An Engineer’s Guide to Mass Timber Structures: Simplifying Design Steps and Connection Details

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Mass Timber Framing Systems
Mass Timber Framing Systems

Gravity Framing Styles

- Post & Beam
- Two-Way Panel Deck
- Hybrid Light-Frame & Mass Timber
- Mass Timber Walls “Honeycomb”
Mass Timber Framing Systems

Gravity Framing Styles

- Post & Beam
- Two-Way Panel Deck
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- Mass Timber Walls “Honeycomb”
Bullitt Center
Seattle, WA

2x4 NLT roof deck
2x6 NLT floor deck

Floor assembly top to bottom:
3” concrete topping, acoustical mat, WSP, 2x6 NLT
Framework
Portland, OR

Photo: joshua jay elliot
T3 Minneapolis
Minneapolis, MN

Image Credit: Blaine Brownell
Mass Timber Framing Systems

Gravity Framing Styles

- Post & Beam
- Two-Way Panel Deck
- Hybrid Light-Frame & Mass Timber
- Mass Timber Walls “Honeycomb”
5 PLY CLT PANELS, 2-WAY SPAN
~9’X13’ GRID OF COLUMNS
Chicago Horizon Pavilion
Chicago, IL

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.

Photo Credit: Tom Harris
Mass Timber Framing Systems

Gravity Framing Styles

- Post & Beam
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Cheney Park Apartments
CLT floor on Panelized Light Frame Walls
Mass Timber Framing Systems

Gravity Framing Styles

- Post & Beam
- Two-Way Panel Deck
- Hybrid Light-Frame & Mass Timber
- Mass Timber Walls “Honeycomb”
Candlewood Suites
Redstone Arsenal, AL

- 62,600 SF, 4 story hotel, 92 private rooms
- CLT utilized for walls, roof panels, and floor panels

Image Credit: Lend Lease
Redstone Arsenal Hotel
Huntsville, AL

Image Credit: Lend Lease
Candlewood Suites
Redstone Arsenal, AL

Photo Credit: IHG® Army Hotels

Photo Credit: Lendlease
## Glulam Design Values

**Bending About X-X Axis**

(Loaded Perpendicular to Wide Faces of Laminations)

<table>
<thead>
<tr>
<th>Combination</th>
<th>Species</th>
<th>Outer/ Core</th>
<th>$F_{bx}^+$ (psi)</th>
<th>$F_{bx}^-$ (psi)</th>
<th>$F_{c,\perp x}$ (psi)</th>
<th>$F_{vx}$ (psi)</th>
<th>$E_x$ ($10^6$ psi)</th>
<th>$E_{x\min}$ ($10^6$ psi)</th>
</tr>
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<tbody>
<tr>
<td>24F-1.8E</td>
<td></td>
<td></td>
<td>2400</td>
<td>1450</td>
<td>650</td>
<td>265</td>
<td>1.8</td>
<td>0.95</td>
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<tr>
<td>24F-V4</td>
<td>DF/DF</td>
<td></td>
<td>2400</td>
<td>1850</td>
<td>650</td>
<td>265</td>
<td>1.8</td>
<td>0.95</td>
</tr>
<tr>
<td>24F-V8</td>
<td>DF/DF</td>
<td></td>
<td>2400</td>
<td>2400</td>
<td>650</td>
<td>265</td>
<td>1.8</td>
<td>0.95</td>
</tr>
<tr>
<td>24F-E4</td>
<td>DF/DF</td>
<td></td>
<td>2400</td>
<td>1450</td>
<td>650</td>
<td>265</td>
<td>1.8</td>
<td>0.95</td>
</tr>
<tr>
<td>24F-E13</td>
<td>DF/DF</td>
<td></td>
<td>2400</td>
<td>2400</td>
<td>650</td>
<td>265</td>
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<td>0.95</td>
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<tr>
<td>24F-E18</td>
<td>DF/DF</td>
<td></td>
<td>2400</td>
<td>2400</td>
<td>650</td>
<td>265</td>
<td>1.8</td>
<td>0.95</td>
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<td>24F-V3</td>
<td>SP/SP</td>
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<td>2400</td>
<td>2000</td>
<td>740</td>
<td>300</td>
<td>1.8</td>
<td>0.95</td>
</tr>
<tr>
<td>24F-V8</td>
<td>SP/SP</td>
<td></td>
<td>2400</td>
<td>2400</td>
<td>740</td>
<td>300</td>
<td>1.8</td>
<td>0.95</td>
</tr>
<tr>
<td>24F-E1</td>
<td>SP/SP</td>
<td></td>
<td>2400</td>
<td>1450</td>
<td>805</td>
<td>300</td>
<td>1.8</td>
<td>0.95</td>
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<tr>
<td>24F-E4</td>
<td>SP/SP</td>
<td></td>
<td>2400</td>
<td>2400</td>
<td>805</td>
<td>300</td>
<td>1.9</td>
<td>1.00</td>
</tr>
</tbody>
</table>

*Source: NDS supplement Table 5A*
Mass Timber and Steel Framing?

Barracuda Condos
Madison WI

Photo Credit: WoodWorks

Public Library
Brentwood CA
Mass Timber Framing Systems

Post & Beam

Horizontal Deck

Primary Frame

NLT

GLT

CLT

T&G Decking

SCL & Composites
Mass Timber Products

Nail-Laminated Timber (NLT)

Cross-Laminated Timber (CLT)

Glue-Laminated Timber (GLT)

Horizontal Framing

Tongue & groove decking (T&G)

Timber concrete composite

Structural Composite Lumber

Image source: StructureCraft
NLT Design Guide includes:

- Architecture
- Fire
- Structure
- Enclosure
- Supply and Fabrication
- Construction and Installation
- Erection engineering

Free download from www.thinkwood.com
NLT shrinkage/expansion design:
Rule of thumb: leave gap between ½” and one ply wide per 8’-10’ wide panel
Fluted NLT Design

<table>
<thead>
<tr>
<th>Key</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. NLT deep lamination depth (d_i)</td>
</tr>
<tr>
<td>2. NLT shallow lamination depth (d_2)</td>
</tr>
<tr>
<td>3. NLT deep lamination thickness (b_{lam1})</td>
</tr>
<tr>
<td>4. NLT shallow lamination thickness (b_{lam2})</td>
</tr>
<tr>
<td>5. NLT panel width (b)</td>
</tr>
<tr>
<td>6. Ratio of lamination depths (x_i), where (n_i) = the number of laminations of depth (d_i)</td>
</tr>
</tbody>
</table>

**Figure 4.3: Staggered NLT Cross Section**

\[
x_i = \frac{n_i b_{lam i}}{b_{panel}}
\]

\[K_{section,E} = X_1 + X_2 \left[ \frac{d_2}{d_1} \right]^3\]

\[K_{section,B} = X_1 + X_2 \left[ \frac{d_2}{d_1} \right]^3\]

\[K_{section,V} = X_1\]

\(K_{section}\) is always <1 and applied assuming full panel depth of \(x_1\)

Example: 2x4 and 2x6 alternating lams

\[x_1 = x_2 = 0.5\]

\[K_{section,B} = 0.5 + 0.5 \left[ \frac{3.5}{5.5} \right]^3 = 0.63\]

See NLT Design & Construction Guide for Details
Cross-Laminated Timber
Cross Laminated Timber

Considerations:

• Large light-weight panels
• Dimensionally stable
• Precise CNC machining available
• Recognized by IBC
• Dual Directional span capabilities
• Often architecturally exposed
• Fast on-site construction
What is CLT?

3+ layers of laminations
Typically Solid Sawn Laminations
Cross-Laminated Layup
Glued with Structural Adhesives

*All dimensions are approximate. Consult with manufacturers.
First Tech Credit Union
Hillsboro, Oregon

Photo Credit: Structurlam Products
Building Code Acceptance of CLT

2015 International Building Code
North American CLT Product Standard

The Standard Covers:
- U.S. and Canada Use
- Panel Dimensions and Tolerances
- Component Requirements
- Structural Performance Requirements
- Panel and Manufacturing Qualification
- Marking (Stamping)
- Quality Assurance

ANSI/APA PRG 320 Standard for Performance-Rated Cross-Laminated Timber
## CLT Basic 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>E5</td>
<td>1650f-1.5E MSR Hem-Fir</td>
<td>#3 Hem-Fir</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>
<tr>
<td>V4</td>
<td>#2 Spruce Pine Fir (South)</td>
<td>#3 Spruce Pine Fir (South)</td>
</tr>
<tr>
<td>V5</td>
<td>#2 Hem-Fir</td>
<td>#3 Hem-Fir</td>
</tr>
</tbody>
</table>

Basic solid sawn CLT stress grade in PRG 320-2019.

Other custom stress grades including structural composite lumber (SCL) permitted.
Common CLT Layups

Most Designs
Least $/sf

3-ply 3-layer

5-ply 5-layer

7-ply 7-layer

9-ply 9-layer

7-ply 5-layer

9-ply 7-layer
### Table A2

**The Allowable Bending Capacities**

<table>
<thead>
<tr>
<th>CLT Grade</th>
<th>Lamination Thickness (in.) in CLT Layup</th>
<th>Major Strength Direction</th>
<th>Minor Strength Direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>E1</td>
<td>4 1/8 13/8 13/8 13/8 13/8 13/8 13/8</td>
<td>4,525 115 0.46 160 3.1 0.61</td>
<td>10,400 440 0.92 1,370 81 1.2</td>
</tr>
<tr>
<td></td>
<td>6 7/8 13/8 13/8 13/8 13/8 13/8 13/8</td>
<td>18,375 1,089 1.4 3,125 309 1.8</td>
<td></td>
</tr>
<tr>
<td></td>
<td>9 5/8 13/8 13/8 13/8 13/8 13/8 13/8 13/8</td>
<td>3,825 102 0.53 165 3.6 0.56</td>
<td></td>
</tr>
<tr>
<td>E2</td>
<td>4 1/8 13/8 13/8 13/8 13/8 13/8 13/8 13/8</td>
<td>8,825 389 1.1 1,430 95 1.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>6 7/8 13/8 13/8 13/8 13/8 13/8 13/8 13/8</td>
<td>15,600 963 1.6 3,275 360 1.7</td>
<td></td>
</tr>
<tr>
<td></td>
<td>9 5/8 13/8 13/8 13/8 13/8 13/8 13/8 13/8</td>
<td>11,325 769 1.0 2,180 232 1.3</td>
<td></td>
</tr>
<tr>
<td>E3</td>
<td>4 1/8 13/8 13/8 13/8 13/8 13/8 13/8 13/8</td>
<td>2,800 81 0.35 110 2.3 0.44</td>
<td></td>
</tr>
<tr>
<td></td>
<td>6 7/8 13/8 13/8 13/8 13/8 13/8 13/8 13/8</td>
<td>6,400 311 0.69 955 61 0.87</td>
<td></td>
</tr>
<tr>
<td></td>
<td>9 5/8 13/8 13/8 13/8 13/8 13/8 13/8 13/8</td>
<td>10,425 441 1.1 1,570 95 1.3</td>
<td></td>
</tr>
<tr>
<td>E4</td>
<td>4 1/8 13/8 13/8 13/8 13/8 13/8 13/8 13/8</td>
<td>4,525 115 0.53 180 3.6 0.63</td>
<td></td>
</tr>
<tr>
<td></td>
<td>6 7/8 13/8 13/8 13/8 13/8 13/8 13/8 13/8</td>
<td>10,425 441 1.1 1,570 95 1.3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>9 5/8 13/8 13/8 13/8 13/8 13/8 13/8 13/8</td>
<td>18,400 1,090 1.6 3,575 360 1.9</td>
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</tr>
<tr>
<td>E5</td>
<td>4 1/8 13/8 13/8 13/8 13/8 13/8 13/8 13/8</td>
<td>2,090 108 0.53 165 3.6 0.59</td>
<td></td>
</tr>
<tr>
<td>V1</td>
<td>6 7/8 13/8 13/8 13/8 13/8 13/8 13/8 13/8</td>
<td>4,800 415 1.1 1,430 95 1.2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>9 5/8 13/8 13/8 13/8 13/8 13/8 13/8 13/8</td>
<td>8,500 1,027 1.6 3,275 360 1.8</td>
<td></td>
</tr>
<tr>
<td>V2</td>
<td>4 1/8 13/8 13/8 13/8 13/8 13/8 13/8 13/8</td>
<td>2,030 95 0.46 160 3.1 0.52</td>
<td></td>
</tr>
<tr>
<td></td>
<td>6 7/8 13/8 13/8 13/8 13/8 13/8 13/8 13/8</td>
<td>4,675 363 0.91 1,370 81 1.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>9 5/8 13/8 13/8 13/8 13/8 13/8 13/8 13/8</td>
<td>9,275 397 1.4 3,195 203 1.6</td>
<td></td>
</tr>
</tbody>
</table>
3rd Party Product Qualification of CLT
### Table 1. Allowable Design Properties\(^{(a)}\) for Lumber Laminations Used in SmartLam CLT (for Use in the U.S.)

<table>
<thead>
<tr>
<th>CLT Grade</th>
<th>$F_{b,0}$ (psi)</th>
<th>$E_{20}$ (10^6 psi)</th>
<th>$F_{1,90}$ (psi)</th>
<th>$F_{v,90}$ (psi)</th>
<th>$F_{b,80}$ (psi)</th>
<th>$F_{v,80}$ (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SL-V4</td>
<td>775</td>
<td>1.1</td>
<td>350</td>
<td>1,000</td>
<td>135</td>
<td>45</td>
</tr>
</tbody>
</table>

For SL: $t = 0.006895$ MPa

\(^{(a)}\) Tabulated values are allowable design values and not permitted to be increased for the lumber flat use or size factor in accordance with the NDS. 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 Tables 2 and 3).

### Table 2. Allowable Design Capacities\(^{(a)}\) for SmartLam Balanced CLT (for Use in the U.S.)

<table>
<thead>
<tr>
<th>CLT Grade</th>
<th>Layup #</th>
<th>Thickness (in.)</th>
<th>Lamination Thickness (in.) in CLT Layup</th>
<th>Major Strength Direction</th>
<th>Minor Strength Direction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$F_{t,S,eff}$ (lb/ft)</td>
<td>$E_{l,b,90}$ (10^9 lb/ft²)</td>
</tr>
<tr>
<td>3-alt</td>
<td>4 1/8</td>
<td>13/8</td>
<td>13/8</td>
<td>1,800</td>
<td>74</td>
</tr>
<tr>
<td>4-maxx</td>
<td>5 1/2</td>
<td>13/8</td>
<td>13/8</td>
<td>2,925</td>
<td>161</td>
</tr>
<tr>
<td>5-alt</td>
<td>6 7/8</td>
<td>13/8</td>
<td>13/8</td>
<td>4,150</td>
<td>286</td>
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<tr>
<td>5-maxx</td>
<td>6 7/8</td>
<td>13/8</td>
<td>13/8</td>
<td>5,150</td>
<td>355</td>
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<td>6-maxx</td>
<td>8 1/4</td>
<td>13/8</td>
<td>13/8</td>
<td>7,200</td>
<td>596</td>
</tr>
<tr>
<td>7-alt</td>
<td>9 5/8</td>
<td>13/8</td>
<td>13/8</td>
<td>7,325</td>
<td>707</td>
</tr>
<tr>
<td>7-maxx</td>
<td>9 5/8</td>
<td>13/8</td>
<td>13/8</td>
<td>8,425</td>
<td>909</td>
</tr>
</tbody>
</table>
Structural Design Standardization

National Design Specification for Wood Construction
2015 & 2018 Edition
Model Building Code Acceptance

2015 International Building Code

Standard for Performance-Rated Cross-Laminated Timber

NDS®
National Design Specification® for Wood Construction
2015 EDITION
Highlights of CLT Provisions in IBC 2015

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

- IBC 2015 Chapter 6 Defines Dimensions of CLT to qualify as Heavy Timber (Type IV Construction)
  - 4” Interior walls
  - 4” Floors
  - 3” Roofs
  - Non Fire-Retardant Treated CLT allowed in Exterior Walls of Type IV construction in many conditions. (IBC 2015 602.4)
Flatwise Properties
FLATWISE Panel Loading

Span in **MAJOR** Strength Direction
“Parallel” Direction

Span in **MINOR** Strength Direction
“Perpendicular” Direction

Reference & Source: ANSI/APA PRG 320
EDGEWISE Panel Loading

Span in **MAJOR** Strength Direction

Span in **MINOR** Strength Direction

Reference & Source: ANSI/APA PRG 320
Design properties based on an 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 stress of outer lamination

Reference: NDS 2015
Flatwise Flexural Strength

Flexural Capacity Check (ASD)

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

per NDS

Commonly 1.0

Provided as combined value

\[
M_b \leq C_D (1.0) (F_b S_{\text{eff}})
\]

Reference: NDS 2015
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
- Analysis of a 1 ft strip of panel as beam

**Calculate ASD Applied Moment (1.0D + 1.0L)**

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

Look for Acceptable CLT Grade from PRG 320: \( F_{bs\text{eff},0} > 2560 \text{ lb-ft/ft} \)

<table>
<thead>
<tr>
<th>CLT Grade</th>
<th>CLT t (in.)</th>
<th>Lamination Thickness (in.) in CLT Layup</th>
<th>Major Strength Direction</th>
<th>Minor Strength Direction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>= ( \perp ) = ( \perp ) = ( \perp ) = ( \perp ) =</td>
<td>( F_{bs\text{eff},0} ) (lbf-ft/ft)</td>
<td>( EI_{eff,0} ) (10^6 lbf-in.^2/ft)</td>
<td>( GA_{eff,0} ) (10^4 lbf-in./ft)</td>
</tr>
<tr>
<td>4 1/8</td>
<td>13/8 13/8 13/8 13/8</td>
<td>2,090</td>
<td>108</td>
<td>0.53</td>
</tr>
<tr>
<td>V1</td>
<td>6 7/8 13/8 13/8 13/8 13/8</td>
<td>4,800</td>
<td>415</td>
<td>1.1</td>
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<tr>
<td>9 5/8</td>
<td>13/8 13/8 13/8 13/8 13/8 13/8 13/8</td>
<td>8,500</td>
<td>1,027</td>
<td>1.6</td>
</tr>
<tr>
<td>V2</td>
<td>6 7/8 13/8 13/8 13/8 13/8</td>
<td>4,675</td>
<td>363</td>
<td>0.91</td>
</tr>
<tr>
<td>9 5/8</td>
<td>13/8 13/8 13/8 13/8 13/8 13/8 13/8</td>
<td>8,275</td>
<td>898</td>
<td>1.4</td>
</tr>
</tbody>
</table>

Select 5-Ply 6 7/8” Thick V1 Panel with \( F_{bs\text{eff},0} = 4800 \text{ lb-ft/ft} \)

Reference: ANSI/APA PRG 320-2012
**Flatwise Flexural Strength Design Example**

**ASD Flexural Capacity:**
Dead + Live load, \( C_D = 1.0 \)

\[
(F_b S_{eff})' = C_D (1.0) (F_b S_{eff})
\]

\[
= 1.0 (1.0) (4800 \text{ lb-ft/ft})
\]

\[
= 4800 \text{ lb-ft/ft}
\]

\[
M_b = 2560 \text{ lb-ft/ft} \leq (F_b S_{eff})' = 4800 \text{ lb-ft/ft}
\]

**Flexural Strength OK**
Flatwise Shear Strength

Design Properties based on Extreme Fiber Model:

Shear Capacity Check:

\[ V_a \leq F_s \left( \frac{lb}{Q} \right)_{eff}' \]

\[ V_a = \text{applied shear} \]

\[ F_s \left( \frac{lbQ_{eff}}{} \right)' = \text{adjusted shear strength} \]

Reference: NDS 2015

Jargon Alert! AKA “Planar Shear”, “Out-of-Plane Shear”, or “Rolling Shear” Strength
Design Properties based on Extreme Fiber Model:

Shear Capacity Check (ASD):

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

Commonly 1.0 From Manufacturer

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

Note: Duration of Load Effects (Cd and \( \lambda \)) NOT applicable to Flatwise Shear Strength in the NDS

Reference: NDS 2015 & Product Reports
Flatwise Shear Strength

Rolling Shear

Source: CSA O86-14, 2016 Supplement
Flatwise Flexural Stiffness

Shear Analogy Method

\[(EI)_{\text{eff},0} = \sum_{i=1}^{n} E_i b_0 \frac{t_i^3}{12} + \sum_{i=1}^{n} E_i b_0 t_i z_i^2\]

\[S_{\text{eff},0} = \frac{(EI)_{\text{eff},0}}{E_{\text{major}}} \frac{2}{t_p}\]

Flatwise Flexural Stiffness

\[ (EI)_{\text{eff},0} = \sum_{i=1}^{n} E_i b_0 \frac{t_i^3}{12} + \sum_{i=1}^{n} E_i b_0 t_i z_i^2 \]

\[ (GA)_{\text{eff},0} = \frac{\left( t_p - \frac{t_1}{2} - \frac{t_n}{2} \right)^2}{\left( \frac{t_1}{2G_1 b_0} \right) + \left( \sum_{i=2}^{z-1} \frac{t_i}{G_i b_0} \right) + \left( \frac{t_n}{2G_n b_0} \right)} \]
Flatwise Flexural Stiffness

\[(EI)_{\text{eff},0} = \sum_{i=1}^{n} E_i b_0 \frac{t_i^3}{12} + \sum_{i=1}^{n} E_i b_0 t_i z_i^2\]

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

\[(GA)_{\text{eff},0} = \frac{\left(\frac{t_1}{2G_1b_0}\right) + \left(\sum_{i=2}^{n-1} \frac{t_i}{G_i b_0}\right) + \left(\frac{t_n}{2G_nb_0}\right)}{\left(\frac{t_1}{2G_1b_0}\right) + \left(\sum_{i=2}^{n-1} \frac{t_i}{G_i b_0}\right) + \left(\frac{t_n}{2G_nb_0}\right)}\]
Flatwise CLT Panel Section Properties

- Flexural Strength: $F_{bS_{\text{eff},0}}$  
- Flexural Stiffness: $E_{I_{\text{eff},0}}$  
- Shear Strength: $V_{s_{,0}}$  
- Shear Stiffness: $G_{A_{\text{eff},0}}$  
  
- Flexural Strength: $F_{bS_{\text{eff},90}}$  
- Flexural Stiffness: $E_{I_{\text{eff},90}}$  
- Shear Strength: $V_{s_{,90}}$  
- Shear Stiffness: $G_{A_{\text{eff},90}}$

Values in RED provided by CLT manufacturer

Reference: PRG 320 and CLT Product Reports
Deflection Calculations

General Purpose: 1 Way, Beam Action

Needed Stiffness: $E_{I_{eff,0}} \quad G_{A_{eff,0}}$

Can model multiple spans, cantilevers, etc.
Uniform loading on one way slab:
Beam Analysis using

- Flexural Stiffness: \( E_{\text{I,eff,0}} \)
- Shear Stiffness: \( \frac{5}{6} G A_{\text{eff,0}} \)

Maximum Deflection @ Mid-Span

\[
\Delta_{\text{max}} = \frac{5}{384} \cdot \frac{wL^4}{E_{I_{\text{eff}}}} + \frac{1}{8} \cdot \frac{wL^2}{5/6 G A_{\text{eff}}}
\]

From Manufacturer

**Flatwise Deflection Example**

\( w = 80 \text{ psf} \)

16 foot span
# Flatwise Deflection Example

For selected 6 7/8” 5-Ply V1, lookup major strength stiffness values

---

<table>
<thead>
<tr>
<th>CLT Grade</th>
<th>CLT $t$ (in.)</th>
<th>Major Strength Direction</th>
<th>Minor Strength Direction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Lamination Thickness (in.) in CLT Layup</td>
<td>$F_{S_{eff}}$ ($10^6$ lbf-in./ft)</td>
<td>$G_{A_{eff}}$ ($10^4$ lbf/ft$^2$)</td>
</tr>
<tr>
<td>4 1/8</td>
<td>1 3/8 1 3/8 1 3/8 1 3/8 1 3/8</td>
<td>2,090</td>
<td>108</td>
</tr>
<tr>
<td>V1</td>
<td>6 7/8 1 3/8 1 3/8 1 3/8 1 3/8 1 3/8</td>
<td>4,800</td>
<td>415</td>
</tr>
<tr>
<td></td>
<td>4 1/8 1 3/8 1 3/8 1 3/8</td>
<td>2,030</td>
<td>95</td>
</tr>
<tr>
<td>V2</td>
<td>6 7/8 1 3/8 1 3/8 1 3/8 1 3/8 1 3/8</td>
<td>4,675</td>
<td>363</td>
</tr>
</tbody>
</table>

**Reference:** ANSI/APA PRG 320-2012
Flatwise Deflection Example

Uniform loading on one way slab:
Beam Analysis using

**Flexural Stiffness:** \( \frac{5}{384} \cdot \frac{wL^4}{EI_{eff}} \)

**Shear Stiffness:** \( \frac{1}{8} \cdot \frac{wL^2}{5/6 \cdot GA_{eff}} \)

Maximum Deflection @ Mid-Span

\[
\Delta_{\text{max}} = \frac{5}{384} \cdot \frac{wL^4}{EI_{eff}} + \frac{1}{8} \cdot \frac{wL^2}{5/6 \cdot GA_{eff}}
\]

\[
= \frac{5}{385} \cdot \frac{80 \text{ psf} \ (16 \text{ ft})^4}{415 \times 10^6 \text{ lbf in}^2/\text{ft}} \cdot \left(\frac{12 \text{ in}}{1 \text{ ft}}\right)^3 + \frac{1}{8} \cdot \frac{80 \text{ psf} \ (16 \text{ ft})^2}{5/6 \cdot 1.1 \times 10^6 \text{ lbf/ft}} \cdot \frac{12 \text{ in}}{1 \text{ ft}}
\]

\[
= 0.284 \text{ in} + 0.034 \text{ in} = 0.318 \text{ in}
\]

\[
= \frac{L}{604}
\]

16 foot span

\( w = 80 \text{ psf} \)
Deflection Creep Factor

Deformation to Long Term Loads

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

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

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

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

Design Example:

\[ \Delta_{ST} \text{ from 40psf} = 0.159 \text{ in} \] (assuming long term = dead)

\[ \Delta_{LT} \text{ from 40psf} = 0.159 \text{ in} \]

\[ \Delta_T = 2.0 \times 0.159 + 0.159 = 0.477 \text{ in} \]

\[ = \frac{L}{403} \]

Reference: NDS 2015
Deflection Calculations

Simplified Beam Deflections:
For single span, simply supported uniform load

\[ \Delta_{max} = \frac{5}{384} \cdot \frac{wL^4}{EI_{eff}} + \frac{1}{8} \cdot \frac{wL^2}{5/6 \cdot G A_{eff}} \]

What is **Apparent** Flexural Stiffness, \( EI_{app} \), such that

\[ \Delta_{max} = \frac{5}{384} \cdot \frac{wL^4}{EI_{app}} \]

Set equal to each other and solve for \( EI_{app} \)

\[ EI_{app} = \frac{EI_{eff}}{1 + \frac{11.5EI_{eff}}{G A_{eff}L^2}} \]

Reference: US CLT Handbook & NDS
Deflection Calculations

General Purpose, 2 Way, Plate Action

Flexural Stiffness

\[ E I_{eff,0} \quad E I_{eff,90} \]

Shear Stiffness:

\[ \frac{5}{6} G A_{eff,0} \quad \frac{5}{6} G A_{eff,90} \]

5/6 from \( A' = 5/6 A \) shape factor for rectangular sections
 Possible, however not common.

Structural design issues include:
- Compression perp to grain at support points
- Bi-directional bending stress interactions
- Punching shear

Not covered in NDS
Using PRG 320 Standard Grades for Design?

PRG 320 includes pre-defined Stress Grades, Layups and related Design Properties.

Is doesn’t tell you what CLT grades and layups are available.

Coordinate with manufacturers availability and information.
Working with CLT: Know Your Supply Chain

- CLT Manufactures different CLT grades and maximum panel sizes
- CLT Manufacturers have specific CNC capabilities
- 3rd Party Fabricators can have additional CNC capabilities
Floor Vibration Design

“One might almost say that strength is essential and otherwise unimportant”

- Hardy Cross
US Building Code Requirements for Vibration

None

Barely discussed in IBC, NDS, etc.
ASCE 7 Commentary Appendix C has some discussion, no requirements
Vibrations vs Acoustics

**Structural Vibrations**
- 1 Hz – 100 Hz
- Transmitted through structure or through ground
- Physical effects

**Acoustic Vibrations**
- 20 Hz – 15,000 Hz
- Transmitted through air, walls, floors, windows
- Audible effects
Illustration: “Sven Jr.” by Sven-Olof Emanuelsson

Human Body Dynamics

- Shoulder Girdle (4-5 Hz)
- Lung Volume
- Lower Arm (30-40 Hz)
- Spinal Column (axial mode) (10-12 Hz)
- Chest Wall (50-100 Hz)
- Abdominal Mass (4-8 Hz)
- Seated Person
- Legs (variable from ca 2 Hz with knees flexing to over 20 Hz with rigid posture)
- Standing Person

Full Body
Vibration sources are complex:

- Footfall, running, aerobics, etc.
- Machinery and equipment
- Vehicular traffic, rail traffic, forklifts
- Ground-borne, structure-borne, air-borne
- Steady-state, episodic, periodic
- Harmonic, pulse, random
- Moving, stationary
Resonant vs Impulsive Response

Excitation Frequency not $\gg$ Natural Frequency
Excitation Creates Resonant Build-up of Vibration

Low Frequency Floor

$f_n \sim< 8 \text{ Hz}$  For Walking Excitation

Excitation Frequency $\gg$ Natural Frequency
Responses decays out between load cycles

High Frequency Floor

$f_n \sim> 8 \text{ Hz}$
<table>
<thead>
<tr>
<th>Material</th>
<th>Floor Weight (psf)</th>
<th>Damping</th>
<th>Material Stiffness ($10^6$ psi)</th>
<th>Material Mass (pcf)</th>
<th>Example Floor System</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete</td>
<td>100-150</td>
<td>1-5%</td>
<td>3.2-5.8</td>
<td>120-150</td>
<td>2-way slab on columns</td>
</tr>
<tr>
<td>Steel</td>
<td>50-100</td>
<td>0.5-5%</td>
<td>30</td>
<td>490</td>
<td>Concrete on metal deck on purlins and girders</td>
</tr>
<tr>
<td>Mass Timber</td>
<td>15-65</td>
<td>1-6%</td>
<td>1.2-1.8</td>
<td>30-40</td>
<td>Beam or wall supported</td>
</tr>
<tr>
<td>Wood Frame</td>
<td>10-40</td>
<td>2-12%</td>
<td>1.2-2.0</td>
<td>30-40</td>
<td>Wall supported</td>
</tr>
</tbody>
</table>
Beam vs Wall Supported Floors

Mass Timber Panels on Grid of Beams.
- Frequency of Floor < Frequency of Panel
- Vibration of Floor > Vibration of Panel
- Vibration Design Depends on Beams

Mass Timber Panels on Bearing Walls

Low Frequency Floor?
- Maybe

High Frequency Floor?
- At all but longer floor spans
Vibration Design Methods

Rules of Thumb
- $\Delta < L/480$
- $f_n > 14 \text{ Hz}$

Empirical Methods
- Woeste & Dolan

Simplified Analytical
- FPI/CLT Handbook

FEM/Modal

FEM/Time History

Wood Frame

Mass Timber

Steel
- AISC Design Guide 11
- CCIP 016
- SCI P354

Concrete
- CRI Design Guide 10

Steel

Concrete
Vibration Design Methods

Rules of Thumb
- \( \Delta < \frac{L}{480} \)
- \( f_n > 14 \text{ Hz} \)

Empirical Methods
- Woeste & Dolan

Simplified Analytical
- FPI/CLT Handbook

FEM/Modal

FEM/Time History

Wood Frame

Mass Timber

Steel
- AISC Design Guide 11
- CCIP 016
- SCI P354

Concrete
- CRSI Design Guide 10
Vibration Design Methods

- **Rules of Thumb**
  - $\Delta < \frac{L}{480}$
  - $f_n > 14$ Hz

- **Empirical Methods**
  - Woeste & Dolan

- **Simplified Analytical**
  - FPI/CLT Handbook

- **FEM/Modal**
  - Mass Timber Design Guide (in development)

- **FEM/Time History**
  - AISC Design Guide 11
  - CCIP 016
  - SCI P354
  - CRSI Design Guide 10

**Materials**
- **Wood Frame**
- **Mass Timber**
- **Steel**
- **Concrete**
One approach: US CLT Handbook, Chapter 7 (FPI Method)

Calculated natural frequency of simple span of bare CLT:

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

Where:

- \( EI_{app} \) = apparent stiffness for pinned supported, uniformly loaded, simple span (\( K_s = 11.5 \)) (lb-in\(^2\))
- \( \rho \) = specific gravity of the CLT
- \( A \) = the cross section area (thickness x 12 inches) (in\(^2\))

Reference: US CLT Handbook, Chapter 7
Floor Vibration-FPI Method

Limit CLT Floor Span such that

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

Based on:
- Un-topped CLT
- Single, Simple span
- Bearing wall supports.

Does not account for:
- Supporting beam flexibility
- Multi-span conditions
- Additional floor mass (topping slab, etc)

Reference: US CLT Handbook, Chapter 7
Floor Vibration-FPI Method

CLT Handbook, Chapter 7 Recommendations

Experimental Verification – Results

Research by Lin Hu, et al. at
# FPI Span Limit for Basic CLT Grades / Layups

<table>
<thead>
<tr>
<th>Grade</th>
<th>Layup</th>
<th>Thickness</th>
<th>FPI Span Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>E1</td>
<td>3ply</td>
<td>4 1/8&quot;</td>
<td>12' 5&quot;</td>
</tr>
<tr>
<td></td>
<td>5ply</td>
<td>6 7/8&quot;</td>
<td>17' 4&quot;</td>
</tr>
<tr>
<td></td>
<td>7ply</td>
<td>9 5/8&quot;</td>
<td>21' 8&quot;</td>
</tr>
<tr>
<td>E2</td>
<td>3ply</td>
<td>4 1/8&quot;</td>
<td>12' 0&quot;</td>
</tr>
<tr>
<td></td>
<td>5ply</td>
<td>6 7/8&quot;</td>
<td>16' 8&quot;</td>
</tr>
<tr>
<td></td>
<td>7ply</td>
<td>9 5/8&quot;</td>
<td>20' 10&quot;</td>
</tr>
<tr>
<td>E3</td>
<td>3ply</td>
<td>4 1/8&quot;</td>
<td>11' 7&quot;</td>
</tr>
<tr>
<td></td>
<td>5ply</td>
<td>6 7/8&quot;</td>
<td>16' 1&quot;</td>
</tr>
<tr>
<td></td>
<td>7ply</td>
<td>9 5/8&quot;</td>
<td>20' 1&quot;</td>
</tr>
<tr>
<td>E4</td>
<td>3ply</td>
<td>4 1/8&quot;</td>
<td>12' 2&quot;</td>
</tr>
<tr>
<td></td>
<td>5ply</td>
<td>6 7/8&quot;</td>
<td>17' 0&quot;</td>
</tr>
<tr>
<td></td>
<td>7ply</td>
<td>9 5/8&quot;</td>
<td>21' 3&quot;</td>
</tr>
</tbody>
</table>

### Approximate FPI Span Limits:
- **3-ply:** 11 to 12 ft
- **5-ply:** 16 to 17 ft
- **7-ply:** 20 to 21 ft

<table>
<thead>
<tr>
<th>Grade</th>
<th>Layup</th>
<th>Thickness</th>
<th>FPI Span Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>V1</td>
<td>3ply</td>
<td>4 1/8&quot;</td>
<td>12' 2&quot;</td>
</tr>
<tr>
<td></td>
<td>5ply</td>
<td>6 7/8&quot;</td>
<td>17' 0&quot;</td>
</tr>
<tr>
<td></td>
<td>7ply</td>
<td>9 5/8&quot;</td>
<td>21' 3&quot;</td>
</tr>
<tr>
<td>V2</td>
<td>3ply</td>
<td>4 1/8&quot;</td>
<td>11' 11&quot;</td>
</tr>
<tr>
<td></td>
<td>5ply</td>
<td>6 7/8&quot;</td>
<td>16' 8&quot;</td>
</tr>
<tr>
<td></td>
<td>7ply</td>
<td>9 5/8&quot;</td>
<td>20' 10&quot;</td>
</tr>
<tr>
<td>V3</td>
<td>3ply</td>
<td>4 1/8&quot;</td>
<td>12' 0&quot;</td>
</tr>
<tr>
<td></td>
<td>5ply</td>
<td>6 7/8&quot;</td>
<td>16' 9&quot;</td>
</tr>
<tr>
<td></td>
<td>7ply</td>
<td>9 5/8&quot;</td>
<td>21' 0&quot;</td>
</tr>
</tbody>
</table>

### Limitations:
- Does not account for strength or deflections
- Does not account for beam flexibility
- Does not account for project specifics
Experience shown it consistently produces well performing floors

Does not consider
- Multi-span panels
- Flexibility of supports, e.g. beams
- Impact of topping slabs

Recommend 20% increase in acceptable span length OK for multi-span panels with non-structural elements that are considered to provide an enhanced stiffening effect, including partition walls, finishes and ceilings, etc.
US Mass Timber Vibration Design Guide

USDA Wood Innovations Grant funded project in progress

Guide to be published by WoodWorks Later in 2020
Project Team: WoodWorks, KPFF, Aspect, StructureCraft, & Fast+Epp

US Mass Timber Floor Vibration Design Guide
Approximate Outline

1. Introduction
   1.1 Preface
   1.2 Scope of this Guide
   1.3 Terminology
   1.4 Symbols
   1.5 Vibration Characteristics of Floor Structures
   1.6 Building Codes and Standards

2. Understanding Floor Vibration
   2.1 Structural Response to Footfall Forces
   2.2 Vibration Background
   2.3 Methods for Evaluating Vibration
   2.4 Human Perception of Vibration

3. Vibration Design Considerations
   3.1 Floor Loading / Mass
   3.2 Damping
   3.3 Component Stiffness
   3.4 Composite Behavior
   3.5 Structural and Floor Configurations
   3.6 Excitation Parameters
   3.7 Floor Vibration Performance Targets
Preliminary Recommendations

Mass Timber Panels on Grid of Beams:
Modal Analysis based methods valid
- AISC Design Guide 11
- CCIP 0-16

Other Mass Timber Panels not covered

CLT Panels on Bearing Walls:
FPI Method simple to implement
Conservative for typical residential

Mass Timber Modeling Guidelines:
- Incidental composite action.

Graphic from ASPECT

Graphic from StructureCraft
Edgewise Structural Properties
Span in **MAJOR** Strength Direction

Span in **MINOR** Strength Direction

*Reference & Source: ANSI/APA PRG 320-2017*
Shear Force Terminology & Jargon

Through-the-Thickness Shear
In-plane Shear Forces
EDGEWISE Shear in PRG 320-2017

Source: ANSI/APA PRG 320-2017

NDS 2015: $F_v(t_v)$
PRG 320-2017: $F_{v,e,0} t_p \& F_{v,e,90} t_p$

Source: NDS 2015 Manual
CLT in Lateral Force Resisting Systems

CLT Panels have a significant in-plane shear strength.

TABLE 3—REFERENCE DESIGN VALUES FOR IN-PLANE SHEAR OF THE STRUCTURLAM CROSSLAM® CLT PANELS

<table>
<thead>
<tr>
<th>GRADE</th>
<th>LAYUP DESIGNATION</th>
<th>FACE LAMINATION ORIENTATION (psi)</th>
<th>=²</th>
<th>L²</th>
</tr>
</thead>
<tbody>
<tr>
<td>V2M1.1</td>
<td>105V</td>
<td>130</td>
<td>196</td>
<td></td>
</tr>
<tr>
<td></td>
<td>175V</td>
<td>180</td>
<td>195</td>
<td></td>
</tr>
<tr>
<td></td>
<td>245V</td>
<td>180²</td>
<td>195</td>
<td></td>
</tr>
<tr>
<td></td>
<td>315V</td>
<td>180²</td>
<td>195</td>
<td></td>
</tr>
</tbody>
</table>

Source: ICC-ES ESR 3631

~75 to 195+ PSI Allowable Edgewise Shear

~900 to 2300 PLF per Inch of Thickness.

Consult with the Manufacturers for Details

Table 3. Allowable In-Plane Shear (psi) for Nordic X-Lam² for use in the U.S.

<table>
<thead>
<tr>
<th>CLT Grade</th>
<th>Layup #</th>
<th>Thickness (in.)</th>
<th>Allowable In-Plane Shear Stress (psi), Fₛ, in-plane, with Face Lamination Orientation of =²</th>
<th>L²</th>
</tr>
</thead>
<tbody>
<tr>
<td>78-3s</td>
<td>3 1/8</td>
<td>105(²)</td>
<td>130(²)</td>
<td></td>
</tr>
<tr>
<td>89-3s</td>
<td>3 1/2</td>
<td>75</td>
<td>130(²)</td>
<td></td>
</tr>
<tr>
<td>105-3s</td>
<td>4 1/8</td>
<td>105(²)</td>
<td>130</td>
<td></td>
</tr>
<tr>
<td>131-5s</td>
<td>5 1/8</td>
<td>125(²)</td>
<td>150(²)</td>
<td></td>
</tr>
<tr>
<td>140-4s</td>
<td>5 1/2</td>
<td>105(²)</td>
<td>130(²)</td>
<td></td>
</tr>
<tr>
<td>143-5s</td>
<td>5 5/8</td>
<td>105(²)</td>
<td>150(²)</td>
<td></td>
</tr>
<tr>
<td>175-5s</td>
<td>6 7/8</td>
<td>125(²)</td>
<td>150(²)</td>
<td></td>
</tr>
<tr>
<td>197-7s</td>
<td>7 3/4</td>
<td>105(²)</td>
<td>150(²)</td>
<td></td>
</tr>
<tr>
<td>213-7l</td>
<td>8 3/8</td>
<td>125(²)</td>
<td>150(²)</td>
<td></td>
</tr>
<tr>
<td>220-7s</td>
<td>8 5/8</td>
<td>125(²)</td>
<td>150(²)</td>
<td></td>
</tr>
<tr>
<td>244-7s</td>
<td>9 5/8</td>
<td>125(²)</td>
<td>150(²)</td>
<td></td>
</tr>
<tr>
<td>244-7l</td>
<td>9 5/8</td>
<td>125(²)</td>
<td>150(²)</td>
<td></td>
</tr>
<tr>
<td>287-9l</td>
<td>10 1/2</td>
<td>105(²)</td>
<td>150(²)</td>
<td></td>
</tr>
<tr>
<td>314-9l</td>
<td>12 3/8</td>
<td>125(²)</td>
<td>150(²)</td>
<td></td>
</tr>
</tbody>
</table>

Source: APA Product Report PR-L306

Standard test method defined using ASTM D198
Connection Details
Connection Styles

Panel to Panel at floors, roofs or walls

Single Surface Spline

Half Lap
Simple connections with:

- Metal angles
- Self tapping Screws and Nails

Source: US CLT Handbook
Mass Timber Design

Connections

Long self tapping screws used extensively throughout mass timber construction

Photo Credit: Alex Schreyer
Proprietary Products

Variety of Self Tapping Screws
Proprietary Products

Source: Simpson Strong-Tie

Source: rothoblaas
Connectors for CLT in NDS 2015: Dowel Type Fasteners, e.g. Lag Screws, Bolts and Nails
Lateral Systems
Mass Timber Lateral Systems

Lateral Force Systems

Vertical Lateral/Seismic Force Resisting Systems
  - Code Recognized Seismic Force Resisting System

Horizontal Lateral/Seismic Force Resisting Systems
  - Innovative System via Alternative Means
Mass Timber Design

Lateral framing systems

Light-frame wood shearwalls

Photo Credit: woodworks
Mass Timber Design

Lateral framing systems

Central Core – concrete shearwalls

Photo Credit: structurecraft
Mass Timber Design

Lateral framing systems

Exterior steel moment frame

Photo Credit: woodworks
Mass Timber Design

Lateral framing systems

Steel Braced Frame

Photo Credit: john stamets
Tall Wood Structural Systems

Lateral Force Systems

Vertical Lateral/Seismic Force Resisting Systems

Horizontal Lateral/Seismic Force Resisting Systems

Code Recognized Seismic Force Resisting System

Innovative System via Alternative Means
Mass Timber Design
Lateral framing systems

Mass Timber Shearwalls
Photo Credit: alex schreyer
CLT Shear Wall Seismic Design Values

What R value can I use?
CLT Seismic Design

CLT Seismic Force Resisting Systems **Not** addressed in

ASCE/SEI 7-10 or 7/16

SDPWS 2015
Range of Possible Shear Wall Systems

Rocking Wall Systems \((R = \sim 6?\))

Ordinary Shear Walls \((R = \sim 1.5?\))
Cross-laminated timber (CLT) is an emerging wood product with applications in both residential and non-residential buildings. Oregon BCD has prepared this alternate method which recognizes nationally adopted acceptance of CLT in Type IV Construction through the International Codes Council process. This classification will allow roughly 50 percent taller and larger buildings than
### Table 12.2-1 Design Coefficients and Factors for Seismic Force-Resisting Systems

<table>
<thead>
<tr>
<th>Seismic Force-Resisting System</th>
<th>ASCE 7 Section Where Detailing Requirements Are Specified</th>
<th>Response Modification Coefficient, $R^a$</th>
<th>Overstrength Factor, $\Omega_k^b$</th>
<th>Deflection Amplification Factor, $C_d^b$</th>
<th>Structural System Limitations Including Structural Height, $h_s$ (ft) Limits$^c$</th>
<th>Seismic Design Category</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. BEARING WALL SYSTEMS</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15. Light-frame (wood) walls sheathed with wood structural panels rated for shear resistance</td>
<td>14.5</td>
<td>6 ½</td>
<td>3</td>
<td>4</td>
<td>NL</td>
<td>NL</td>
</tr>
<tr>
<td>19. Cross-laminated timber shear walls$^d$</td>
<td>14.1 and 14.5</td>
<td>2</td>
<td>2 ½</td>
<td>2</td>
<td>NL</td>
<td>NL</td>
</tr>
</tbody>
</table>
Platform Framed CLT Shear Walls

2021 SDPWS Update *In Process*
- Platform Frame CLT Shear Walls
- Prescribed nailed metal plate connectors
- Panel aspect ratio, h:b_p from 2:1 to 4:1

2022 ASCE 7 Update *In Process*
- Include Platform Frame CLT Shear Walls
- R = 3
- 65 ft height limit – all Seismic Design Categories

*Final contents subject to ongoing balloting
Platform Framed CLT Shear Walls

- **Top and Bottom of Wall Connector**: 0.105” A653 Grade 33 Steel
- **Panel to Panel Connector**: 0.105” A653 Grade 33 Steel

Shear Wall System

- (8) 16d Box nails
- (2) 5/8” bolts or lag screws
- (8) 16d Box nails each side
Innovative Systems

Cross-Laminated Timber Post-Tensioned Rocking Shear Walls
Mass timber design

Lateral framing systems

Timber braced frame

Photo Credit: alex schreyer
Mass Timber Lateral Systems

- Lateral Force Systems
  - Vertical Lateral/Seismic Force Resisting Systems
  - Horizontal Lateral/Seismic Force Resisting Systems
Pre-fabricated panels often pre-sheathed

Once installed, add splice strips, tape joint if applicable

NLT Diaphragm Design
NLT Diaphragm Design

Figure 4.7: Prefabricated Pre-sheathed Panels

Key
1. Field-installed Plywood/OSB
2. Plywood/OSB splice location with typical diaphragm nailing
3. Plywood/OSB splice location for high load diaphragm nailing
4. Shop-installed plywood/OSB diaphragm sheathing
5. Prefabricated NLT panel A
6. Prefabricated NLT panel B
7. NLT expansion gap location fire stopped as required
8. Self-tapping screw pairs crossing plywood/OSB splice location

Source: NLT Design & Construction Guide
Strength of CLT rarely governs.

Strength of Connections covered by NDS and Proprietary Fastener Evaluation Reports.
CLT Panels have a significant in-plane shear strength.

**TABLE 3—REFERENCE DESIGN VALUES FOR IN-PLANE SHEAR OF THE STRUCTURAL LAM CROSSLAM® CLT PANELS**

<table>
<thead>
<tr>
<th>CLT LAYUP</th>
<th>CLT PANEL THICKNESS DESIGNATION</th>
<th>FACE LAMINATION ORIENTATION</th>
<th>FACE LAMINATION ORIENTATION</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>(psi)</td>
<td>(lbf/ft of width)</td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>a</strong></td>
<td><strong>b</strong></td>
</tr>
<tr>
<td>V2M1</td>
<td>99 V</td>
<td>175°F</td>
<td>235°F</td>
</tr>
<tr>
<td></td>
<td>169 V</td>
<td>175°F</td>
<td>235°F</td>
</tr>
<tr>
<td></td>
<td>239 V</td>
<td>175°F</td>
<td>235°F</td>
</tr>
<tr>
<td></td>
<td>309 V</td>
<td>175°F</td>
<td>235°F</td>
</tr>
<tr>
<td>V2M1.1</td>
<td>105V</td>
<td>196°F</td>
<td>290°F</td>
</tr>
<tr>
<td></td>
<td>175V</td>
<td>270°F</td>
<td>23°F</td>
</tr>
<tr>
<td></td>
<td>245V</td>
<td>270°F</td>
<td>290°F</td>
</tr>
<tr>
<td></td>
<td>315V</td>
<td>270°F</td>
<td>290°F</td>
</tr>
</tbody>
</table>

Shear Stress for Nordic X-Lam® (For Use in the U.S.)

<table>
<thead>
<tr>
<th>ID</th>
<th>Thickness, ( t ) (in.)</th>
<th>( F_{W,L0} ) (psi)</th>
<th>( F_{W,A00} ) (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>s</td>
<td>3 1/8</td>
<td>155(b)</td>
<td>190(b)</td>
</tr>
<tr>
<td>s</td>
<td>3 1/2</td>
<td>155</td>
<td>190(b)</td>
</tr>
<tr>
<td>s</td>
<td>4 1/8</td>
<td>155</td>
<td>190</td>
</tr>
<tr>
<td>s</td>
<td>5 1/8</td>
<td>185(c)</td>
<td>215(c)</td>
</tr>
<tr>
<td>s</td>
<td>5 1/2</td>
<td>145</td>
<td>190(b)</td>
</tr>
<tr>
<td>s</td>
<td>5 5/8</td>
<td>185(c)</td>
<td>215(c)</td>
</tr>
<tr>
<td>s</td>
<td>6 7/8</td>
<td>185</td>
<td>215</td>
</tr>
<tr>
<td>s</td>
<td>7 3/4</td>
<td>155(b)</td>
<td>215(c)</td>
</tr>
<tr>
<td>s</td>
<td>8 3/8</td>
<td>185(c)</td>
<td>215(c)</td>
</tr>
<tr>
<td>s</td>
<td>8 5/8</td>
<td>185(c)</td>
<td>215(c)</td>
</tr>
<tr>
<td>s</td>
<td>9 5/8</td>
<td>185(c)</td>
<td>215(c)</td>
</tr>
<tr>
<td>s</td>
<td>9 5/8</td>
<td>185(c)</td>
<td>215(c)</td>
</tr>
<tr>
<td>s</td>
<td>10 1/2</td>
<td>155(b)</td>
<td>215(c)</td>
</tr>
<tr>
<td>s</td>
<td>12 3/8</td>
<td>185(c)</td>
<td>215(c)</td>
</tr>
</tbody>
</table>

Source: ICC-ES/APA Joint Evaluation Report ESR 3631

145 to 290 PSI Allowable Edgewise Shear  
= 1.7 to 3.5 kips/ft/in  
\( Cd = 1.6 \) for short term loading  
= 2.8 to 5.6 kips/ft length (ASD)  
per Inch of Thickness.

Source: APA Product Report PR-L306
CLT in Lateral Force Resisting Systems

CLT Panels have a significant in-plane shear strength.

<table>
<thead>
<tr>
<th>GRADE</th>
<th>LAYUP DESIGNATION</th>
<th>FACE LAMINATION ORIENTATION (psi)</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>105V</td>
<td>130</td>
<td>196</td>
<td></td>
</tr>
<tr>
<td>V2M1.1</td>
<td>175V</td>
<td>180</td>
<td>195</td>
<td></td>
</tr>
<tr>
<td></td>
<td>245V</td>
<td>180</td>
<td>195</td>
<td></td>
</tr>
<tr>
<td></td>
<td>315V</td>
<td>180</td>
<td>195</td>
<td></td>
</tr>
</tbody>
</table>

Source: ICC-ES ESR 3631

~75 to 195+ PSI Allowable Edgewise Shear

~900 to 2300 PLF per Inch of Thickness.

Consult with the Manufacturers for Details

Table 3. Allowable In-Plane Shear (psi) for Nordic X-Lam (for use in the U.S.)

<table>
<thead>
<tr>
<th>CLT Grade</th>
<th>Layup #</th>
<th>Thickness (in.)</th>
<th>Allowable In-Plane Shear Stress (psi), F_s, in-plane, with Face Lamination Orientation of E1</th>
</tr>
</thead>
<tbody>
<tr>
<td>78-3s</td>
<td>3 1/8</td>
<td>105</td>
<td>130</td>
</tr>
<tr>
<td>89-3s</td>
<td>3 1/2</td>
<td>75</td>
<td>130</td>
</tr>
<tr>
<td>105-3s</td>
<td>4 1/8</td>
<td>105</td>
<td>130</td>
</tr>
<tr>
<td>131-5s</td>
<td>5 1/8</td>
<td>125</td>
<td>150</td>
</tr>
<tr>
<td>140-4s</td>
<td>5 1/2</td>
<td>105</td>
<td>130</td>
</tr>
<tr>
<td>143-5s</td>
<td>5 5/8</td>
<td>105</td>
<td>150</td>
</tr>
<tr>
<td>175-5s</td>
<td>6 7/8</td>
<td>125</td>
<td>150</td>
</tr>
<tr>
<td>197-7s</td>
<td>7 3/4</td>
<td>105</td>
<td>150</td>
</tr>
<tr>
<td>213-7t</td>
<td>8 3/8</td>
<td>125</td>
<td>150</td>
</tr>
<tr>
<td>220-7s</td>
<td>8 5/8</td>
<td>125</td>
<td>150</td>
</tr>
<tr>
<td>244-7s</td>
<td>9 5/8</td>
<td>125</td>
<td>150</td>
</tr>
<tr>
<td>244-7t</td>
<td>9 5/8</td>
<td>125</td>
<td>150</td>
</tr>
<tr>
<td>267-9t</td>
<td>10 1/2</td>
<td>105</td>
<td>150</td>
</tr>
<tr>
<td>314-9t</td>
<td>12 3/8</td>
<td>125</td>
<td>150</td>
</tr>
</tbody>
</table>

Source: APA Product Report PR-L306

Standard test method defined using ASTM D198
Suggestions for CLT Diaphragm Design

Until CLT diaphragms are formally defined through a consensus standardization, following are suggestions when considering diaphragms with CLT through an alternative means and methods process.
CLT Diaphragm Design

- CLT diaphragms shall be designed in accordance with the principles of mechanics using fastener and member strength in accordance with the provisions of the NDS. (or proprietary connectors using 3rd party verified equivalence)

*Calculations per NDS, not capacity tables in SDPWS*
CLT Diaphragm Design *Suggestions*

- Diaphragm **shear connections** at CLT panel edges and diaphragm boundary connections shall be designed to ensure that the connection capacity is limited by fastener yielding in accordance with **Mode III** or **Mode IV** per NDS 12.3.1.

\[
Z'_C \geq E_h
\]

**Design capacity of connection (ductile mode governing)**

**Applied Seismic Forces**
Connection Yield Modes Per the NDS

Single Shear Connections

- Mode $I_m$
- Mode $I_s$
- Mode $II$
- Mode $III_m$
- Mode $III_s$
- Mode $IV$

Double Shear Connections

“m” denotes main member, “s” denotes side member
Conceptual Fastener Behavior

- Adhesive
- Screw in Tension
- Smooth Nail in Tension
- Screw or Nail in Shear
Well behaved seismic systems have ductile failure modes.
Connection Styles
An Efficient Panel to Panel Connection

Self-Tapping Screws as “erection bolts” @ 18” – 24” o.c

5 ½” to 6” plywood strip ¾” or 1” Thick

Nails at spacing required for shear transfer

Graphics: ASPECT Structural Engineers
Connection Styles

Panel to Beam Connection Styles

5/16"Øx12 5/8" ASSY 3.6 SCREWS @ 24" o.c.

CL OF BEAM

SIMPSON STRONG-TIE
SDWS22800 LOG

GLULAM BEAM
Fastener Vendor Design Support

Surface Splines

Table 1. Surface Spline Reference Design Values

<table>
<thead>
<tr>
<th>CLT Details</th>
<th>Spline Thickness</th>
<th>Dimensions</th>
<th>Bureau Details</th>
<th>Reference Design Values</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3/8 in.</td>
<td>3/8 in. x 3/8 in.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3/8 in.</td>
<td>5/6 in. x 3/8 in.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3/8 in.</td>
<td>1 in. x 3/8 in.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>5/8 in.</td>
<td>3/8 in. x 5/8 in.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>5/8 in.</td>
<td>1 in. x 5/8 in.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 1. Reference allowable load and slip modulus for SDWS Timber Screws (SDWS22060DB and SDWS22600DB) for CLT surface fastening with 1 1/8-in. APA rated Strand I-Floor wood structural panel, single-surface splines.

- CLT Wood Species Combination: Allowable load per Fastener (lb) | Fastener slip modulus (in/lbf)
- SPF | SPF-2
350 | 0.12

Notes:
1. Reference design values valid for allowable stress design in the USA for a single ASSY fastener connecting to the connection geometry and loading condition described on this page.
2. It is recommended to stagger the screws across the line of the joint, as illustrated in the left.
3. Listed reference lateral design values are only valid for ASSY Endfed and ASSY IN.
4. Fastener must be installed in pairs, one screw in each panel to transmit the load through the spline connection.
5. CLT panel ply thicknesses are assumed to be 1/8 in. (3 mm).
6. Listed reference lateral design values given are estimated by load direction factor C ≤ 0.5.

Figure 1: Typical end elevation - Single surface spline with 5-ply CLT panels, 1 1/8-in. spline (plywood spline)
Wood Solution Papers

Mass Timber Cost and Design Optimization Checklists
Guides coordination between designers and builders (GCS, construction managers, estimators, fabricators, installers, etc.) as they are estimating and making cost-related decisions on mass timber projects.

Fire Design of Mass Timber Members: Code Applications, Construction Types and Fire Ratings
Focuses on how to meet fire-resistance requirements in the IBC, including calculation and testing-based methods.
Companion piece to WoodWorks’ Inventory of Fire Resistance-Tested Mass Timber Assemblies.

Tall Wood Buildings in the 2021 IBC – Up to 18 Stories of Mass Timber
Summarizes the changes as well as the background and technical research that supported their adoption.

Acoustics and Mass Timber: Room-to-Room Noise Control
Emphasizing room-to-room noise control, this paper covers key aspects of mass timber acoustical design. Companion piece to WoodWorks’ Inventory of Mass Timber Acoustic Assemblies.
Additional Resources – WoodWorks.org

Inventory of Fire-Resistance Tested Mass timber Assemblies

<table>
<thead>
<tr>
<th>LT Grade</th>
<th>Fire Resistance Achieved (Hours)</th>
<th>Source</th>
<th>Testing Lab</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 1/2 Type X gypsum, 1 layer 5/8&quot; Type X gypsum, 3/4&quot; proprietary gypsum, over Mason</td>
<td>1 hour, Labeled, See Manufacturer</td>
<td>NRC Fire Laboratory</td>
<td>1 (Test 1)</td>
</tr>
<tr>
<td>2 1/2 Type X gypsum, 1 layer 5/8&quot; Type X gypsum, 3/4&quot; proprietary gypsum, over Mason</td>
<td>2 hours, Labeled, See Manufacturer</td>
<td>NRC Fire Laboratory</td>
<td>2 (Test 2)</td>
</tr>
<tr>
<td>2 1/2 Type X gypsum, 1 layer 5/8&quot; Type X gypsum, 3/4&quot; proprietary gypsum, over Mason</td>
<td>3 hours, Labeled, See Manufacturer</td>
<td>NRC Fire Laboratory</td>
<td>3 (Test 3)</td>
</tr>
</tbody>
</table>

WoodWorks has developed the following checklists to assist in the design and cost optimization of mass timber projects.

The design optimization checklists are intended for building designers (architects and engineers), but many of the topics should also be discussed with the fabricators and builders. The checklists are intended to provide a starting point for discussions and a framework for integrating new materials and technologies into existing building practices.
Inventory of Mass Timber Acoustic Assemblies

Table 1: CLT Floor Assemblies with Concrete/Gypsum Topping, Ceiling Side Exposed

<table>
<thead>
<tr>
<th>Acoustical Mat Product Between CLT and Topping</th>
<th>Finish Floor</th>
<th>STC</th>
<th>IIC</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPC</td>
<td>LF</td>
<td>65</td>
<td>45</td>
<td></td>
</tr>
<tr>
<td>Acoustic Fiberglass</td>
<td>LF</td>
<td>60</td>
<td>40</td>
<td></td>
</tr>
</tbody>
</table>

Acoustics and Mass Timber: Room-to-Room Noise Control

Tall Wood Buildings in the 2021 IBC
Up to 18 Stories of Mass Timber
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Questions?

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Links to online resources at www.woodworks.org: