Design of Mass Timber Diaphragms and the New CLT Diaphragm Design Guide

July 12, 2023

Presented by
Scott Breneman, WoodWorks
Eric McDonnell, Holmes
Background
Glue Laminated Timber (Glulam)
Beams & columns

Cross-Laminated Timber (CLT)
Solid sawn laminations

Cross-Laminated Timber (CLT)
SCL laminations
Cheney Park Apartments
Cheney, WA
Cooley Landing Education Center
East Palo Alto, CA
Hybrid Mass Timber and Steel Framing?

Brentwood Library
Brentwood, CA

Barracuda Condos
Madison, WI

Photo Credit: WoodWorks
What is CLT?

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

*All dimensions are approximate. Consult with manufacturers
FLATWISE Panel Loading

Span in MAJOR Strength Direction
“Parallel” Direction
Use subscript ‘0’ in Notation

Span in MINOR Strength Direction
“Perpendicular” Direction
Use subscript ‘90’ in Notation

Reference & Source: ANSI/APA PRG 320
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>$F_{L,0}$ (psi)</th>
<th>$E_x$ (10^6 psi)</th>
<th>$F_{L,0}$ (psi)</th>
<th>$F_{L,0}$ (psi)</th>
<th>$F_{L,0}$ (psi)</th>
<th>$F_{L,0}$ (psi)</th>
<th>$F_{L,0}$ (psi)</th>
<th>$F_{L,0}$ (psi)</th>
<th>$F_{L,0}$ (psi)</th>
<th>$F_{L,0}$ (psi)</th>
<th>$F_{L,0}$ (psi)</th>
<th>$F_{L,0}$ (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SL-V4</td>
<td>775</td>
<td>1.1</td>
<td>350</td>
<td>1000</td>
<td>135</td>
<td>45</td>
<td>775</td>
<td>1.1</td>
<td>350</td>
<td>1000</td>
<td>135</td>
<td>45</td>
</tr>
</tbody>
</table>

For SL-V4: $k = 0.006895$ 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>SL-V4(b)</td>
<td>3-alt</td>
<td>4 1/8</td>
<td>1 3/8, 1 3/8, 1 3/8</td>
<td>1,800</td>
<td>74, 0.41, 1,430</td>
</tr>
<tr>
<td></td>
<td>4-maxx</td>
<td>5 1/2</td>
<td>1 3/8, x 2</td>
<td>2,925</td>
<td>161, 0.49, 1,740</td>
</tr>
<tr>
<td></td>
<td>5-alt</td>
<td>6 7/8</td>
<td>1 3/8, x 2, 1 3/8, 1 3/8</td>
<td>4,150</td>
<td>286, 0.83, 1,980</td>
</tr>
<tr>
<td></td>
<td>5-maxx</td>
<td>6 7/8</td>
<td>1 3/8, x 2, 1 3/8, 1 3/8</td>
<td>5,150</td>
<td>355, 1.4, 2,460</td>
</tr>
<tr>
<td></td>
<td>7-alt</td>
<td>9 5/8</td>
<td>1 3/8, x 2, 1 3/8, 1 3/8</td>
<td>7,200</td>
<td>596, 1.2, 2,875</td>
</tr>
<tr>
<td></td>
<td>7-maxx</td>
<td>9 5/8</td>
<td>1 3/8, x 2, 1 3/8, 1 3/8</td>
<td>7,325</td>
<td>707, 1.2, 2,500</td>
</tr>
</tbody>
</table>

\(^{(a)}\) 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).
Structural Design Standardization

Table 10.3.1 Applicability of Adjustment Factors for Cross-Laminated Timber

<table>
<thead>
<tr>
<th></th>
<th>ASD only</th>
<th>ASD and LRFD</th>
<th>LRFD only</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Figure 12T</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>End Distance, Edge Distance and Fastener Spacing Requirements in Narrow Edge of Cross-Laminated Timber</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Required Fire Endurance (hr.)</th>
<th>1-Hour</th>
<th>1½-Hour</th>
<th>2-Hour</th>
</tr>
</thead>
<tbody>
<tr>
<td>(EI)$<em>{38}$ lamination thicknesses, $h</em>{lamin}$ (in.)</td>
<td>5/8</td>
<td>3/4</td>
<td>7/8</td>
</tr>
<tr>
<td>5/8</td>
<td>2.2</td>
<td>2.2</td>
<td>2.1</td>
</tr>
<tr>
<td>3/4</td>
<td>3.4</td>
<td>3.4</td>
<td>3.1</td>
</tr>
<tr>
<td>7/8</td>
<td>4.4</td>
<td>4.3</td>
<td>4.1</td>
</tr>
</tbody>
</table>
CLT Recognized in the Model Building Code!*
(*for gravity systems with existing Construction Types)
EDGEWISE Panel Loading

Span in **MAJOR** Strength Direction

Span in **MINOR** Strength Direction

*Reference & Source: ANSI/APA PRG 320-2017*
EDGEWISE Panel Loading

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

Through-the-Thickness Shear

Source: NDS 2015 Manual

NDS 2015: $F_v(t_v)$
PRG 320-2017: $F_{v,e,0} t_p$ & $F_{v,e,90} t_p$
CLT in In-Plane (Edgewise) Strength

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

<table>
<thead>
<tr>
<th>CLT LAYUP</th>
<th>CLT PANEL THICKNESS DESIGNATION</th>
<th>FACE LAMINATION ORIENTATION (psi)</th>
<th>FACE LAMINATION ORIENTATION (lb/ft of width)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>(\alpha)</td>
<td>(\beta)</td>
</tr>
<tr>
<td>V2M1</td>
<td>99 V</td>
<td>175°</td>
<td>236°</td>
</tr>
<tr>
<td></td>
<td>169 V</td>
<td>175°</td>
<td>236°</td>
</tr>
<tr>
<td></td>
<td>239 V</td>
<td>175°</td>
<td>236°</td>
</tr>
<tr>
<td></td>
<td>309 V</td>
<td>175°</td>
<td>236°</td>
</tr>
<tr>
<td>V2M1.1</td>
<td>105V</td>
<td>195</td>
<td>250</td>
</tr>
<tr>
<td></td>
<td>175V</td>
<td>270</td>
<td>290°</td>
</tr>
<tr>
<td></td>
<td>245V</td>
<td>290°</td>
<td>31,300°</td>
</tr>
<tr>
<td></td>
<td>315V</td>
<td>290°</td>
<td>40,200°</td>
</tr>
</tbody>
</table>

### Reference Design Values for Nordic X-Lam Listed in Table 1 (For Use in the Design of X-Lam Shear Panel Systems)**

<table>
<thead>
<tr>
<th>Major Strength Direction</th>
<th>Minor Strength Direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>(F_{x,0.00}(\text{psi}))</td>
<td>(G_{x,0 \text{ lb/ft}}(\text{psi}))</td>
</tr>
<tr>
<td>--------------------------</td>
<td>--------------------------</td>
</tr>
<tr>
<td>155^{(k)}</td>
<td>1.36</td>
</tr>
<tr>
<td>155</td>
<td>1.52</td>
</tr>
<tr>
<td>155</td>
<td>1.79</td>
</tr>
<tr>
<td>185^{(k)}</td>
<td>2.23</td>
</tr>
<tr>
<td>145</td>
<td>2.39</td>
</tr>
<tr>
<td>185^{(k)}</td>
<td>2.44</td>
</tr>
<tr>
<td>185</td>
<td>2.99</td>
</tr>
<tr>
<td>185^{(k)}</td>
<td>3.37</td>
</tr>
<tr>
<td>185^{(k)}</td>
<td>3.64</td>
</tr>
<tr>
<td>185^{(k)}</td>
<td>4.48</td>
</tr>
<tr>
<td>185^{(k)}</td>
<td>4.56</td>
</tr>
<tr>
<td>185^{(k)}</td>
<td>5.38</td>
</tr>
</tbody>
</table>

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

145 to 290 PSI Edgewise Shear Capacity = 1.7 to 3.5 kips/ft (ASD) per inch of thickness!

Consult with the Manufacturers for Values

Multiply by \(Cd = 1.6\) for short term ASD strength

**CLT Panels can have > 9 kips / ft in-plane shear capacity**

Source: APA Product Report PR-L306
No explicitly recognized requirements for CLT Lateral Systems in 2018 IBC
CLT in the U.S. Building Code – IBC 2021

With new and improved adhesive qualification tests

Now with IV-A, IV-B and IV-C Construction Types

New Type IV Mass Timber Construction up to 18 Stories!
New Requirements for CLT Lateral Systems in SDPWS 2021!

Referenced from IBC 2021
2021 Special Design Provisions for Wind and Seismic

Top Changes Relevant to CLT Lateral Systems:

- New unified nominal shear capacity
- New CLT Shear Wall requirements
- New CLT Diaphragm requirements

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PowerPoint IS NOT the CODE!
Top Changes Relevant to CLT Lateral Systems:

- **New unified nominal shear capacity**
- New CLT Shear Wall requirements
- New CLT Diaphragm requirements
2021 SDPWS – Unified Nominal Shear Capacity

For sheathed wood frame shear walls and diaphragms, SDPWS 2015 has two nominal shear capacities

\[ v_s \] Nominal shear capacity for seismic loads

\[ v_w \] Nominal shear capacity for wind loads

SDPWS 2021 has one nominal shear capacity for both wind and seismic (for all systems such as WSP and CLT)

\[ v_n \] Nominal shear capacity
To calculate the ASD or LRFD shear capacity, SDPWS 2021 has different reduction factors for wind and seismic

<table>
<thead>
<tr>
<th></th>
<th>Design shear capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ASD</strong></td>
<td><strong>LRFD</strong></td>
</tr>
<tr>
<td>Wind</td>
<td>$\nu_n/2.0$</td>
</tr>
<tr>
<td>Seismic</td>
<td>$\nu_n/2.8$</td>
</tr>
</tbody>
</table>

SDPWS 2021 Section 4.1.4
Top Changes Relevant to CLT Lateral Systems:

- New unified nominal shear capacity
- **New CLT Shear Wall requirements**
- New CLT Diaphragm requirements

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CLT Shear Walls in SDPWS 2021

CLT Shear Walls (other)
not meeting Appendix B

CLT Shear Walls
meeting SDPWS 2021 Appendix B

Seismic Design Category A
or SDC B and ≤ 65’ tall
in SDPWS 4.6.3 Exception

Panel aspect ratios
2 ≤ \( \frac{h}{b_s} \) ≤ 4

with shear resistance provided by high aspect ratio panels only (SDPWS B.3.7)

Panel aspect ratios
\( \frac{h}{b_s} = 4 \)
R Values for CLT Shear Walls in SDPWS 2021

(Other)

CLT Shear Walls
not meeting Appendix B

\[ R = 1.5 \]
\[ C_d = 1.5 \quad \Omega_o = 2.5 \]

In SDPWS 2021 4.6.3

Platform Framed

CLT Shear Walls
meeting SDPWS 2021 Appendix B

Panel aspect ratios

\[ 2 \leq h/b_s \leq 4 \]

Panel aspect ratios

\[ h/b_s = 4 \]

\[ R = 3.0^* \]
\[ C_d = 3.0 \quad \Omega_o = 3.0 \]

\[ R = 4.0^* \]
\[ C_d = 4.0 \quad \Omega_o = 3.0 \]

* ASCE 7-22
New Requirements for CLT Lateral Systems!
(but R values for CLT Shear Walls not in ASCE 7-16)
CLT in the U.S. Building Code – Lateral in the IBC 2024?

Future Full Recognition of CLT Shear Wall

- AWC SDPWS 2021
- ASCE/SEI 7-22
- IBC 2024 (in process)

Now with CLT shear wall and diaphragm requirements
Now with Platform Framed CLT Shear Walls
To Be Made
Mass Timber Diaphragms
Diaphragm Strategies with Horizontal CLT

- Option 1: Structural Topping as Horizontal Diaphragm
- (1A) Structural Concrete Topping

Careful detailing to provide adequate load path, minimum rebar cover, etc.
Diaphragm Strategies with Horizontal CLT

• Option 1: Structural Topping as Horizontal Diaphragm
• (1B) Wood Structural Panel Topping

Classify as blocked WSP diaphragm per SDPWS 2015 4.2.7.1?

19/32” thick 4ft by 8ft panel vs 4 1/8” thick 8ft by 24 ft panel?
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
Pre-fabricated panels often pre-sheathed

Once installed, add splice strips, tape joint if applicable

Photo Credit: structurecraft
Diaphragm Strategies with Horizontal CLT

• Option 2: CLT as a Diaphragm

Topping and Flooring as needed

CLT Panel as Diaphragm
2021 Special Design Provisions for Wind and Seismic

Top Changes Relevant to CLT Lateral Systems:

- New unified nominal shear capacity
- New CLT Shear Wall requirements
- **New CLT Diaphragm requirements**

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Strength of CLT rarely governs.

Strength of Connections covered by NDS and Proprietary Fastener Evaluation Reports.
24’ x 24’ CLT Diaphragm Test with Plywood Spline by AWC

Strong and Stiff Panels

Diaphragm behavior controlled by connections
4.5 Cross-Laminated Timber (CLT) Diaphragms

4.5.1 Application Requirements

CLT diaphragms shall be permitted to be used to resist lateral forces provided the deflection in the plane of the diaphragm as determined by calculations, tests, or analogous design procedures, does not exceed the maximum permissible deflection limit of attached load distributing or resisting elements. Permissible deflection shall be that deflection that will permit the diaphragm and any attached elements to maintain their structural integrity and continue to support their prescribed loads as determined by the applicable building code or standard.

4.5.2 Deflection

CLT diaphragm deflection shall be determined using principles of engineering mechanics.

4.5.3 Unit Shear Capacity

CLT diaphragms shall be designed in accordance with principles of engineering mechanics using design values for wood members and connections in accordance with NDS provisions.

The nominal unit shear capacity, $v_u$, of CLT diaphragms shall be based on the nominal shear capacity for dowel-type fastener connections used to transfer diaphragm shear forces, as calculated per 4.5.4. Item 1. ASD allowable shear capacity or LRFD factored shear resistance for the CLT diaphragm and diaphragm shear connections shall be determined in accordance with 4.1.1.

4.5.4 Additional CLT Diaphragm Design Requirements

CLT diaphragms shall meet the following additional requirements:

1. The nominal shear capacity for dowel-type fastener connections used to transfer diaphragm shear forces between CLT panels and between CLT panels and diaphragm boundary elements (chords and collectors) shall be taken as $v_u$, where $v_u = \frac{Z \cdot f}{2}$, where $Z^*$ is $Z$ multiplied by all applicable NDS adjustment factors except $C_r$, $K_r$, and $I_r$, and $Z$ shall be controlled by Mode III or Mode IV fastener yielding in accordance with NDS 12.3.1.
2. Connections used to transfer diaphragm shear forces shall not be used to resist diaphragm tension forces.
3. Wood elements, steel parts, and wood or steel chord splice connections shall be designed for 2.0 times the diaphragm forces associated with the shear forces induced from the design loads.

Exceptions:

1. Wood elements and wood splice connections shall be permitted to be designed for 1.5 times the diaphragm forces associated with the shear forces induced by the wind design loads.
2. Where dowel-type fasteners are used in chord splice connections and the connection is controlled by Mode III or Mode IV fastener yielding in accordance with NDS 12.3.1, fasteners in the connection shall be permitted to be designed for 1.3 and 1.0 times the diaphragm forces associated with the shear forces induced by the prescribed seismic and wind design loads, respectively.

Diaphragm chord elements and chord splice connections using materials other than wood or steel shall be designed using provisions in NDS 1.4.
CLT Diaphragm Design Guide based on SDPWS 2021

1 page of requirements leading to 140 page guide
Chapter Organization
1. Introduction
2. Codes and Standards
3. Methodology of CLT Diaphragm Design
4. Diaphragm Shear Components
5. Diaphragm Boundary Elements
6. Diaphragm Deflection and Stiffness
7. Special Design Considerations
8. Example 12-Story Office with Distributed Frames
9. Example 12-Story Office with Reinforced Concrete Cores
10. Example 5-Story Residence with Wood-Frame Shear walls
Appendix A – Precalculated Design Capacities
Appendix B – Literature Review
4.5 Cross-Laminated Timber (CLT) Diaphragms

4.5.1 Application Requirements

CLT diaphragms shall be permitted to be used to resist lateral forces provided the deflection in the plane of the diaphragm, as determined by calculations, tests, or analogies drawn therefrom, does not exceed the maximum permissible deflection limit of attached load distributing or resisting elements. Permissible deflection shall be that deflection that will permit the diaphragm and any attached elements to maintain their structural integrity and continue to support their prescribed loads as determined by the applicable building code or standard.

4.5.2 Deflection

CLT diaphragm deflection shall be determined using principles of engineering mechanics.

4.5.3 Unit Shear Capacity

CLT diaphragms shall be designed in accordance with principles of engineering mechanics using design values for wood members and connections in accordance with NDS provisions.

The nominal unit shear capacity, \( V_{ue} \), of CLT diaphragms shall be based on the applicable shear capacity for dowel-type fastener connections used to transfer diaphragm shear forces, as calculated per 4.5.4, Item 1. ASD allowable shear capacity or LRFD factored shear resistance for the CLT diaphragms and diaphragm connections shall be determined in accordance with 4.1.1.

4.5.4 Additional CLT Diaphragm Design Requirements

CLT diaphragms shall meet the following additional requirements:

1. The nominal shear capacity for dowel-type fastener connections used to transfer diaphragm shear forces between CLT panels and between CLT panels and diaphragm boundary elements (chords and collectors) shall be taken as 4.5Z*, where Z* is Z multiplied by all applicable NDS adjustment factors except \( C_D \), \( K_F \), \( \phi \), and \( \lambda \); and Z shall be controlled by Mode III or Mode IV fastener yielding in accordance with NDS 12.3.1.

Requirements for the shear connections
Generic Mass Timber Floor System

- Typical Panel
- Gravity Joist not at panel edges

Diagram showing:
- Columns
- Girders
- Purlins/Joists
- CLT Panels
- Shear Wall

Lateral Load, w
Example CLT Diaphragm Design

Collector

Chord

Shear Zone

Lateral Load
Example CLT Diaphragm Design

Shear Transfer Details:
- a – panel to panel
- b – panel to panel over beam
- c – panel to wall / collector
- d – panel to chord
- e – shear in panel
- z – chord and chord splice
- y – collector and collector splice

Diaphragm Shear, $v$
Collector

Lateral Load
CLT Diaphragm Shear Transfer Connections

**Shear Transfer Details:**

- **a** – panel to panel
- **b** – panel to panel over beam
- **c** – panel to wall / collector
- **d** – panel to chord
- **e** – shear in panel

**Other:**

- **z** – chord and chord splice
- **y** – collector and collector splice
Diaphragm shear connections at CLT panel edges:
- Use dowel-type fasteners in shear (nails, screws, bolts)
- Yield Mode Ills or Mode IV per NDS 12.3.1 controls capacity
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
Panel to Panel Connection Styles

• Single Surface Spline
Panel to Panel Connection Styles

- Half-Lap

Source: Simpson Strong-Tie
Fastener Vendor Design Support

Quick Drive Tool Setup
1. Assemble the Quick Drive PRO20002 and PRO20002L-SCS.
2. If using a cordless drill, replace with a battery pack on the drill.
3. Make sure the drill is fully charged before using.
4. Insert the Fastener into the drill and tighten to the correct torque.
5. Use a torque wrench to ensure proper installation.

Installation
1. Place the strap on the surface of the mass timber panels with the centerline aligned with joists or girders.
2. Secure the strap to the surface of the panel using a Fastener as per the manufacturer’s instructions.
3. Use a Fastener to secure the strap to the surface of the panel using a Fastener as per the manufacturer’s instructions.

Table 1: Reference allowable load and slip modulus for SDRS Timber Screws (SDWS22X1000D and SDWS22X1000D) for CLT surface splines fastening with 1-1/8-in. APA rated Sturd-I-Floor wood structural panel, single-surface splines.

<table>
<thead>
<tr>
<th>CLT Wood Species Combination</th>
<th>Allowable Load per Fastener (lb)</th>
<th>Fastener Slip Modulus (in/ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DIF</td>
<td>792</td>
<td>0.15</td>
</tr>
<tr>
<td>SPF</td>
<td>588</td>
<td>0.15</td>
</tr>
<tr>
<td>SPF-5</td>
<td>355</td>
<td>0.15</td>
</tr>
</tbody>
</table>

1. Allowable loads are given at C_L = 1.0 and maybe increased up to C_L = 1.0 as permitted by the building code.
2. Applyable adjustments shall be applied following the ANSI/AWC NDS-18 or NDS-18.
3. Design values are applicable for all grain orientation combinations of major strength directions in the CLT and the wood structural panel spline and species for the species combinations listed.
4. The designer is responsible to check shear capacity of spline (shear through the thickness and rolling shear).

Light Diaphragm Spline Strap (LDSS) for Mass Timber

Product Information

<table>
<thead>
<tr>
<th>Model No.</th>
<th>CLT Type</th>
<th>Fastener Type</th>
<th>Allowable Load (lb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LDSSA1</td>
<td>Three Ply</td>
<td>Fastener Type</td>
<td>Allowable Load (lb)</td>
</tr>
<tr>
<td>15</td>
<td>Plywood</td>
<td>0.15</td>
<td>792</td>
</tr>
</tbody>
</table>

1. Allowable loads are given at C_L = 1.0 and maybe increased up to C_L = 1.0 as permitted by the building code.
2. Applyable adjustments shall be applied following the ANSI/AWC NDS-18 or NDS-18.
3. Design values are applicable for all grain orientation combinations of major strength directions in the CLT and the wood structural panel spline and species for the species combinations listed.
4. The designer is responsible to check shear capacity of spline (shear through the thickness and rolling shear).
An Efficient Panel to Panel Connection

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

Nails at spacing required for shear transfer

5 ½” to 5 7/8” plywood strip ¾” or 1” Thick

Graphics: ASPECT Structural Engineers
Panel to Panel Connection Tolerances

Specify gaps between splines and shoulders of CLT panel (like spacing of WSP panels)

Plan for construction tolerances.
Panel to Panel Connection Tolerances

One reason for size of cut rabbet in CLT for spline to include gaps:

BUILT CONDITION

POTENTIAL BEHAVIOR UNDER HIGH DIAPHRAGM LOADING
Panel to Panel Connections Options

Is a butt joint with angled screws compliant?

Shear resisted by dowels in shear. OK if Mode III or IV

Shear resisted by dowels in tension & compression. Not compliant!
Panel to Beam Connection Styles

CL OF BEAM

5/16"Øx12 5/8" ASSY 3.0 SCREWS @ 24" o.c.

SIMPSON STRONG-TIE SDWS22800 LOG

GLULAM BEAM
Nominal capacity of CLT diaphragm shear connection fastener:

\[ Z_n = 4.5 \ Z^* \]

Where \( Z^* \) is reference lateral capacity of the fastener, \( Z \), of NDS multiplied by all NDS adjustment factors except \( C_D, K_F, \phi, \lambda = 1.0 \)

SDPWS 2021 Section 4.5.4(1) and NDS Table 11.3.1
### Table 11.3.1 Applicability of Adjustment Factors for Connections

<table>
<thead>
<tr>
<th>Load Duration Factor</th>
<th>ASD Only</th>
<th>ASD and LRFD</th>
<th>LRFD Only</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wet Service Factor</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temperature Factor</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Group Action Factor</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Geometry Factor</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Penetration Depth Factor</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>End Grain Factor</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Metal Side Plate Factor</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diaphragm Factor</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Toe-Nail Factor</td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### Lateral Loads

Dowel-type Fasteners (e.g. bolts, lag screws, wood screws, nails, spikes, drift bolts, & drift pins)

\[ Z^* = Z \times \begin{bmatrix} 1.0 \\ C_M \\ C_t \\ C_g \\ C_\Delta \\ C_{eg} \\ C_{tn} \end{bmatrix} \]

Also 1.0 for CLT Diaphragm Shear Connections

SDPWS 2021 Section 4.5.4(1) and NDS Table 11.3.1
CLT Diaphragm Shear Connection Design

Nominal capacity of CLT diaphragm shear connection fastener:

\[ Z_n = 4.5 \, Z^* \]

Where \( Z^* \) is reference lateral capacity of the fastener, \( Z \), of NDS multiplied by all NDS adjustment factors except \( C_D, K_F, \phi, \lambda = 1.0 \)

Fastener with regular spacing, \( S \), nominal unit shear connection capacity is:

\[ v_n = Z_n/S = 4.5 \, Z^*/S \]

SDPWS 2021 Section 4.5.4(1) and NDS Table 11.3.1
To calculate the ASD or LRFD shear capacity, SDPWS 2021 has different reduction factors for wind and seismic.

<table>
<thead>
<tr>
<th></th>
<th>Design shear capacity</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ASD</td>
<td>LRFD</td>
</tr>
<tr>
<td>Wind</td>
<td>$v_n/2.0$</td>
<td>0.8 $v_n$</td>
</tr>
<tr>
<td>Seismic</td>
<td>$v_n/2.8$</td>
<td>0.5 $v_n$</td>
</tr>
</tbody>
</table>

ASD seismic design capacity:

$$4.5 \frac{Z^*}{2.8} = 1.61 \frac{Z^*}{2.8} \approx C_D \frac{Z}{2.8} = 1.6 Z$$
CLT Diaphragm Shear Connection Design

Fastener with regular spacing, $S$, nominal unit shear connection capacity is:

$$v_n = Z_n / S = 4.5 \frac{Z^*}{S}$$

Required unit shear strength $\leq$ Design unit shear capacity

**ASD**

$$v = v_{ASD} \leq \frac{v_n}{RF}$$

**LRFD**

$$v = v_u \leq \phi v_n$$

$RF$ = 2.8 (seismic)  
$\phi$ = 0.5 (seismic)  
$\phi$ = 2.0 (wind)  
$\phi$ = 0.8 (wind)

*SDPWS 2021 Section 4.1.4 and 4.5.4(1)*
Shear Transfer Details:
- a – panel to panel
- b – panel to panel over beam
- c – panel to wall / collector
- d – panel to chord
- e – shear in panel

Other
- z – chord and chord splice
- y – collector and collector splice
4.5 Cross-Laminated Timber (CLT) Diaphragms

4.5.1 Application Requirements

CLT diaphragms shall be permitted to be used to resist lateral forces provided the deflection in the plane of the diaphragm, as determined by calculations, tests, or analogies drawn therefrom, does not exceed the maximum permissible deflection limit of attached load distributing or resisting elements. Permissible deflection shall be that deflection that will permit the diaphragm and any attached elements to maintain their structural integrity and continue to support their prescribed loads as determined by the applicable building code or standard.

4.5.2 Deflection

CLT diaphragm deflection shall be determined using principles of engineering mechanics.

4.5.3 Unit Shear Capacity

CLT diaphragms shall be designed in accordance with principles of engineering mechanics using design values for wood members and connections in accordance with NDS provisions.

The nominal unit shear capacity, \( v_a \), of CLT diaphragms shall be based on the nominal shear capacity for dowel-type fastener connections used to transfer diaphragm shear forces, as calculated per 4.5.4, from 1. ASD allowable shear capacity or LRFD factored shear resistance for the CLT diaphragm and diaphragm shear connections shall be determined in accordance with 4.1.1.

4.5.4 Additional CLT Diaphragm Design Requirements

CLT diaphragms shall meet the following additional requirements:

1. The nominal shear capacity for dowel-type fastener connections used to transfer diaphragm shear forces between CLT panels and between CLT panels and diaphragm boundary elements (chords and columns) shall be taken as \( 0.5 v_a \), where \( v_a \) is \( v \) multiplied by all applicable NDS

3. Wood elements, steel parts, and wood or steel chord splice connections shall be designed for 2.0 times the diaphragm forces associated with the shear forces induced from the design loads.

Exceptions:

1. Wood elements and wood splice connections shall be permitted to be designed for 1.5 times the diaphragm forces associated with the shear forces induced by the wind design loads.

2. Where dowel-type fasteners are used in chord splice connections and the connection is controlled by Mode III, or Mode IV fastener yielding in accordance with NDS 12.3.1, fasteners in the connection shall be permitted to be designed for 1.5 and 1.0 times the diaphragm forces associated with the shear forces induced by the prescribed seismic and wind design loads, respectively.
Other CLT Diaphragm Components

1/8" gap, typical

CLT panel typical

1/16" gap

Plywood or LVL spline in oversized recess

Section view

Maintain required edge distances

Installation options for fasteners

Threads only in beam

Screws through pre-drilled holes

a) Over wood beam
b) Over steel beam
c) Over wood stud wall
Other CLT Diaphragm Components

Increased Diaphragm Design Forces ≤ Design Capacity

\[ \gamma_D \cdot \nu \leq \nu' \]

\( \nu = \) wind or seismic force demand

\[ \gamma_D = \]

2.0 for wood and steel components, except:

1.5 wood members resisting wind loads
1.5 chord splice connections controlled by Mode III or IV (seismic)
1.0 chord splice connections controlled by Mode III or IV (wind)

\[ \nu' = \] Adjusted capacity calculated per the NDS

*not 4.5 Z*

See SDPWS 2021 Section 4.5.4 for the full information
Other CLT Diaphragm Components

\[ R'_{NDS} \geq \gamma_D F_{design, ASD} \]
\[ R'_{NDS} \geq \gamma_D F_{design, LRFD} \]

3. Wood elements, steel parts, and wood or steel chord splice connections shall be designed for 2.0 times the diaphragm forces associated with the shear forces induced from the design loads.

Exceptions:
1. Wood elements and wood splice connections shall be permitted to be designed for 1.5 times the diaphragm forces associated with the shear forces induced by the wind design loads.
2. Where dowel-type fasteners are used in chord splice connections and the connection is controlled by Mode III, or Mode IV fastener yielding in accordance with NDS 12.3.1, fasteners in the connection shall be permitted to be designed for 1.5 and 1.0 times the diaphragm forces associated with the shear forces induced by the prescribed seismic and wind design loads, respectively.

See SDPWS 2021 Section 4.5.4 for the full information
Example Calculation – Shear through Surface Spline

4.5 Example Calculation of Surface Spline Connection

An example calculation for a single surface spline detail is provided in Figure 4.8.

- 10d common nails
- Group 1, 23/32-in.-thick, 48/24 span-rated, general sheathing grade 4-ply plywood spline
- CLT panel with specific gravity, $G = 0.50$

An ASCE 7-16 diaphragm unit shear wind demand of 1,600 lbf per ft at strength (LRFD) is assumed.
Calculate reference shear capacity of 10d nail connection the spline to the CLT panel following NDS 12.3

Specific Gravity: \( G := 0.5 \)
Dowel diameter: \( D := 0.148 \text{ in} \)
Dowel length: \( l_{dowel} := 3 \text{ in} \)
Dowel bending yield strength: \( F_{yb} := 90000 \text{ psi} \)
Side member bearing length: \( l_s := 0.72 \text{ in} \)
Estimated length of tapered tip: \( E := 2 \cdot D = 0.296 \text{ in} \) per NDS §12.3.5.3
Main member bearing length:
\[
 l_m := l_{dowel} - l_s - \frac{E}{2} = 2.132 \text{ in}
\]
Main member bearing strength: \( F_{em} := 4650 \text{ psi} \) per NDS Table 12.3.3
Side member bearing strength: \( F_{es} := 3350 \text{ psi} \) per NDS Table 12.3.3B
Bearing strength ratio:
\[
 R_e := \frac{F_{em}}{F_{es}} = 1.39
\]
Bearing length ratio:
\[
 R_t := \frac{l_m}{l_s} = 2.96
\]
Reduction term: \( R_a := 2.2 \) per NDS Table 12.3.1B

CLT Diaphragm Design Guide Section 4.5
Example Calculation – Shear through Surface Spline

Calculate reference shear capacity of 10d nail connection the spline to the CLT panel following NDS 12.3

Strength fit factors per NDS Table 12.3.1A:

\[ k_1 := \sqrt{\frac{R_e + 2 \cdot R_e}{1 + R_e}} \cdot \left(1 + R_e + R_e^2\right) + R_e^2 \cdot R_e - R_e \cdot \left(1 + R_e\right) = 1.3 \]

\[ k_2 := -1 + \sqrt{2 \cdot (1 + R_e) + \frac{2 \cdot F_{yb} \cdot (1 + 2 \cdot R_e)}{3 \cdot F_{em} \cdot l_m^2}} = 1.24; \quad k_3 := -1 + \sqrt{\frac{2 \cdot (1 + R_e)}{R_e} + \frac{2 \cdot F_{yb} \cdot (2 + R_e)}{3 \cdot F_{em} \cdot l_s^2}} = 1.3 \]

Single shear yield limit equations per NDS Table 12.3.1A:

Mode I_m:

\[ Z_{Im} := \frac{D \cdot l_m \cdot F_{em}}{R_d} = 666.9 \text{ lbf} \]

Mode I_s:

\[ Z_{Is} := \frac{D \cdot l_s \cdot F_{es}}{R_d} = 162.3 \text{ lbf} \]

Mode II:

\[ Z_{II} := \frac{k_1 \cdot D \cdot l_s \cdot F_{es}}{R_d} = 210.5 \text{ lbf} \]

Mode III:

\[ Z_{III} := \frac{k_2 \cdot D \cdot l_m \cdot F_{em}}{(1 + 2 \cdot R_e) \cdot R_d} = 218.7 \text{ lbf} \]

Controlling:

\[ Z := Z_{III} = 86.4 \text{ lbf} \]

CLT Diaphragm Design Guide Section 4.5
Example Calculation – Shear through Surface Spline

Calculate *nominal CLT diaphragm* shear capacity of nail (interior, dry application with sufficient edge distances):

\[
Z_{\text{star}} := Z \cdot C_M \cdot C_t \cdot C_g \cdot C_{\Delta} \cdot C_{eg} \cdot C_{di} \cdot C_{tn} = 86 \text{ lb}
\]

\[
V_n := 4.5 \cdot Z_{\text{star}} = 389 \text{ lb}
\]

ASD and LRFD *CLT diaphragm shear* capacity of nail:

\[
\Omega_D := 2.0 \quad \text{per SDPWS §4.1.4 for wind design}
\]

\[
\frac{V_n}{\Omega_D} = 194 \text{ lb}
\]

\[
\phi_D := 0.8 \quad \text{per SDPWS §4.1.4 for wind design}
\]

\[
\phi_D \cdot V_n = 311 \text{ lb}
\]

*CLT Diaphragm Design Guide Section 4.5*
Example Calculation – Shear through Surface Spline

Determine required nail spacing and compare resulting capacity with design shear demand (ASD)

\[ V_{\text{design, ASD}} = 0.6 \cdot 1600 \, \text{lbf/ft} = 960 \, \text{lbf/ft} \]

ASD load combination factor of 0.6 applied

\[ s_{\text{max}} = \frac{V_n}{\Omega_D} = 2.43 \, \text{in} \]

maximum fastener spacing

\[ s = 2.0 \, \text{in} \]

specify 2.0 inches for design and construction

Check assumed Geometry Adjustment Factor depending on fastener diameter:

\[ C_A := 1.0 \]

adjustment factor value confirmed per NDS 12.5.1

Determine design capacity and compute the DCR.

\[ v_n := V_n \cdot \frac{12 \, \text{in}}{s} = 2333 \, \text{lbf/ft} \]

\[ \frac{v_n}{\Omega_D} = 1166 \, \text{lbf/ft} \]

\[ DCR := \frac{V_{\text{design, ASD}}}{\frac{v_n}{\Omega_D}} = 0.82 \]

\[ DCR < 1.0, \, \text{OK} \]

1166 plf ASD wind shear capacity of nails

> ASD wind shear demand 960 plf

CLT Diaphragm Design Guide Section 4.5
Example Calculation – Shear through Surface Spline

Alternatively, use the pre-calculated design table in the Appendix A of the Guide, first calculate the required nominal fastener shear capacity (ASD or LRFD):

\[
v_{n.\text{req.ASD}} := \frac{\Omega_D \cdot V_{\text{design.ASD}}}{C_M \cdot C_t \cdot C_g \cdot C_D \cdot C_{eg} \cdot C_{di} \cdot C_{tn}}
\]

\[
v_{n.\text{req.ASD}} := \frac{2.0 \cdot (960 \text{ lbf/ft})}{1.0 \cdot 1.0 \cdot 1.0 \cdot 1.0 \cdot 1.0 \cdot 1.0 \cdot 1.0} = 1920 \text{ lbf/ft}
\]

CLT Diaphragm Design Guide Section 4.5
Example Calculation – Shear through Surface Spline

Pre-calculated design tables in the Appendix A of the Guide

<table>
<thead>
<tr>
<th>TABLE A.1.1: Example fastener properties for spline capacities</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Diameter, D</strong></td>
</tr>
<tr>
<td>-----------------</td>
</tr>
<tr>
<td>8d common nail</td>
</tr>
<tr>
<td>10d common nail</td>
</tr>
<tr>
<td>16d common nail</td>
</tr>
<tr>
<td>Example screw 1</td>
</tr>
<tr>
<td>Example screw 2</td>
</tr>
<tr>
<td>Example screw 3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>TABLE A.1.2: Example WSP properties for spline capacities</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Spline Spline Diameter:</strong></td>
</tr>
<tr>
<td>-----------------------------</td>
</tr>
<tr>
<td>8d common nail</td>
</tr>
<tr>
<td>10d common nail</td>
</tr>
<tr>
<td>16d common nail</td>
</tr>
<tr>
<td>Example screw 1</td>
</tr>
<tr>
<td>Example screw 2</td>
</tr>
<tr>
<td>Example screw 3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>TABLE A.1.3: Reference design value and controlling yield mode for fasteners in splines</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Reference Lateral Design Value for Single Fastener, Zs (lf)</strong></td>
</tr>
<tr>
<td>-------------------------------------------------</td>
</tr>
<tr>
<td>12-in. o.c.</td>
</tr>
<tr>
<td>8d common nail</td>
</tr>
<tr>
<td>10d common nail</td>
</tr>
<tr>
<td>16d common nail</td>
</tr>
<tr>
<td>Example screw 1</td>
</tr>
<tr>
<td>Example screw 2</td>
</tr>
<tr>
<td>Example screw 3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>TABLE A.1.4: Nominal diaphragm shear capacity for spaced fastener in spline</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Nominal Diaphragm Shear Capacity of Fasteners,</strong></td>
</tr>
<tr>
<td><strong>Reference Spline Shear Capacity,</strong></td>
</tr>
<tr>
<td><strong>Spline Material</strong></td>
</tr>
<tr>
<td>---------------------</td>
</tr>
<tr>
<td>CLT SG = 0.36</td>
</tr>
<tr>
<td>General sheathing (23/32)</td>
</tr>
<tr>
<td>General sheathing (23/32)</td>
</tr>
<tr>
<td>General sheathing (23/32)</td>
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<tr>
<td>General sheathing (23/32)</td>
</tr>
<tr>
<td>Structural 1 sheathing (23/32)</td>
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</tr>
<tr>
<td>Structural 1 sheathing (23/32)</td>
</tr>
</tbody>
</table>
Example Calculation – Shear in Surface Spline

Using the pre-calculated design table in the Appendix A of the Guide, reference Appendix A.1.4 to find spline detail with required nominal capacity

<table>
<thead>
<tr>
<th>Spline Material</th>
<th>Fastener</th>
<th>Nominal Diaphragm Shear Capacity of Fasteners, ( v_n = 4.5Z^*/S ), @ Spacing, ( S^{a,c} ) (plf)</th>
<th>Reference Spline Shear Capacity, ( F_{YV}V^b ) (plf)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CLT SG = 0.50</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>General sheathing (23/32)</td>
<td>8d common nail</td>
<td>330 659 989 1,318 1,977 1,176</td>
<td></td>
</tr>
<tr>
<td>General sheathing (23/32)</td>
<td>10d common nail</td>
<td>388 776 1,164 1,552 2,328 1,176</td>
<td></td>
</tr>
</tbody>
</table>

> req. nominal 1920 plf

---

c. Before using highlighted fastener capacity values, verify the adjusted design spline capacity is greater than the amplified demands per SDPWS §4.5.4:

- Verify adjusted spline capacity is greater than SDPWS §4.5.4.3 Exception 1 for wind design.
- Verify adjusted spline capacity is greater than SDPWS §4.5.4.3 for seismic design and SDPWS 4.5.4.3 Exception 1 for wind design.

**CLT Diaphragm Design Guide Section 4.5**
Example Calculation – Shear in Surface Spline

Check the plywood spline capacity per NDS against the increased load from SDPWS 4.5.4.3

Find the SDPWS increased ASD design shear:

\[ Y_D \cdot V_{design, ASD} = (1.5) \times 960 \text{ plf} = 1440 \text{ plf} \]

Compare to the NDS adjusted plywood spline capacity (ASD)

Reference in-plane shear capacity:

\[ F_{vtv} := 98 \frac{\text{lbf}}{\text{in}} \cdot 12 \frac{\text{in}}{\text{ft}} = 1176 \frac{\text{lbf}}{\text{ft}} \]

Apply NDS adjustment factors:

- Load duration factor: \( C_D := 1.6 \)
- Wet service factor: \( C_M := 1.0 \)
- Temperature factor: \( C_t := 1.0 \)

ASD adjusted strength:

\[ F_{vtv \text{,NDS,ASD}} := F_{vtv} \cdot C_D \cdot C_M \cdot C_t = 1882 \frac{\text{lbf}}{\text{ft}} \]

> req. ASD shear 1440 plf, spline OK

CLT Diaphragm Design Guide Section 4.5
Chapter Organization
1. Introduction
2. Codes and Standards
3. Methodology of CLT Diaphragm Design
4. Diaphragm Shear Components
5. Diaphragm Boundary Elements
6. Diaphragm Deflection and Stiffness
7. Special Design Considerations
8. Example 12-Story Office with Distributed Frames
9. Example 12-Story Office with Reinforced Concrete Cores
10. Example 5-Story Residence with Wood-Frame Shear walls
Appendix A – Precalculated Design Capacities
Appendix B – Literature Review
This concludes The American Institute of Architects Continuing Education Systems Course

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Funding provided in part by the Softwood Lumber Board