yielding connections with overstrength design of non-desirable limit states.
   - Based on yielding connection technologies of proven cyclic behavior
     - Relatively equivalent to Wood Structural Panel diaphragm behavior OR
     - Advanced Engineering with supporting testing to justify design

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**ASCE 7-16 Alternative Diaphragm Design**

Not finalized and published, however

Many new equations including *Diaphragm Design Force Reduction Factor*

**ASCE 7-16 Table 12.11.5-1 Diaphragm design force reduction factor, \( R_s \)**

<table>
<thead>
<tr>
<th>Diaphragm System</th>
<th>Shear-Controlled</th>
<th>Flexure-Controlled</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cast-in-place concrete designed in accordance with Section 14.2 and ACI 318</td>
<td>2.0</td>
<td>2.0</td>
</tr>
<tr>
<td>Precast concrete designed in accordance with Section 14.2.4 and ACI 318</td>
<td>EDO 1.0</td>
<td>0.7</td>
</tr>
<tr>
<td>BDO 1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>RDO 1.4</td>
<td>1.4</td>
<td>1.4</td>
</tr>
<tr>
<td>Wood sheathed designed in accordance with Section 14.5 and AERA/PA (now AWC) Special Design Provisions for Wind and Seismic</td>
<td>1.0</td>
<td>NA</td>
</tr>
</tbody>
</table>

1. EDO is precast concrete diaphragm Elastic Design Option.
2. BDO is precast concrete diaphragm Basic Design Option.
3. RDO is precast concrete diaphragm Reduced Design Option.
June 2016 Structures Magazine Article


Questions?

This concludes The American Institute of Architects Continuing Education Systems Course

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Wood Innovation Design Center
Prince George, British Columbia
8 Levels/6 Stories
97 feet tall
Completed Fall 2014

Architect: Michael Green Architecture
Structural Engineer: Equilibrium Consulting
Contractor: PCL Constructors Westcoast
Photos: Ema Peter Photography
Cooley Landing Education Center

East Palo Alto, CA
Structural CLT Floor and Roof Construction
Woodwork Webinar

East Palo Alto Cooley Landing Education Center
Photo: Structurlam

East Palo Alto Cooley Landing Education Center
Photo: Structurlam
New Stanford Heat Recovery Center
Stanford, CA

Image Credit: ZGF Architects

Stanford Heat Recovery Center
Photo: Structurlam
CLT Roof Panels used over entrance/walkway

Part of 125,000 sf building that is expected to reduce campus carbon emissions by 50% and save an estimated $300M over the next 35 years
56’ square kiosk

2 Layers of 3-ply, 4-1/8” CLT roof panels in opposite directions, each panel 8’ x 56’, creating 2 way spanning plate
Total roof structure thickness 8-1/4”
Spans up to 30 feet between columns at points

Chicago Horizon Won Chicago Architecture Biennial’s 2015 Lakefront Kiosk Competition

Photo Credit: Tom Harris
2,000 sf visitor center
CLT utilized for roof panels
Use of CLT allowed elimination of 20 percent of the steel beams originally needed to support the standard wood decking
1st Oregon CLT project
International Community Health Services
Shoreline Clinic
Shoreline, WA

Photo Credit: Andrew Pogue Photography
45,000 sf, 3 story medical and dental services center
CLT utilized for roof panels with large expressed overhangs
Completed Fall 2014

Project currently pending LEED Gold approval
Largest CLT project in State of WA at time of construction
Use of CLT roof panels resulted in schedule and labor savings, with the panels being set in a matter of days
Structural CLT Floor and Roof Construction
Woodwork Webinar

ICH5 Shoreline Clinic
Photo: ICHS

Sauter Timber Production Facility
Rockwood, TN

Photo Credit: Andreas Sauter, Tim Clay Photography
9,000 sf Industrial production facility
CLT roof and wall panels, glulam beam & column frame
23’ tall walls

$55/sf installed structure cost
2015 Wood Design Award Winner

Glulam Moment Frame Provides Facility’s Lateral Resistance
Redstone Arsenal Hotel
Huntsville, AL

Image Credit: Lend Lease

62,600 sf, 4 story hotel, 92 private rooms
CLT utilized for walls, roof panels, and floor panels
1,557 CLT Panels; Typical floor panel is 8’x50’ & weighs 8,000 lbs
Completed Late 2015

Redstone Arsenal Hotel
Photos: Lend Lease & Schaefer
Franklin Elementary School
Franklin, WV

45,200 sf, 2 story school
CLT utilized for walls, roof panels, and floor panels
CLT chosen for its construction schedule benefits
Completed January 2015

Photo Credit: Pam Wean, MSES Architects
Structural CLT Floor and Roof Construction
Woodwork Webinar

Brelsford WSU Visitor Center
Pullman, WA

Photo Credit: Pam Wean, MSLS Architects

Photo Credit: Washington State University
4,277 sf, 1 story visitor center
CLT utilized for roof panels with large, expressed overhangs
Completed Late 2013

CLT Benefits: Structure Mass, Thickness & Construction Speed
4” CLT roof panels were 6 times lighter and 1/3 thinner than concrete roof panels. Installed faster as no cure time is required