STRUCTURAL DESIGN OF MASS TIMBER

A short primer on the basics of mass timber design

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President and CEO, KL&A Engineers and Builders

Disclaimer: This presentation was developed by a third party and is not funded by WoodWorks or the Softwood Lumber Board.
STRUCTURAL DESIGN OF MASS TIMBER

Outline

1. Materials
2. Gravity Load Design
3. Deflection and Vibration
4. Connections
5. Lateral Load Design
6. Fire Resistance
7. Constructability
MASS TIMBER MATERIALS
• IT’S MADE OF TREES
MASS TIMBER

WHAT IS IT?

• IT’S MADE OF TREES

• IT’S SOLID WOOD
  (BIG PIECES MADE OUT OF LITTLE PIECES)
• **IT’S MADE OF TREES**

• **IT’S SOLID WOOD (BIG PIECES MADE OUT OF LITTLE PIECES)**

• **IT’S FLAT PANELS (CLT, NLT, etc.)**

Images Source: Structurecraft
• IT’S MADE OF TREES

• IT’S SOLID WOOD (BIG PIECES MADE OUT OF LITTLE PIECES)

• IT’S FLAT PANELS (CLT, NLT, etc.)

• IT’S ALSO BEAMS AND COLUMNS
• IT’S MADE OF TREES
• IT’S SOLID WOOD (BIG PIECES MADE OUT OF LITTLE PIECES)
• IT’S FLAT PANELS (CLT, NLT, etc.)
• IT’S ALSO BEAMS AND COLUMNS
• IT’S PREFABRICATED
Cross Laminated Timber

Image Courtesy of Fast and Epp
Cross Laminated Timber

Image Courtesy of Fast and Epp

- Structurlam
- Nordic
- DR Johnson
- Smartlam
- Freres Lumber Co
- Katerra
- Vaagen Timber
- Kalesnikoff
- ...

Not a commodity!
Nail Laminated Timber
Dowel Laminated Timber

Design and Profile Guide

Dowel Laminated Timber
Mass Plywood Panel
GRAVITY DESIGN OF CLT
Strong Axis vs Weak Axis: CLT is Orthotropic
FLEXURAL STRENGTH

\[ M_b \leq C_D C_M C_t C_L (F_b S_{eff}) \]

Per NDS

Typically = 1

Provided as combined value by manufacturer

\[ M_b \leq C_D (F_b S_{eff}) \]
## FLEXURAL STRENGTH

### TABLE A2

**ASD REFERENCE DESIGN VALUES\(^a,b,c\) FOR CLT (FOR USE IN THE U.S.)**

<table>
<thead>
<tr>
<th>CLT Layup</th>
<th>CLT Thickness (in.) in CLT Layup</th>
<th>Major Strength Direction</th>
<th>Minor Strength Direction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(F_{ls, req}) (lbf-ft/ft of width)</td>
<td>((E)_{lw,req}) (10(^6) lbf-in./in.(^2) of width)</td>
<td>((G)_{lw,req}) (10(^6) lbf/ft of width)</td>
</tr>
<tr>
<td>-----------</td>
<td>----------------------------------</td>
<td>--------------------------</td>
<td>--------------------------</td>
</tr>
<tr>
<td>E1</td>
<td>4/8 1/4 1/8 1/4 1/8 1/4 1/8 1/4 1/8</td>
<td>4,525 115 0.46 1,430</td>
<td>160 3.1 0.61 495</td>
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<tr>
<td></td>
<td>6/8 1/8 1/8 1/8 1/8 1/8 1/8 1/8 1/8</td>
<td>10,400 440 0.92 1,970</td>
<td>1,370 81 1.2 1,430</td>
</tr>
<tr>
<td></td>
<td>9/8 1/8 1/8 1/8 1/8 1/8 1/8 1/8 1/8</td>
<td>18,375 1,089 1.4 2,490</td>
<td>3,125 309 1.8 1,960</td>
</tr>
<tr>
<td>E2</td>
<td>4/8 1/4 1/8 1/8 1/8 1/8 1/8 1/8 1/8</td>
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<td>165 3.6 0.56 660</td>
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<td>8,825 389 1.1 2,625</td>
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</tr>
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<td>9/8 1/8 1/8 1/8 1/8 1/8 1/8 1/8 1/8</td>
<td>15,600 963 1.6 3,325</td>
<td>3,275 360 1.7 2,625</td>
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<td>110 2.3 0.44 385</td>
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<td>6,400 311 0.69 1,530</td>
<td>955 61 0.87 1,110</td>
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<td>11,325 769 1.0 1,940</td>
<td>2,180 232 1.3 1,520</td>
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<tr>
<td>E4</td>
<td>4/8 1/4 1/8 1/8 1/8 1/8 1/8 1/8 1/8</td>
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<td>140 3.4 0.62 605</td>
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<td>10,400 440 1.0 2,410</td>
<td>1,230 88 1.2 1,750</td>
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<td>18,400 1,089 1.5 3,050</td>
<td>2,800 335 1.9 2,400</td>
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<td>4/8 1/4 1/8 1/8 1/8 1/8 1/8 1/8 1/8</td>
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</tr>
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<td>V2</td>
<td>4/8 1/4 1/8 1/8 1/8 1/8 1/8 1/8 1/8</td>
<td>2,030 95 0.46 1,430</td>
<td>160 3.1 0.52 495</td>
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<tr>
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<td>6/8 1/8 1/8 1/8 1/8 1/8 1/8 1/8 1/8</td>
<td>4,675 363 0.91 1,970</td>
<td>1,370 81 1.0 1,430</td>
</tr>
<tr>
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<td>9/8 1/8 1/8 1/8 1/8 1/8 1/8 1/8 1/8</td>
<td>8,275 898 1.4 2,490</td>
<td>3,125 309 1.6 1,960</td>
</tr>
<tr>
<td>V3</td>
<td>4/8 1/4 1/8 1/8 1/8 1/8 1/8 1/8 1/8</td>
<td>1,740 95 0.49 1,750</td>
<td>140 3.4 0.52 605</td>
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<td>6/8 1/8 1/8 1/8 1/8 1/8 1/8 1/8 1/8</td>
<td>4,000 363 0.98 2,420</td>
<td>1,230 88 1.0 1,750</td>
</tr>
<tr>
<td></td>
<td>9/8 1/8 1/8 1/8 1/8 1/8 1/8 1/8 1/8</td>
<td>7,100 899 1.5 3,050</td>
<td>2,800 335 1.6 2,400</td>
</tr>
</tbody>
</table>

For SI: 1 in. = 25.4 mm; 1 ft = 304.8 mm; 1 lbf = 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 layer arrangements in the layup.
c. Custom CLT layups that are not listed in this table shall be permitted in accordance with 7.2.1.
“Planar Shear” = “Out-of-plane Shear” = “Rolling Shear”
SHEAR STRENGTH

\[ V_{\text{planar}} \leq C_M C_t \left( F_s (I_b Q)_{\text{eff}} \right) = 1.0 \ V_s \]

Typically = 1

Provided as combined value by manufacturer

\[ V_{\text{planar}} \leq V_s \]
# SHEAR STRENGTH

## TABLE A2

**ASD Reference Design Values**<sup>a,b,c</sup> **for CLT (for use in the U.S.)**

<table>
<thead>
<tr>
<th>CLT Layup</th>
<th>CLT L, [in.]</th>
<th>Lamination Thickness (in.) in CLT Layup</th>
<th>( \frac{F_{st, in.}}{I_{el, 100}} ) (lb-ft/ft of width)</th>
<th>( \frac{E_{el, 100}}{10^3 \text{ lb-lbf} \cdot \text{in.}^2/\text{ft of width}} )</th>
<th>( \frac{G_{el, in.}}{10^3 \text{ lb-lbf} \cdot \text{ft of width}} )</th>
<th>( V_{s,0} ) (lb/ft of width)</th>
<th>( \frac{F_{st, in.}}{I_{el, 100}} ) (lb-ft/ft of width)</th>
<th>( \frac{E_{el, 100}}{10^3 \text{ lb-lbf} \cdot \text{in.}^2/\text{ft of width}} )</th>
<th>( \frac{G_{el, in.}}{10^3 \text{ lb-lbf} \cdot \text{ft of width}} )</th>
<th>( V_{s,90} ) (lb/ft of width)</th>
</tr>
</thead>
<tbody>
<tr>
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<td>13/8</td>
<td>13/8</td>
<td>13/8</td>
<td>13/8</td>
<td>13/8</td>
<td>4,525</td>
<td>115</td>
<td>0.46</td>
<td>1,430</td>
<td>160</td>
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<tr>
<td>E1</td>
<td>6 7/8</td>
<td>13/8</td>
<td>13/8</td>
<td>13/8</td>
<td>13/8</td>
<td>13/8</td>
<td>18,375</td>
<td>1,089</td>
<td>1.4</td>
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<td>13/8</td>
<td>13/8</td>
<td>8,825</td>
<td>389</td>
<td>1.1</td>
<td>2,625</td>
</tr>
<tr>
<td>E2</td>
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<td>13/8</td>
<td>13/8</td>
<td>13/8</td>
<td>13/8</td>
<td>13/8</td>
<td>15,600</td>
<td>963</td>
<td>1.6</td>
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<td>13/8</td>
<td>2,800</td>
<td>81</td>
<td>0.35</td>
<td>1,110</td>
</tr>
<tr>
<td>E3</td>
<td>6 7/8</td>
<td>13/8</td>
<td>13/8</td>
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<td>13/8</td>
<td>13/8</td>
<td>6,400</td>
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<td>1,530</td>
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<td>13/8</td>
<td>13/8</td>
<td>13/8</td>
<td>13/8</td>
<td>13/8</td>
<td>11,325</td>
<td>769</td>
<td>1.0</td>
<td>1,940</td>
</tr>
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<td>13/8</td>
<td>13/8</td>
<td>13/8</td>
<td>13/8</td>
<td>10,400</td>
<td>440</td>
<td>1.0</td>
<td>2,410</td>
</tr>
<tr>
<td>V1</td>
<td>4 1/8</td>
<td>13/8</td>
<td>13/8</td>
<td>13/8</td>
<td>13/8</td>
<td>13/8</td>
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<td>13/8</td>
<td>13/8</td>
<td>13/8</td>
<td>13/8</td>
<td>13/8</td>
<td>13/8</td>
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<td>1.6</td>
<td>3,325</td>
</tr>
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<td>13/8</td>
<td>13/8</td>
<td>13/8</td>
<td>13/8</td>
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<td>13/8</td>
<td>2,030</td>
<td>95</td>
<td>0.46</td>
<td>1,430</td>
</tr>
<tr>
<td>V2</td>
<td>6 7/8</td>
<td>13/8</td>
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<td>13/8</td>
<td>7,100</td>
<td>899</td>
<td>1.5</td>
<td>3,050</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 layer arrangements in the layup.
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FLEXURE AND SHEAR DISFORMATIONS

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

\[
(GA)_{\text{eff,0}} = \frac{\left( t_p - \frac{t_i}{2} - \frac{t_n}{2} \right)^2}{\left[ \left( \frac{t_i}{2G_i b_0} \right) + \left( \sum_{i=2}^{n-1} \frac{t_i}{G_i b_0} \right) + \left( \frac{t_n}{2G_n b_0} \right) \right]}
\]
## FLEXURE AND SHEAR DEFORMATIONS

### TABLE A2

**ASD Reference Design Values** for CLT (For Use in the U.S.)

<table>
<thead>
<tr>
<th>Lamination Thickness (in.) in CLT Layup</th>
<th>Major Strength Direction</th>
<th>Minor Strength Direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>CLT Layup</td>
<td>$F_{S,5,LEO}$ (lbf-ft/ft of width)</td>
<td>$(E)_{lol,LEO}$ (10^9 lbf/in.²/ft of width)</td>
</tr>
<tr>
<td>----------</td>
<td>---------------------------------</td>
<td>---------------------------------</td>
</tr>
<tr>
<td>4 1/8</td>
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</tr>
<tr>
<td>E1</td>
<td>10,400</td>
<td>440</td>
</tr>
<tr>
<td>6 7/8</td>
<td>18,375</td>
<td>1,089</td>
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<tr>
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<td>389</td>
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<td>9 5/8</td>
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</tbody>
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c. Custom CLT layups that are not listed in this table shall be permitted in accordance with 7.2.1.
FLEXURE AND SHEAR DEFORMATIONS

Example:

Short-term mid-span deflection of a uniformly loaded one-way slab

\[ \Delta_{ST} = \frac{5}{384} \cdot \frac{wL^4}{E I_{eff}} + \frac{1}{8} \cdot \frac{wL^2}{5/6 G A_{eff}} \]
FLEXURE AND SHEAR DEFORMATIONS

Example:

**Short-term** mid-span deflection of a uniformly loaded one-way slab

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

**Long-term** deflection

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

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

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

\[
K_{cr} \quad \text{Creep factor for CLT = 2.0 for dry service conditions}
\]
PROPERTIES FOR STRENGTH AND DEFORMATION

Flexural Strength: $F_b S_{\text{eff},0}$
Flexural Stiffness: $E I_{\text{eff},0}$
Shear Strength: $V_s,0$
Shear Stiffness: $G A_{\text{eff},0}$

Values in RED provided by CLT manufacturer

Major Axis
Minor Axis
DESIGN FOR VIBRATION
U.S. Building Code Requirements for Vibration: NONE

Barely discussed in IBC, NDS, etc.
ASCE 7 Commentary Appendix C has some discussion, no requirements
Floor Vibration Design Methods

Rules of Thumb

Empirical Methods

Simplified Analytical

FEM/Modal

FEM/Time History

\[ \Delta < L/480 \]

\[ f_n > 14 \text{ Hz} \]

FPI / CLT Handbook


AISC Design Guide 11 (Steel)

SCI P354 (Steel)

CCIP 016 (Concrete)

CRSI Design Guide 10 (Concrete)

Slide content by Scott Breneman and WoodWorks
One possible approach to vibration analysis:
U.S. CLT Handbook, Chapter 7 (FPI Method)

Limit CLT Floor Span such that:

\[
\text{Span } L \leq \frac{1}{12.05} \frac{(EI_{app})^{0.293}}{(\rho A)^{0.122}}
\]

Based on:
• Un-topped CLT
• Single, simple span
• Bearing wall supports
FPI Span Limits for Basic CLT Grades / Layups

Approximate rules of thumb based on FPI Span Limits:
- 3-ply: 11 to 12 ft
- 5-ply: 16 to 17 ft
- 7-ply: 20 to 21 ft

These span limits do not account for:
- Strength or deflection limits
- Effect of beam flexibility on vibration
- Effect of panel continuity on vibration

<table>
<thead>
<tr>
<th>Grade</th>
<th>Layup</th>
<th>Thickness</th>
<th>FPI Span Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>V1</td>
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<td>12' 2&quot;</td>
</tr>
<tr>
<td></td>
<td>5ply</td>
<td>6 7/8&quot;</td>
<td>17' 0&quot;</td>
</tr>
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<td></td>
<td>7ply</td>
<td>9 5/8&quot;</td>
<td>21' 3&quot;</td>
</tr>
<tr>
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<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>
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<table>
<thead>
<tr>
<th>Grade</th>
<th>Layup</th>
<th>Thickness</th>
<th>FPI Span Limit</th>
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<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>
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<td>5ply</td>
<td>6 7/8&quot;</td>
<td>16' 8&quot;</td>
</tr>
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<td>7ply</td>
<td>9 5/8&quot;</td>
<td>20' 10&quot;</td>
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<td>3ply</td>
<td>4 1/8&quot;</td>
<td>11' 7&quot;</td>
</tr>
<tr>
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<td>6 7/8&quot;</td>
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<tr>
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<td>7ply</td>
<td>9 5/8&quot;</td>
<td>20' 1&quot;</td>
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<tr>
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<td>3ply</td>
<td>4 1/8&quot;</td>
<td>12' 2&quot;</td>
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<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>
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</table>
Long self-tapping screws used extensively in mass timber construction
Connection “Classes”

Simple Bearing

Custom Steel

Proprietary - Exposed

Proprietary - Concealed
Panel to beam connections

Photo Credit: myticon
Simple bearing with screws
Connection Considerations For Mass Timber

High Loads
Connection Considerations For Mass Timber

High Loads Parallel to Grain
Connection Considerations For Mass Timber

Aesthetics
Connection Considerations For Mass Timber

Shrinkage
Connection Considerations For Mass Timber

Fire Ratings
CLT SHEAR WALLS
3-Story, small building maxed out potential of rigid CLT shear walls.

Next step: rocking walls
Significant Hold-down Forces
CLT DIAPHRAGMS
CLT Diaphragm design not yet codified

Strength of CLT rarely governs.

Strength of Connections covered by NDS and Proprietary Fastener Evaluation Reports

Slide content by Scott Breneman and WoodWorks
**Suggestion:** Diaphragm shear connections at CLT panel edges and diaphragm boundary connections should be designed to ensure that the connection capacity is limited by ductile fastener yielding in accordance with **Mode III** or **Mode IV** per NDS 12.3.1.
**Suggestion:** Diaphragm shear connections at CLT panel edges and diaphragm boundary connections should be designed to ensure that the connection capacity is limited by ductile fastener yielding in accordance with **Mode III** or **Mode IV** per NDS 12.3.1
Half-lap Panel-Panel Connection

TOLERANCE GAP

FULLY THREADED TIMBER SCREW FOR SHEAR REINFORCEMENT ONLY

PARTIALLY THREADED TIMBER SCREW

TOLERANCE GAP

Image: Structurlam
Spline Panel-Panel Connection
NAILED SPLINE CONNECTION AT CLT DIAPHRAGM

<table>
<thead>
<tr>
<th>Spline Thickness</th>
<th>10d 6&quot;o.c.</th>
<th>10d 4&quot;o.c.</th>
<th>10d 2 1/2&quot;o.c.</th>
<th>2 rows 10d 4&quot;o.c.</th>
<th>2 rows 10d 2 1/2&quot;o.c.</th>
</tr>
</thead>
<tbody>
<tr>
<td>19/32&quot;</td>
<td>505</td>
<td>672</td>
<td>1007</td>
<td>995</td>
<td>1427</td>
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<tr>
<td>23/32&quot;</td>
<td>360</td>
<td>480</td>
<td>720</td>
<td>710</td>
<td>1020</td>
</tr>
</tbody>
</table>

**Wind**

**Seismic**
Diaphragm chords and collectors
FIRE RESISTANCE
Mass timber requires design for fire rated assemblies.

Mass wood has inherent fire resistant rating.
MT Fire Resistance Ratings (FRR)

NDS Chapter 16 addresses FRR of NLT, CLT, Glulam, Solid Sawn and SCL wood products

\[ \beta_{\text{eff}} = \frac{1.2\beta_n}{t^{0.187}} \]

**Table 16.2.1B Effective Char Depths (for CLT with \( \beta_n = 1.5\) in./hr.)**

<table>
<thead>
<tr>
<th>Required Fire Endurance (hr.)</th>
<th>5/8</th>
<th>3/4</th>
<th>7/8</th>
<th>1</th>
<th>1-1/4</th>
<th>1-3/8</th>
<th>1-1/2</th>
<th>1-3/4</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-Hour</td>
<td>2.2</td>
<td>2.2</td>
<td>2.1</td>
<td>2.0</td>
<td>2.0</td>
<td>1.9</td>
<td>1.8</td>
<td>1.8</td>
<td>1.8</td>
</tr>
<tr>
<td>1½-Hour</td>
<td>3.4</td>
<td>3.2</td>
<td>3.1</td>
<td>3.0</td>
<td>2.9</td>
<td>2.8</td>
<td>2.8</td>
<td>2.8</td>
<td>2.6</td>
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<tr>
<td>2-Hour</td>
<td>4.4</td>
<td>4.3</td>
<td>4.1</td>
<td>4.0</td>
<td>3.9</td>
<td>3.8</td>
<td>3.6</td>
<td>3.6</td>
<td>3.6</td>
</tr>
</tbody>
</table>
MT Fire Resistance Ratings (FRR)

IBC 722.7
The fire resistance rating of the mass timber elements shall consist of the fire resistance of the unprotected element (MT) added to the protection time of the noncombustible (NC) protection
DU Burwell Center for Career Achievement, Denver, Colorado

Not fire protected
Provide (3) 1/2" welded threaded stud centered on cap E.

GROUT SPACE REQUIRED BETWEEN COLUMN BEARING E AND STANDOFF CAP E.

1 1/2" washer stack at ea. epoxied rod.

EPOXIED RODS RE: TIMBER SUPPLIER
COLUMN BEARING E 1/8" x 10" x 1/2" x 3".
PROVIDE OVERSIZED HOLE FOR THREADED STUB. PROVIDE HOLE FOR EPOXIED RODS.
STANDOFF CAP E 1 1/4" x 15" x 1/2" x 3".

EMBED 3/4" threaded rods at 1/16" gauge.

CONC SLAB RE: PLAN

NOTE AT GRID HL INCREASE EMBED E AND CAP E SIZE TO 1 1/4" x 15" x 1/2" x 3".
INCREASE BEARING E TO 1/8" x 15" x 1/2" x 3".
CONCLUSIONS
CONCLUSIONS

1. Materials
   - Are not commodities
2. Gravity Load Design
   - For strength rarely governs
3. Deflection and Vibration
   - Often govern floor design
4. Connections
   - Are cost drivers
5. Lateral Load Design
   - Is still evolving in the code
6. Fire Resistance
   - Is part of structural design
7. Constructability
   - Is key to economy
QUESTIONS?

Greg Kingsley
KL&A Engineers and Builders
gkingsley@klaa.com