6.1 Overview - Cross-Laminated Timber (CLT) Shear Wall Example

- This example features the seismic design of cross-laminated timber shear walls used in a three-story, six-unit townhouse cross-laminated timber building of platform construction.

- The CLT shear wall design in this example includes:
  - Check of CLT shear wall shear strength
  - Check of CLT shear wall hold-down size and compression zone length for overturning
  - Check of CLT shear wall deflection for conformance to seismic drift
6.1 Overview - Useful Design Aid Resources

- The following documents are used in this example
  - ASCE/SEI 7-22 Minimum Design Loads and Associated Criteria for Buildings and Other Structures

6.2 Background

- NEHRP (2020a) proposed additions for ASCE/SEI 7-22 Table 12.2-1 featuring cross-laminated timber (CLT) shear walls

<table>
<thead>
<tr>
<th>Seismic Force-Resisting System</th>
<th>Detailing Requirements, ASCE/SEI 7-22 Section</th>
<th>R</th>
<th>Ω₀</th>
<th>C₂</th>
<th>Structural System Limitations Including Structural Height, $h_s$ (ft) Limits*</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>A. BEARING WALL SYSTEMS</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Structural Height, $h_s$ (ft) Limits*</td>
</tr>
<tr>
<td>Cross laminated timber shear</td>
<td>14.5</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>65</td>
</tr>
<tr>
<td>walls</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Structural System Limitations Including Structural Height, $h_s$ (ft) Limits*</td>
</tr>
<tr>
<td>Cross laminated timber shear</td>
<td>14.5</td>
<td>4</td>
<td>3</td>
<td>4</td>
<td>65</td>
</tr>
<tr>
<td>walls with shear resistance provided by high aspect ratio panels only</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Structural System Limitations Including Structural Height, $h_s$ (ft) Limits*</td>
</tr>
</tbody>
</table>
6.2 Background

- Cross-laminated timber (CLT)
  - Usually 3, 5 or 7 layers of dimension lumber stacked in alternating directions and bonded together with adhesive
  - Research and development for CLT began in the early 1990s in Europe
  - The first production facilities established in 1994 in Austria, Germany and Switzerland
  - The term coined in 2000 at the COST E5 conference in Italy

CLT panel with layers stacked in alternating (crossing) directions

6.2 Background

- Cross-laminated timber (CLT)
  - Stadthaus, London, 2009
  - Residential
  - 9 stories
  - 9 weeks of CLT construction
  - 4 laborers
  - 1 supervisor

Photo credit: Will Pryce

Federal Emergency Management Agency
6.2 Background

Photo credit: Will Pryce

FEMA

Building Seismic Safety Council

Federal Emergency Management Agency
6.2 Background

Ft. Drum, NY (4-story), 2017; Courtesy Jeff Morrow, Lendlease

- FEMA P-695: Quantification of Building Seismic Performance Factors
  - Peer review throughout
  - Archetypes
  - Design methodology
  - Nonlinear time history analysis
  - Performance evaluation (CMR & ACMR)
6.2 Background

![Force vs Displacement Graph](image1)

Note: Scaled results

![Construction Site](image2)

Federal Emergency Management Agency
6.2 Background
6.3 Cross-Laminated Timber Shear Wall Example Description

- A three-story, six-unit townhouse cross-laminated timber building of platform construction
- The CLT shear wall design in this example includes:
  - Check of CLT shear wall shear strength
  - Check of CLT shear wall hold-down size and compression zone length for overturning
  - Check of CLT shear wall deflection for conformance to seismic drift

Table 6-1: Weights of Roof/Ceiling, Floors, and Walls

<table>
<thead>
<tr>
<th>Item</th>
<th>Description</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roof/Ceiling</td>
<td>Light-frame roof, gypsum board ceiling, roofing, insulation</td>
<td>25 psf</td>
</tr>
<tr>
<td>Floor</td>
<td>5-layer CLT (6.875 in. thick), gypsum board ceiling, flooring. Includes 8 psf of floor area for wall partitions</td>
<td>35 psf</td>
</tr>
<tr>
<td>Interior Walls</td>
<td>3-layer CLT (4.125 in. thick), light-frame wall, gypsum board finish, sound insulation</td>
<td>20 psf</td>
</tr>
<tr>
<td>Exterior Walls</td>
<td>3-layer CLT (4.125 in. thick), light-frame wall, gypsum board interior finish, stucco exterior, insulation</td>
<td>30 psf</td>
</tr>
</tbody>
</table>
6.3 Cross-Laminated Timber Shear Wall Example Description

Table 6-3: Design Coefficients and Factors for CLT Seismic Force-Resisting Systems (ASCE/SEI 7-22)

<table>
<thead>
<tr>
<th>Seismic Force-Resisting System</th>
<th>Detailing Requirements, ASCE/SEI 7-22 Section</th>
<th>R</th>
<th>Ω₀</th>
<th>C₄</th>
<th>Structural Height, hₑ, Limit Seismic Design Category B, C, D, E &amp; F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cross-laminated timber shear walls</td>
<td>14.5</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>65 feet</td>
</tr>
<tr>
<td>Cross-laminated timber shear walls with shear resistance provided by high aspect ratio panels only</td>
<td>14.5</td>
<td>4</td>
<td>3</td>
<td>4</td>
<td>65 feet</td>
</tr>
</tbody>
</table>

6.4 Seismic Forces

- Seismic base shear calculation assumptions:
  - $S_{DS} = 1.0$
  - $I_0 = 1.0$
  - $R = 3$ (for CLT shear walls)

- Seismic base shear, $V$, per ASCE/SEI 7-22 Equation 12.8-2 (for short-period structures):
  $$V = C_v W = \frac{S_{DS}}{R/I} W = \frac{1.0}{(3.0/1.0)} W = 0.333 W \text{ kips}$$

- The portion of base shear tributary to the CLT shear walls of interest is:
  $$V_{(Line\ 4)} = 42.3 \text{ kips}$$
6.4 Seismic Forces

Table 6-4: Summary of Cumulative Lateral Seismic Force and Unit Shear Force per Story (Along Line 4)

<table>
<thead>
<tr>
<th>Story</th>
<th>Lateral force, (V_x) (kips)</th>
<th>Unit Shear Force per Foot of Shear Wall Length (plf)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>15.9</td>
<td>477</td>
</tr>
<tr>
<td>2</td>
<td>33.5</td>
<td>1,009</td>
</tr>
<tr>
<td>1</td>
<td>42.3</td>
<td>1,273</td>
</tr>
</tbody>
</table>

\[ V_{\text{Line 4}} = 42.3 \text{ kips} \]

Figure 6-4. Vertical Distribution of Seismic Force and Dead Load Tributary to the CLT Shear Walls Located Along Line 4

6.5.1 Shear Capacity of Prescribed Connectors

- LRFD design unit shear capacity for seismic:
  \[ v_{s(\text{seismic})} = \phi(n) \left( \frac{2605}{b_s} \right) C_G \]  
  (SDPWS-21 Eq. B-2)

where:
- \(n\) = number of angle connectors along bottom of panel face
- 2,605 = connector nominal shear capacity (lb)
- \(b_s\) = individual CLT panel length (ft)
- \(C_G\) = CLT panel specific gravity factor which equals 1.0 for \(G \geq 0.42\) specific gravity panels used in this example, and
- \(\phi\) = resistance factor equal to 0.5 for seismic design
6.5.1 Shear Capacity of Prescribed Connectors

Table 6-5: CLT Shear Wall Connectors and LRFD Design Unit Shear Capacity

<table>
<thead>
<tr>
<th>Story</th>
<th>Panel thickness (in.)</th>
<th>Panel length, b_s (ft)</th>
<th>Panel height, h (ft)</th>
<th>Number of connectors per panel at top and bottom panel edge (n)</th>
<th>Number of connectors at each adjoining vertical panel edge (n x h/b_s)</th>
<th>Nominal unit shear capacity, V_n = (n x 2605)/b_s (plf)</th>
<th>Seismic design unit shear capacity, V_s (plf)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>4.125</td>
<td>4.75</td>
<td>9.5</td>
<td>2</td>
<td>4</td>
<td>1,096</td>
<td>548</td>
</tr>
<tr>
<td>2</td>
<td>4.125</td>
<td>4.75</td>
<td>9.5</td>
<td>4</td>
<td>8</td>
<td>2,193</td>
<td>1,097</td>
</tr>
<tr>
<td>1</td>
<td>4.125</td>
<td>4.75</td>
<td>9.5</td>
<td>5</td>
<td>10</td>
<td>2,742</td>
<td>1,371</td>
</tr>
</tbody>
</table>

Figure 6-5. CLT Shear Walls at 1st, 2nd, and 3rd Story with Connector And Hold-down Location

Figure 6-6. Wall-floor Intersections
6.5.2 Shear Capacity of CLT Panel

- For this 3-layer E1 grade CLT panel, the allowable stress design (ASD) in-plane shear unit shear capacity is converted to LRFD using NDS-2018 Table 10.3.1:

\[ \nu'_v = \phi \lambda \kappa_f F_v(t_v) = 0.75(1.0)(2.88)(9,700) = 20,849 \text{ plf} \]

where:

- \( F_v(t_v) = 9,700 \text{ plf} \) (ASD value from CLT panel manufacturer’s evaluation report)
- CLT panel in-plane unit shear capacity, \( \nu'_v = 20,849 \text{ plf} \) is greater than the largest unit shear force story demand of 1,273 plf (from Table 6-4)

\[ 20,849 \text{ plf} \gg 1,273 \text{ plf} \]
- In-plane unit shear capacity value does not account for holes, cuts or other modifications

---

6.6.1 CLT Shear Wall Hold-down Design

- Figure 6-1. Illustration of Rocking Behavior of Seven Individual Panels in A Multi-panel CLT Shear Wall Designed in Accordance with SDPWS-21 Appendix B
- Figure 6-7. Free-body Diagram for the Tension End Panel of the CLT Multi-panel Shear Wall
6.6.1 CLT Shear Wall Hold-down Design

- $\sum M_0 = 0$
- $T (b_{eff}) - v b_s h + w b_s \left(\frac{b_s}{2}\right) - T_T (b_{eff}) = 0$ (SDPWS-21 Eq. C-B.1)
- $T = \frac{v b_s h - w b_s \left(\frac{b_s}{2}\right)}{b_{eff}} + T_T$ (SDPWS-21 Eq. C-B.2)

Table 6-6: Solution for Tension Force, T, for Hold-down Strength Requirement

<table>
<thead>
<tr>
<th>Story</th>
<th>Unit shear force per foot of shear wall length</th>
<th>LRFD design unit shear capacity, $(\phi = 0.5)$</th>
<th>$2 x \nu_{\text{seismic}}$</th>
<th>$T_T$ from story above</th>
<th>T for 2 x $\nu_{\text{seismic}}$ requirement for load combination $1.0E - 0.7D$</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>477 (plf)</td>
<td>548 (plf)</td>
<td>1.097 (lb)</td>
<td>0 (lb)</td>
<td>11,293 lbs</td>
</tr>
<tr>
<td>2</td>
<td>1,009</td>
<td>1,097 (lb)</td>
<td>2,194 (lb)</td>
<td>11,293 (lb)</td>
<td>34,540 lbs</td>
</tr>
<tr>
<td>1</td>
<td>1,273</td>
<td>1,371 (lb)</td>
<td>2,742 (lb)</td>
<td>34,540 (lb)</td>
<td>63,968 lbs</td>
</tr>
</tbody>
</table>

6.6.1 CLT Shear Wall Hold-down Design

- The same screw attached hold-down is used for all locations with each having an LRFD design tension capacity of 17,678 lb and associated deflection of 0.253 in.
  - 1st story walls to foundation, four hold-downs
    - $4 \times 17,687 \text{ lb} = 70,748 \text{ lb} > 63,968 \text{ lbs}$
  - 2nd story to top of 1st story, four hold-downs
    - $4 \times 17,687 \text{ lb} = 70,748 \text{ lb} > 34,540 \text{ lbs}$
  - 3rd story to top of 2nd story, two hold-downs
    - $2 \times 17,687 \text{ lb} = 37,374 \text{ lb} > 11,293 \text{ lbs}$
- Check CLT panel for tension, row and group tear out
6.6.1 CLT Shear Wall Hold-down Design

- From SDPWS-21 Section B.3.4, hold-down device deformation for each story shall not exceed 0.185 in. for T forces from strength design load combinations (see Table 6-7).

Table 6-7: Solution for Tension Force, T, for Hold-down Deflection Requirement

<table>
<thead>
<tr>
<th>Story</th>
<th>Unit shear force per foot of shear wall length (plf)</th>
<th>T for load combination (lb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>477</td>
<td>4,714</td>
</tr>
<tr>
<td>2</td>
<td>1,009</td>
<td>14,604</td>
</tr>
<tr>
<td>1</td>
<td>1.273</td>
<td>27,472</td>
</tr>
</tbody>
</table>

- Deflection of most highly loaded hold-down is less than 0.185 in. The SDPWS-21 deflection limit is satisfied:

\[ \Delta_{\text{hold-down}} = \frac{27,472 \text{ lb}}{4(17.678 \text{ lb})} \times 0.253 \text{ in.} = 0.098 \text{ in.} < 0.185 \text{ in.} \]

6.6.2 CLT Shear Wall Compression Zone

- Compression force, C, and length of compression zone, x, from compression end panel moment equilibrium:

\[ \sum M_o = 0 \]

\[ C \left( b_s - \frac{x}{2} \right) - \nu b_s h - w b_s \left( \frac{b_s}{2} \right) - C_T \left( b_s - \frac{x_T}{2} \right) = 0 \quad (\text{SDPWS-21 Eq. C-B.3}) \]

\[ C = F_{C1} \left( t \right) \left( x \right) \left( \frac{12\text{ in.}}{H} \right) \quad (\text{SDPWS-21 Eq. C-B.4}) \]

\[ C = F \left( c^\prime \right) \left( t_{\text{parallel}} \right) \left( x \right) \left( \frac{12\text{ in.}}{H} \right) \quad (\text{SDPWS-21 Eq. C-B.5}) \]

- C and x summarized in Table 6-8.
6.6.2 CLT Shear Wall Compression Zone

Table 6-8: Solution for Compression Zone Length, x, and Force C

<table>
<thead>
<tr>
<th>Story</th>
<th>Unit shear force per foot of shear wall length</th>
<th>Dead load, $w_{DL}$</th>
<th>Live load, $w_{LL}$</th>
<th>$C_T$, Compression from top</th>
<th>Compression zone length, x</th>
<th>$C$, for load combination 1.0E + 1.4D +0.5L</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>(plf)</td>
<td>477</td>
<td>190</td>
<td>0</td>
<td>2.00</td>
<td>5,257</td>
</tr>
<tr>
<td>2</td>
<td>(plf)</td>
<td>1,009</td>
<td>793</td>
<td>690</td>
<td>5,257</td>
<td>20,144</td>
</tr>
<tr>
<td>1</td>
<td>(plf)</td>
<td>1,273</td>
<td>793</td>
<td>690</td>
<td>20,144</td>
<td>36,545</td>
</tr>
</tbody>
</table>

* Check of CLT wall panel axial capacity is required

6.7 CLT Shear Wall Deflection

$$
\delta_{SW} = \frac{576\nu b_y h^3}{E_{eff}(\text{in–plane})} + \frac{vh}{G_{eff}(\text{in–plane})} + 3\Delta_{rail\, stip.h} + 2\Delta_{rail\, stip.v} \left( \frac{h}{b_y} \right) + \Delta \frac{h}{\Sigma b_y}
$$

(SDPWS-21 Eq. B-1)

<table>
<thead>
<tr>
<th>Total shear wall deflection, $\delta_{SW}$</th>
<th>Panel bending and shear +</th>
<th>Sliding +</th>
<th>Panel rotation +</th>
<th>Rigid body rotation</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="" /></td>
<td><img src="image2.png" alt="" /></td>
<td><img src="image3.png" alt="" /></td>
<td><img src="image4.png" alt="" /></td>
<td><img src="image5.png" alt="" /></td>
</tr>
</tbody>
</table>
6.7 CLT Shear Wall Deflection

Table 6-9: CLT Shear Wall Deflection Components and Total Shear Wall Deflection, $\delta_{SW}$

<table>
<thead>
<tr>
<th>Story</th>
<th>$\frac{576v b_s h^2}{E I_{eff} (in-plane)}$ (in.)</th>
<th>$\frac{v h}{G A_{eff} (in-plane)}$ (in.)</th>
<th>$3\Delta_{nail slip,h} + 2\Delta_{nail slip,v} \left(\frac{h}{b_s}\right)$ (in.)</th>
<th>$\frac{h}{\sum b_s}$</th>
<th>$\delta_{SW}$, shear wall deflection (in.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>0.02</td>
<td>0.04</td>
<td>0.15</td>
<td>0.04</td>
<td>0.24</td>
</tr>
<tr>
<td>2</td>
<td>0.04</td>
<td>0.09</td>
<td>0.16</td>
<td>0.04</td>
<td>0.33</td>
</tr>
<tr>
<td>1</td>
<td>0.05</td>
<td>0.11</td>
<td>0.16</td>
<td>0.03</td>
<td>0.35</td>
</tr>
</tbody>
</table>

- For allowable story drift limit is 2.5% $h$ from ASCE/SEI 7-22 Table 12.12-1, corresponding allowable deflection calculated using, $C_{dh}$ equal to 3 for cross-laminated timber shear walls:

$$\delta_e = \frac{0.025(h)}{C_{dh}} = \frac{0.025(114 \text{ in.})}{3.0} = 0.95 \text{ in.} > \delta_{SW}$$

6.8 References

- See the “Other Useful Design Aid Resources” in Section 6.1 for additional references.
Building Code Reference of SDPWS Standard

2021 IBC
• References 2021 SDPWS in Section 2305 for lateral design and construction

Building Code Reference of ASCE 7-22 Standard

Targeted for reference in 2024 IBC
NEHRP Provisions

- 2020 NEHRP Recommended Seismic Provisions for New Buildings and Other Structures (FEMA P-2082)
  

NEHRP Provisions Design Examples

- 2020 NEHRP Recommended Seismic Provisions: Design Examples, Training Materials, and Design Flow Charts, FEMA P-2192
  
- Volume 1: Design Examples
  
Cross-Laminated Timber (CLT) Shear Wall

Thank You

Contact Slide

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