DES440 - Primer for the use of Cross-laminated Timber
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Description

Increased availability of cross-laminated timber (CLT) in North America, combined with successful use in projects worldwide, has generated interest in its properties and performance within the U.S. design community. With the inclusion of CLT in the 2015 International Building Code (IBC) and 2015 National Design Specification® (NDS®) for Wood Construction, curiosity is evolving throughout the construction industry to use CLT in projects. Applications for the use of CLT include roof and floor systems as well as walls systems. This presentation will cover the available U.S. design standards and methods being used by engineers on these projects.
Learning Objectives

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

Polling Question

1. What is your profession?
   a) Architect/Building Designer
   b) Engineer
   c) Code Official
   d) Builder/Product Manufacturer
   e) Other
Outline

- CLT Building Examples
- CLT intro IBC, NDS, ANSI/APA PRG-320
- Overall structural system approaches
- CLT Floor & Roof design
- Wall/Column considerations
- Horizontal Diaphragms
- Vertical lateral resisting system

Traditional Stick Framed Construction
Stadhaus, London, UK

Climate Change

Carbon Footprint – Climate Change

Natural or Anthropogenic? (human activity)

Solar Radiation

Greenhouse Gases:
- Water vapor
- Carbon dioxide
- Methane
- Ozone
The Story of Wood – Wood Carbon Cycle

Climate Change: The Role of CO₂

2,400 sf home = 32 m³ structural wood = 29 metric tons CO₂ = 5.7 passenger annual emissions

Source: FP Innovations
Climate Change

Stradthaus – 24 Murray Grove
London infill project
29 flats
4x less weight than concrete
~1/2 construction time of precast concrete
(saved 22 weeks 30%)
Saves 300 metric tons of CO2
21 years of building energy usage

Cross-laminated Timber (CLT)

Photo provided by FPInnovations
Mass Timber Concept - History of CLT

- 1985 1st CLT patent - France
- 1993 1st CLT projects - Switzerland and Germany
- 1995-1996 Improved press technology
- 1998 1st multi-story res building - Austria
- Early 2000’s
  - CLT use (Europe) increased significantly
  - Green building movement driven
  - Better efficiencies, product approvals, improved marketing and distribution channels
  - Over 500 CLT buildings in England
- Recent - US and Canadian use of CLT

CLT vs. GLT

Cross Laminated Timber

Glued Laminated Timber

Thick Orthotropic Plate

Beam-like member

Graphics provided by WoodWorks

Graphics provided by APA
International Projects

Bridport House

• Hackney, London, England
• 8 Stories
• Residential
Canadian Projects

**The Arbora**

- Québec, Canada
- 8 Stories
- 434 Residential condo, townhouse and rental units
The Arbora
Canadian Projects

Brock Commons
- Vancouver, British Columbia, Canada
- 18 Stories
- Mixed use student housing

US Projects

Elementary School, Franklin, West Virginia

Source: LignaTerra
US Projects

Private Army Hotel
Redstone Arsenal Huntsville, AL

Four stories 58,000 sq ft
Architect: Lend Lease

US Projects

• Albina Yard
  • Portland, Oregon
  • 4 Story (3 over 1)
  • Office, Retail
  • 16,000SF
  • Summer 2016

Client/Owner: Albina Yard LLC
Architect: Lever Architecture
General Contractor: Reworks
Structural Engineer: KPFF Consulting Engineers
US Projects

• **Framework**
  - Portland, Oregon
    - 12 Story
    - Currently in plan review, and is anticipated to be the tallest wood building in US when completed.
    - tallest Wood Building in US
    - Street-level retail, office, workforce housing and community space
    - U.S. Tall Wood Building Prize Competition winner *

* Sponsored by the U.S. Department of Agriculture, the Softwood Lumber Board, and the Binational Softwood Lumber Council

Photo provided by Next Portland
Outline

• CLT Building Examples
• CLT intro IBC, NDS, ANSI/APA PRG-320
• Overall structural system approaches
• CLT Floor & Roof design
• Wall/Column considerations
• Horizontal Diaphragms
• Vertical lateral resisting system

Fire Tests


Fire Test

American Wood Council
ASTM E119 Fire Endurance Test
• 5-Ply CLT (approx. 7” thick)
• 5/8” Type X GWB each side
• Sought 2 hour rating
• RESULTS: 3 hours 6 minutes

Where is CLT Allowed in IBC 2015?

**Code modifications to Ch. 23 Wood**
2303.1.4 Structural glued **cross laminated timber**. Cross-laminated timbers shall be manufactured and identified as required in ANSI/APA PRG 320-2011.

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

**Code modifications to Ch. 35 Reference Standards**
ANSI/APA PRG 320-2011 Standard for Performance-Rated **Cross-Laminated Timber**
### Where is CLT Allowed in IBC 2015?

**Type IV Construction**

602.4 Type IV. Type IV construction (Heavy Timber, HT) is that type of construction in which the exterior walls are of noncombustible materials and the interior building elements are of solid or laminated wood without concealed spaces. *Cross laminated timber (CLT)* dimensions used in this section are actual dimensions.

### Where is CLT allowed in IBC 2015?

**Type IV Construction – Exterior Walls**

602.4.2 *Cross-laminated timber* complying with Section 2303.1.4 shall be permitted within exterior wall assemblies with a 2-hour rating or less provided:

- Exterior surface of the *cross-laminated timber* is protected *fire retardant treated wood* sheathing complying with 2303.2 and not less than 15/32 inch thick;
- OR
- *gypsum board* not less than ½ inch thick;
- OR
- a noncombustible material.
Where is CLT allowed in IBC 2015?

Type IV Construction – Floors

602.4.6.2 CLT. Cross laminated timber shall be not less than 4 inches (102 mm) in thickness. It shall be continuous from support to support and mechanically fastened to one another. Cross laminated timber shall be permitted to be connected to walls without a shrinkage gap providing swelling or shrinking is considered in the design...

Where is CLT allowed in IBC 2015?

Type IV Construction – Roofs

602.4.7 Roofs. Roofs shall be without concealed spaces and wood roof decks shall be sawn or glued laminated... or of cross laminated timber... Cross laminated timber roofs shall be not less than 3 inch nominal in thickness and shall be continuous from support to support and mechanically fastened to one another.
Where is CLT allowed in IBC 2015?

Type IV Construction – Walls & Partitions

602.4.8.1 Interior walls and partitions. Interior walls and partitions shall be of solid wood construction formed by not less than two layers of 1-inch (25 mm) matched boards or laminated construction 4 inches (102 mm) thick, or of 1-hour fire-resistance-rated construction.

602.4.8.2 Exterior walls. All exterior walls shall be of one of the following:
1. Noncombustible materials; or
2. Not less than 6 inches in thickness and constructed of one of the following:
   2.1 Fire retardant treated wood in accordance with 2303.2 and complying with 602.4.1 or
   2.2. Cross laminated timber complying with 602.4.2.

Where is CLT allowed in IBC 2015?

Type III Construction –

602.3 Type III. Type III construction is that type of construction in which the exterior walls are of noncombustible materials and the interior building elements are of any material permitted by this code. Fire-retardant-treated wood framing complying with Section 2303.2 shall be permitted within exterior wall assemblies of a 2-hour rating or less.
Type III Construction

- So where could CLT go?
  - Almost anywhere!
- Exterior Walls need to be non-combustible or FRT Wood (2 hour or less)
- Interior any material permitted by code
- Roof

Where is CLT allowed in IBC 2015?

Type V Construction –

602.5 Type V. Type V construction is that type of construction in which the structural elements, exterior walls and interior walls are of any materials permitted by this code.
Where is CLT allowed in IBC 2015?

- All structural elements can be combustible construction
- Exterior walls
- Floor
- Roof
- Interior walls

Governing Codes for Wood Design

2015 IBC references in 2015 NDS
### 2015 NDS Chapter Reorganization

<table>
<thead>
<tr>
<th>2012 NDS</th>
<th>2015 NDS</th>
</tr>
</thead>
<tbody>
<tr>
<td>• 1-3 General</td>
<td>• 1-3 General</td>
</tr>
<tr>
<td>• 4-9 Products</td>
<td>• 4-10 Products +CLT</td>
</tr>
<tr>
<td>• 10-13 Connections</td>
<td>• 11-14 Connections</td>
</tr>
<tr>
<td>• 14 Shear Walls &amp; Diaphragms</td>
<td>• Shear Walls &amp; Diaphragms</td>
</tr>
<tr>
<td>• 15 Special Loading</td>
<td>• 15 Special Loading</td>
</tr>
<tr>
<td>• 16 Fire</td>
<td>• 16 Fire</td>
</tr>
</tbody>
</table>

### CLT Design: 2015 NDS

2015

1. General Requirements for Building Design
2. Design Values for Structural Members
3. Design Provisions and Equations
4. Sawn Lumber
5. Structural Glued Laminated Timber
6. Round Timber Poles and Piles
7. Prefabricated Wood I-Joists
8. Structural Composite Lumber
9. Wood Structural Panels
10. **Cross-laminated Timber**
11. Mechanical Connections
12. Dowel-Type Fasteners
13. Split Ring and Shear Plate Connectors
14. Timber Rivets
15. Special Loading Conditions
16. Fire Design of Wood Members
Chapter 10 – Cross-Laminated Timber

Product Marking

Marks contain the following:

a) CLT grade qualified
b) CLT thickness or identification
c) Mill name or identification number
d) Approved agency name or logo
e) “ANSI/APA PRG 320”
f) Manufacturer’s designation
g) “Top” stamped on top face (only for unbalanced layup)
Chapter 10 – Cross-Laminated Timber

1, 2, 3, 4 transverse layers
Single or multiple surface layers

Laminations: 5/8”-2” sawn lumber or SCL
Panel thickness: 20” max
In-Service MC: 16%

Graphics provided by FPInnovations

Chapter 10 – Cross-Laminated Timber

10.2 Reference Design Values

10.2.1 Reference Design Values

Reference design values for cross-laminated timber shall be obtained from the manufacturer’s literature or code evaluation report.

10.2.2 Design Section Properties

Reference design values shall be used with design section properties provided by the manufacturer based on the actual layup used in the manufacturing process.

10.3 Adjustment of Reference Design Values

10.3.1 General

Reference design values: F_{u}(S), F_{u}(A_{u}L_{u}), F_{u}(A), E_{u}, and E_{u}\text{nom}

10.3.2 Load Duration Factor, C_{b} (ASD only)

All reference design values except stiffness, E\text{nom}, E_{u}\text{nom}, rolling shear, F_{u}(B\text{nom})\text{nom}, and compression perpendicular to grain, F_{u}(A), shall be multiplied by load duration factors, C_{b}, as specified in 2.3.2.
CLT Product Reports

Cross-Laminated Timber (CLT)

INNOVATIVE SOLID WOOD PANELS OFFER NEW LARGE-SCALE DESIGN OPTIONS

CLT Basics
Cross-laminated timber (CLT) is a large-scale, prefabricated solid engineered wood panel. Lightweight yet very strong.

https://www.apawood.org/cross-laminated-timber

CLT Product Reports

APA PRODUCT REPORT

APA PRODUCT REPORT

APA PRODUCT REPORT

APA PRODUCT REPORT
**Chapter 10 – Cross-Laminated Timber**

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

<table>
<thead>
<tr>
<th>New</th>
<th>ASD only</th>
<th>ASD and LRFD</th>
<th>LRFD only</th>
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<tr>
<td></td>
<td>Load Distribution Factor</td>
<td>Wind Distribution Factor</td>
<td>Temperature Factor</td>
</tr>
<tr>
<td></td>
<td>$F_a(S_{aw}) = F_a(S_{sat})$</td>
<td>$C_D$</td>
<td>$C_M$</td>
</tr>
<tr>
<td></td>
<td>$F_a(A_{resistance}) = F_a(A_{resistance})$</td>
<td>$C_D$</td>
<td>$C_M$</td>
</tr>
<tr>
<td></td>
<td>$F_a(A_{resistance}) = F_a(A_{resistance})$</td>
<td>$C_D$</td>
<td>$C_M$</td>
</tr>
<tr>
<td></td>
<td>$F_d(B_{l}Q_{l}) = F_d(B_{l}Q_{l})$</td>
<td>$C_D$</td>
<td>$C_M$</td>
</tr>
<tr>
<td></td>
<td>$F_d(A_{resistance}) = F_d(A_{resistance})$</td>
<td>$C_D$</td>
<td>$C_M$</td>
</tr>
<tr>
<td></td>
<td>$F_d(A'Y = F_d(A)$</td>
<td>$C_D$</td>
<td>$C_M$</td>
</tr>
<tr>
<td></td>
<td>$(E_d)_{yp} = (E_d)$</td>
<td>$C_D$</td>
<td>$C_M$</td>
</tr>
<tr>
<td></td>
<td>$(E_d)_{yp} = (E_d)$</td>
<td>$C_D$</td>
<td>$C_M$</td>
</tr>
</tbody>
</table>

**CLT Manufacturing Standard**

### Table 1 Required Characteristic Test Values (ksi) for PRG 320 CLT

<table>
<thead>
<tr>
<th>CLT Grades</th>
<th>$f_{ty}$ (ksi)</th>
<th>$f_{ty}$ (10^3 psi)</th>
<th>$f_{ty}$ (psi)</th>
<th>$f_{ty}$ (psi)</th>
<th>$f_{ty}$ (psi)</th>
<th>$f_{ty}$ (psi)</th>
<th>$f_{ty}$ (psi)</th>
<th>$f_{ty}$ (psi)</th>
<th>$f_{ty}$ (psi)</th>
<th>$f_{ty}$ (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>E1</td>
<td>4,095</td>
<td>1.7</td>
<td>2,885</td>
<td>3,420</td>
<td>425</td>
<td>140</td>
<td>1,050</td>
<td>1.2</td>
<td>425</td>
<td>140</td>
</tr>
<tr>
<td>E2</td>
<td>3,465</td>
<td>1.5</td>
<td>2,140</td>
<td>3,230</td>
<td>565</td>
<td>190</td>
<td>1,100</td>
<td>1.4</td>
<td>565</td>
<td>190</td>
</tr>
<tr>
<td>E3</td>
<td>2,500</td>
<td>1.2</td>
<td>1,260</td>
<td>2,640</td>
<td>345</td>
<td>115</td>
<td>735</td>
<td>0.9</td>
<td>345</td>
<td>115</td>
</tr>
<tr>
<td>E4</td>
<td>4,095</td>
<td>1.7</td>
<td>2,885</td>
<td>3,420</td>
<td>550</td>
<td>180</td>
<td>1,205</td>
<td>1.4</td>
<td>550</td>
<td>180</td>
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<tr>
<td>V1</td>
<td>1,890</td>
<td>1.6</td>
<td>1,155</td>
<td>2,755</td>
<td>550</td>
<td>180</td>
<td>1,205</td>
<td>1.4</td>
<td>550</td>
<td>180</td>
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<tr>
<td>V2</td>
<td>1,825</td>
<td>1.4</td>
<td>945</td>
<td>2,185</td>
<td>425</td>
<td>140</td>
<td>1,050</td>
<td>1.2</td>
<td>425</td>
<td>140</td>
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<tr>
<td>V3</td>
<td>2,045</td>
<td>1.6</td>
<td>1,155</td>
<td>2,755</td>
<td>550</td>
<td>180</td>
<td>1,205</td>
<td>1.4</td>
<td>550</td>
<td>180</td>
</tr>
</tbody>
</table>

Typical standard layups 3 (roof) or 5 (floor) plies of lumber.
CLT Manufacturing Standard

TABLE A1
ALLOWABLE DESIGN PROPERTIES** FOR PRG 320 CLT (FOR USE IN THE U.S.)

<table>
<thead>
<tr>
<th>CLT Grades</th>
<th>CLT Grades</th>
<th>F_{ck} (ksi)</th>
<th>F_{m} (ksi)</th>
<th>F_{ek} (ksi)</th>
<th>F_{ck} (psi)</th>
<th>F_{m} (psi)</th>
<th>F_{ek} (psi)</th>
<th>F_{ck} (ksi)</th>
<th>F_{m} (ksi)</th>
<th>F_{ek} (ksi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>E1</td>
<td>1.950</td>
<td>1.2</td>
<td>1.375</td>
<td>1.800</td>
<td>135</td>
<td>500</td>
<td>1.2</td>
<td>135</td>
<td>45</td>
<td>500</td>
</tr>
<tr>
<td>E2</td>
<td>1.650</td>
<td>1.5</td>
<td>1.020</td>
<td>1.700</td>
<td>180</td>
<td>60</td>
<td>1.4</td>
<td>180</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>E3</td>
<td>1.200</td>
<td>1.2</td>
<td>1.600</td>
<td>1.400</td>
<td>110</td>
<td>33</td>
<td>0.9</td>
<td>110</td>
<td>33</td>
<td>330</td>
</tr>
<tr>
<td>E4</td>
<td>1.950</td>
<td>1.7</td>
<td>1.375</td>
<td>1.800</td>
<td>135</td>
<td>500</td>
<td>1.2</td>
<td>135</td>
<td>45</td>
<td>500</td>
</tr>
<tr>
<td>V1</td>
<td>1.900</td>
<td>1.6</td>
<td>1.575</td>
<td>1.350</td>
<td>180</td>
<td>60</td>
<td>1.4</td>
<td>180</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>V2</td>
<td>1.975</td>
<td>1.6</td>
<td>1.450</td>
<td>1.150</td>
<td>135</td>
<td>45</td>
<td>1.2</td>
<td>135</td>
<td>45</td>
<td>500</td>
</tr>
<tr>
<td>V3</td>
<td>1.975</td>
<td>1.6</td>
<td>1.450</td>
<td>1.150</td>
<td>135</td>
<td>45</td>
<td>1.2</td>
<td>135</td>
<td>45</td>
<td>500</td>
</tr>
</tbody>
</table>

For SI: 1 psi = 0.006895 MPa
(a) See Section 4 for symbols.
(b) Tabulated values are allowable design values and are permitted to be increased for the lumber size adjustment factor in accordance with the NDS. The design values shall be used in conjunction with the section properties provided by the CLT manufacturer based on the actual layup used in manufacturing the CLT panel (see Table 4.2).
(c) Custom CLT grades that are not listed in this table shall be permitted in accordance with Section 7.7.1

CLT Grades:

- **E1**: 1900F-1.7E Spruce-pine-fir MSR lumber in all parallel layers and No. 3 Spruce-pine-fir lumber in all perpendicular layers
- **E2**: 1650F-1.5E Douglas fir-Larch MSR lumber in all parallel layers and No. 3 Douglas fir-Larch lumber in all perpendicular layers
- **E3**: 1200F-1.2E Eastern Softwoods, Northern Species, or Western Woods MSR lumber in all parallel layers and No. 3 Eastern Softwoods, Northern Species, or Western Woods lumber in all perpendicular layers
- **E4**: 1900F-1.7E Southern pine MSR lumber in all parallel layers and No. 3 Southern pine lumber in all perpendicular layers
- **V1**: No. 2 Douglas fir-Larch lumber in all parallel layers and No. 3 Douglas fir-Larch lumber in all perpendicular layers
- **V2**: No. 2 No. 2 Spruce-pine-fir lumber in all parallel layers and No. 3 Spruce-pine-fir lumber in all perpendicular layers
- **V3**: No. 2 Southern pine lumber in all parallel layers and No. 3 Southern pine lumber in all perpendicular layers
CLT Manufacturing Standard

Polling Question

2. CLT has the following characteristics
   a) Laminations of 5/8”-2” thick
   b) Laminations of sawn lumber or SCL
   c) Laminations all oriented in one direction
   d) All of the above
   e) a) and b)
Seismic Design Options

- **ASCE 7 Minimum Design Loads for Buildings and Other Structures**
- **Response Modification Coefficient, R**
  - CLT not recognized system in ASCE 7 Table 12.2-1
- **Options**
  - Performance-based design procedure per ASCE 7
  - Demonstrating equivalence to an existing ASCE 7 system
  - ASCE 7-10, FEMA P695, and FEMA P795 Quantification of Building Seismic Performance Factors; Component Equivalency Methodology
Chapter 16 – Fire (ASD)

- Fire resistance up to **two hours**
  - Columns
  - Beams
  - Tension Members
  - ASD only
- **Products**
  - Lumber
  - GLT
  - SCL
  - Decking
  - CLT - NEW

**SECTION 722**
**CALCULATED FIRE RESISTANCE**

722.1 General. The provisions of this section contain procedures by which the fire resistance of specific materials or combinations of materials is established by calculations. These procedures apply only to the information contained in this section and shall be otherwise used. The calculated fire resistance of concrete, concrete masonry and clay masonry assemblies shall be permitted in accordance with ACI 216.1/MTS 0216. The calculated fire resistance of steel assemblies shall be permitted in accordance with Chapter 5 of ASCE 19. The calculated fire resistance of exposed wood members and wood decking shall be permitted in accordance with Chapter 10 of ANSI/AF&PA National Design Specification for Wood Construction (NDS).

Heavy Timber Fire Resistance Rating

Photo by Structure Magazine
Fire Performance Glulam vs. Steel

NDS Chapter 16 – Calculated Resistance

- Fire resistance of exposed wood members may be calculated using the provisions of NDS Chapter 16

Predictable
Chapter 16 – Fire Design of Wood Members

- Mechanics Based Model
- Supported by empirical data
- NLT, GLT & CLT

### 2015 NDS Methodology

#### Fire Design of Exposed Wood Members

#### Allowable Stress Design

*Table 16.2.2 Adjustment Factors for Fire Design*

<table>
<thead>
<tr>
<th>Strength Type</th>
<th>Design Stress Factor</th>
<th>Size Factor</th>
<th>Volume Factor</th>
<th>Plant Use Factor</th>
<th>Beam Stability Factor</th>
<th>Column Stability Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bending Strength</td>
<td>$F_b$</td>
<td>2.85</td>
<td>$C_F$</td>
<td>$C_V$</td>
<td>$C_{fs}$</td>
<td>$C_L$</td>
</tr>
<tr>
<td>Beam Buckling Strength</td>
<td>$F_{bm}$</td>
<td>2.03</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Tensile Strength</td>
<td>$F_t$</td>
<td>2.85</td>
<td>$C_P$</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Compressive Strength</td>
<td>$F_c$</td>
<td>2.58</td>
<td>$C_P$</td>
<td>-</td>
<td>-</td>
<td>$C_P$</td>
</tr>
<tr>
<td>Column Buckling Strength</td>
<td>$F_{cv}$</td>
<td>2.03</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

1. See 4.3, 5.3, 8.3, and 10.3 for applicability of adjustment factors for specific products.
2. Factor shall be based on initial cross-section dimensions.
3. Factor shall be based on rebated cross-section dimensions.
Fire Design of Exposed Wood Members

Cross-laminated Timber - Effective Char Depth

\[ a_{\text{char}} = 1.2 \left[ n_{\text{lam}} h_{\text{lam}} + \beta_n \left( t - (n_{\text{lam}} t_{gi}) \right)^{0.813} \right] \]

\[ t_{gi} = \left( \frac{h_{\text{lam}}}{\beta_n} \right)^{1.23} \]

- \( t_{gi} \): time for char front to reach glued interface (hr.)
- \( h_{\text{lam}} \): lamination thickness (in.)
- \( n_{\text{lam}} \): number of laminations charred (rounded to lowest integer)
- \( t \): exposure time (hr.)

CLT manufactured with laminations of equal thickness

<table>
<thead>
<tr>
<th>Required</th>
<th>Effective Char Depths, ( a_{\text{char}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fire Endurance</td>
<td>lamination thickness, ( h_{\text{lam}} ) (in.)</td>
</tr>
<tr>
<td>(hr.)</td>
<td>5/8 3/4 7/8 1 1-1/4 1-3/8 1-1/2 1-3/4 2</td>
</tr>
<tr>
<td>1-Hour</td>
<td>2.2 2.2 2.1 2.0 2.0 1.9 1.8 1.8 1.8</td>
</tr>
<tr>
<td>1/2-Hour</td>
<td>3.4 3.2 3.1 3.0 2.9 2.8 2.8 2.8 2.6</td>
</tr>
<tr>
<td>2-Hour</td>
<td>4.4 4.3 4.1 4.0 3.9 3.8 3.6 3.6 3.6</td>
</tr>
</tbody>
</table>
GLT and CLT Adhesives

CLT - ANSI/APA PRG 320-2011 references ANSI/AITC 405-2008
GLT - ANSI/AITC 405-2008 – references D7247

CLT-ANSI/APA PRG 320-2012 references ANSI/APA 405-2008
GLT - ANSI/APA 405-2008 – references D7247
Fire-Resistance of Exposed Wood

- **16.3 Wood Connections**
  - Where fire endurance is required, connectors and fasteners shall be protected from fire exposure
    - Wood
    - Fire-rated gypsum board

NDS Chapter 16 – Fire (ASD)

Technical Report No. 10
- Background on NDS provisions
- Design examples
- Updated with CLT

Free download www.awc.org
TR-10 CLT Design Example

4.5 Exposed CLT Floor Example (Allowable Stress Design)

Simply-supported cross-laminated timber (CLT) floor spanning L=18 ft in the long-axis direction. The design loads are q_{sta} = 80 psf and q_{int} = 30 psf including estimated self-weight of the CLT panel. Floor decking, nailed to the unexposed face of CLT panel, is spaced to restrict hot gases from venting through half-lap joints at edges of CLT panel sections. Calculate the required section dimensions for a one-hour fire resistance.

4.6 Exposed CLT Wall Example (Allowable Stress Design)

Cross-laminated timber (CLT) wall with an unbraced height of L=120 inches and loaded in compression in the long-axis direction. The design loads are w_{sta} = 14,000 psf and w_{int} = 6,150 psf including estimated self-weight of the CLT panel. Walls above are supported on a CLT floor slab and aligned with a CLT wall below. Use of fire-rated caulkings of wall joints restricts hot gases from venting through half-lap joints at edges of CLT panel sections. Calculate the required section dimensions for a 2-hr fire resistance time from the CLT.

Calculate column load:

\[ P_{\text{load}} = P_{\text{dead}} + P_{\text{live}} = 6,150 \text{ psf} + 14,000 \text{ psf} = 20,150 \text{ lb/foot of width}. \]

From PRG 320, select a 7-ply CLT panel made from 1/16 in x 3/4 in thickness (CLT thickness of 9 in). For CLT grade E1, tabulated properties are:

- Compression stress, \( f_{c,l} = 1800 \text{ psi} \) (PRG 320 Annex A, Table A1)
- Bending moment, \( f_{b,l} = 18.375 \text{ ft-lb/ft of width} \) (PRG 320 Annex A, Table A2)
- Bending stiffness, \( E_{l,\text{eff}} = 1.089 \times 10^{6} \text{ lb-in}^{2}/\text{ft of width} \) (PRG 320 Annex A, Table A2)
- Shear stiffness, \( G_{l,\text{eff}} = 1.4 \times 10^{5} \text{ lb/ln of width} \) (PRG 320 Annex A, Table A2)

Recent Demonstration Fire Tests
Recent Demonstration Fire Tests

Heat Release Rate

Compartment Temperatures (°F)

ASTM E119 Curve

Recent Demonstration Fire Tests

Room after 60 minutes

Room after drywall removed following the three-hour test

CLT Test

American Wood Council Webinar, September 18, 2015

Furnished Living Room Fire Tests in Compartments Of CLT and NLT Construction

Marc L. Janssens, Ph.D., FSFPE
Senior Engineer
Southwest Research Institute
6220 Culebra Road, San Antonio, TX
Resources

- [www.awc.org](http://www.awc.org)
- Print versions
- PDF versions
Resources

• **Structure Magazine**
  - 2015 NDS
    - January 2015
  - 2015 SDPWS
    - July 2015

• **www.awc.org**

Outline

• CLT Building Examples
• CLT intro IBC, NDS, ANSI/APA PRG-320
• **Overall structural system approaches**
• CLT Floor & Roof design
• Wall/Column considerations
• Horizontal Diaphragms
• Vertical lateral resisting system
Wood Building Systems

Mass Timber Structural Systems

Mass Timber Structural Systems

Gravity Framing Styles

Lateral Force Systems
Mass Timber Framing Styles

Gravity Framing Styles

- Post & Beam
- Two-Way Panel Deck
- “Honeycomb”

ALBINA YARD
PORTLAND, OR

ARCHITECT: Lever Architecture
Photo: Scott Breneman

4 stories
16,000 sf
Green Roof
• 3 Stories
• 25’x25’ Grid
• 15’-18’ floor to floor heights
• Composite floor: 2x4 and 2x6 NLT floor panels with 3 ½” reinforced concrete topping
• All MEP exposed

HUDSON BUILDING
VANCOUVER, WA

DEVELOPER: Killian Pacific and Mackenzie
PHOTO CREDIT: WoodWorks

T3 Minneapolis
Minneapolis, MN

Image Credit: Blaine Brownell
Innovative Floor Systems

Considerations:

• Connection needs to be carefully designed
• Difficult to ensure design capacity if concrete is poured on site
• Detail needs to accommodate the moisture conflict between the materials

Timber Concrete Composites

Graphic Credit: StructureCraft
Wood Innovation Design Center
Prince George, British Columbia
8 Levels/6 Stories
97 feet tall
Completed Fall 2014
Mass Timber Framing Styles

- Gravity Framing Styles
- Post & Beam
- Two-Way Panel Deck
- “Honeycomb”

BROCK COMMONS
17 Stories of Timber Installation
Started June 6, 2016
Finished August 10, 2016
VANCOUVER, BC

Copyright 2017 WoodWorks
STARTED NOVEMBER 2015
BROCK COMMONS
BRITISH COLUMBIA, CANADA

TallWood House at Brock Commons
https://vimeo.com/woodproductscouncil/review/201122225/d69a9226

Chicago Horizon Pavilion
Chicago, IL

Photo Credit: Tom Harris
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

Mass Timber Framing Styles

- Gravity Framing Styles
- Post & Beam
- Two-Way Panel Deck
- “Honeycomb”
• 62,600 sf, 4 story hotel, 92 private rooms
• CLT utilized for walls, roof panels, and floor panels
• 1,557 CLT Panels; Typical floor panel is 8’x50’ & weighs 8,000 lbs
• Completed Late 2015
Polling Question

3. Which of the Following is NOT a common framing style used with CLT?
   a) Post & Beam Framing
   b) 2-Way CLT panel spans
   c) 3-D Space Truss
   d) CLT floors supported on CLT Walls

Product Availability

- Producers of structural CLT certified to the ANSI/APA PRG-320 standard:
  - D.R. Johnson Lumber, Riddle, Oregon
  - Nordic Structures in Quebec, Canada
  - SmartLam, Columbia Fall, Montana
  - Structurlam in Penticton British Columbia, Canada
**Structural Section Properties**

Non-homogenous, anisotropic material

---

**Flexural Strength**

Design Properties based on Extreme Fiber Model:

Flexural Capacity Check:

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

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

*Reference: NDS 2015*
**Flexural Strength**

Design Properties based on Extreme Fiber Model:

Flexural Capacity Check (ASD)

\[(F_{bS_{eff}})' = C_D \cdot C_M \cdot C_t \cdot C_L \cdot (F_{bS_{eff}})\]

From Manufacturer

Commonly 1.0

per NDS

\[M_b \leq C_D \cdot (1.0) \cdot (F_{bS_{eff}})\]

*Reference: NDS 2015 & Product Reports*

---

**Design Example: Flexure**

Select acceptable CLT section

**Given:**

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

**Assume:**

- one-way spanning action in major axis of CLT

ASD Dead + Live Flexural Demands:

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

---
Design Example: Flexure

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

Reference: ANSI/APA PRG 320-2012

Design Example: Flexure

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

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

\[= 1.0 (1.0) (4675 \text{ lb-ft/ft})\]

\[= 4675 \text{ lb-ft/ft}\]

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

Flexural Strength OK
Shear Strength

Design Properties based on Extreme Fiber Model:

Shear Capacity Check (ASD):

\[ V_{\text{planar}} \leq F_s (\text{Ib/Q})_{\text{eff}}' \]

\[ V_{\text{planar}} = \text{applied shear} \]

\[ F_s (\text{Ib/Q})_{\text{eff}}' = \text{adjusted shear strength} \]

Reference: NDS 2015 & Product Reports
**Flexural Stiffness**

Shear Analogy Method

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

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

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

*Reference: US CLT Handbook Chapter 3*
Important to develop properties of new CLT Sections. Not to use standard CLT Sections.

Flexural Stiffness

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

Shear Stiffness

\[ GA_{\text{eff}} = \left( \frac{h}{2 \cdot G_i \cdot b} \right) + \left( \frac{\sum h_i}{\sum G_i \cdot b} \right) + \left( \frac{h_s}{2 \cdot G_s \cdot b} \right) \]

Structural Section Properties

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

Values in RED provided by CLT manufacturer

Reference: PRG 320 and CLT Product Reports
Deflection Calculations

General Purpose, 2 Way, Plate Action

Flexural Stiffness

\[ E_{I_{\text{eff}},0} \quad E_{I_{\text{eff}},90} \]

Shear Stiffness:

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

5/6 from \( A' = \frac{5}{6} A \) shape factor for rectangular sections

Deflection Calculations

General Purpose: 1 Way, Beam Action

Stiffness: \( E_{I_{\text{eff}},0} \quad \frac{5}{6} G_{A_{\text{eff}},0} \)

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

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

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

Design Example:
$= 0.161 \text{ in} + 0.02 \text{ in} = 0.183 \text{ in}$
$= L / 1050$

Deflection Calculations

Simplified Beam Deflections:
Given load pattern and support conditions:

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

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

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

Reference: US CLT Handbook
Deflection Calculations

Simplified Beam Deflections

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

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

US CLT Handbook & NDS 2015 Commentary

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

NDS 2015

For Major Axis Spans:

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

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

$$G_o = E_o / 16$$


Deflection Calculations

Simplified Beam Deflections

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

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

Apparent Flexural Stiffness depends on Span Length

$L_1 = 20$ foot

$Ei_{app1} \neq Ei_{app2}$

$L_2 = 16$ foot
Creep Factor

Deformation to Long Term Loads

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

NDS Eq 3.5-1

- \( \Delta_{ST} \): 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

Reference: NDS 2015

Floor Vibration

Occupant perception of vibration is a highly recommended design consideration.

One approach: CLT Handbook, Chapter 7

Calculated natural frequency of simple span:

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

Where:

- \( EI_{app} \): apparent stiffness for 1 foot strip, pinned supported, uniformly loaded, simple span
  \( (K_s = 11.5) \text{ (lb-in}^2\text{)} \)
- \( \rho \): specific gravity of the CLT
- \( A \): the cross section area (thickness x 12 inches) (in\(^2\))

Reference: US CLT Handbook, Chapter 7
Floor Vibration

CLT Handbook, Chapter 7 recommends,

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

and

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

Reference: US CLT Handbook, Chapter 7

Floor Vibration

CLT Handbook, Chapter 7 method:

Natural frequencies above 9 Hz and:

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

\[ EI_{app} = \frac{EI_{eff}}{1 + \frac{K}{G A_L} L} \]

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

Only depends on CLT section properties, so...

Values calculated and provided by CLT Manufactures

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

Reference: US CLT Handbook, Chapter 7
Floor Vibration

Occupant perception of vibration a recommended design consideration

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

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

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

Alternative Vibration Criteria

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

_ Calibration of dynamic modeling with physical testing valuable_
Alternative Vibration Criteria

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

AISC Design Guide 11 not for dynamic modeling of CLT floors

Connection Styles

Floor Panel to Floor Panel
- Single Surface Spline
- Half Lap
Connection Styles

Floor Panel to Wall

- Platform Frame with Double Brackets
- Platform Frame with Single Brackets

Platform Frame With Only Screws
Long self tapping screws used extensively throughout mass timber construction.

Proprietary Connector Products

Variety of Self Tapping Screws
Polling Question

4. TRUE or FALSE: CLT deflections can only be calculated using a simply supported beam strip analysis?
   a) TRUE
   b) FALSE
CLT in Lateral Force Resisting Systems

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

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

Source: The Cross Laminated Timber Design Guide v11 from Structurlam
Connections Determine Lateral Strength

Similar to Wood Structural Panel Shear Walls

Light frame shear wall strength is dependent on perimeter (edge) nailing

Source: SDPWS 2008

Connections Determine Lateral Strength

Similar to Wood Structural Panel Shear Walls

CLT Shear Strength Depends on Connections

Source: US CLT Handbook
CLT in NDS 2015 - Connectors

Connectors for CLT in NDS 2015:
Dowel Type Fasteners, e.g. Lag Screws, Bolts and Nails

Figure 12T

Seismic Design

CLT Seismic Force Resisting Systems Not addressed In

ASCE/SEI 7-10
SDPWS 2015
Commercial Office
Portland, OR

4 Stories of Wood (office) over 1 Story of Concrete
(Retail & Parking)
6,800 sf
Completed 2015

Mass Timber Design
Lateral Framing Systems

Interior Wood Shearwalls
Photo Credit: woodworks
“This is a terrific building that echoes the historic character of the workspaces in the Central Eastside, but takes it a step further with this incredible wood construction.”
Portland Metro Councilor Bob Stacey
CLT Shear Wall Seismic Design Values

*What R value can I use?*
FEMA P-695 Research in Progress for CLT Shear Walls

- Project Lead: John van de Lindt, Colorado State University

Design Method

Testing

Modeling

Peer Review

Report

State of Oregon Statewide Alternative
### State of Oregon Statewide Alternative

- ASCE 7-10 Table 12.2-1 modified by Oregon Buildings Code Division

#### Table 12.2-1 Design Coefficients and Factors for Seismic Force-Resisting Systems

| Seismic Force-Resisting System | ASCE 7 Section Where Detailing Requirements Are Specified | Response Modification Coefficient, \( R^* \) | Overstrength Factor, \( \Omega^* \) | Deflection Amplification Factor, \( C^* \) | Structural System Limitations Including Structural Height, \( H_s \) (ft) Limita[
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>A. BEARING WALL SYSTEMS</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>
</tr>
<tr>
<td>19. Cross-laminated timber shear walls</td>
<td>14.1 and 14.5</td>
<td>2</td>
<td>2 ½</td>
<td>2</td>
<td>NL</td>
</tr>
</tbody>
</table>

---

### Mass Timber Design

Lateral Framing Systems

Central Core – Mass Timber Shearwalls

Photo Credit: Alex Schreyer
Structural Testing – Lateral Systems

Cross-Laminated Timber Post-Tensioned Rocking Shear Walls

CLT Post Tension Rocking Shear Wall Test

Source: S. PEI et al.
Framework, Portland, OR

• Owner: Beneficial Bank & Home Forward
• Developer: Project^*
• Architect: Lever Architecture
• Structural: KPFF
• Fire: Arup
• Height: 130’ / 12 stories
• Total Building Area: 90,000 square feet
• Mixed Use: Retail, Office, Residential
• Materials: Cross Laminated Timber floors and lateral force resisting system; Glue laminated beams and columns
Polling Question

**5. Lateral Force Resisting Systems which have been used with CLT floors and roofs include:**

a) CLT shear walls via alternative-means
b) Wood structural panel sheathed shear walls
c) Steel braced frames
d) All of the above
CLT Diaphragm Design?

Source: A Ceccotti in the US CLT Handbook

Completed Panel to Panel Tests

- MyTiCon & University of British Columbia
- Also Colorado State, Oregon State

![Completed Panel to Panel Tests Diagram]

Copyright 2017 WoodWorks
Diaphragm Design Example by Spickler et al.

CROSS LAMINATED TIMBER
Horizontal Diaphragm Design Example

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

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

Applicable Building Code, reference standards, and other information sources:
- IBC, 2015 International Building Code
- SHWC Special Design Provisions for Wood and Concrete
- ASCE 7-10 Minimum Design Loads for Buildings and Other Structures
- AISC 341-10 Specification for Structural Steel Buildings

Diaphragm Design Example by Spickler et al.

3 Ply CLT Panels

Shear Wall

Lateral load, w
1000 plf (14.6 kN/m)
CLT Diaphragms in US Seismic Applications

Calculated Diaphragm Deflections

OR

Enveloped Diaphragm Design

(check for both flexible and rigid diaphragm behavior)

(check for conservatively flexible and conservatively stiff semi-rigid behavior)

Diaphragm Design Example by Spickler et al.

• Detailed design example for simple diaphragm following NDS 2015, US CLT Handbook

• Includes approximate deflection equation:
  • Modified 4-term wood panel sheathed diaphragm equation in SDWPS 15

\[
\delta_{dia} = \frac{5\nu L^3}{8EAW} + \frac{\nu L}{4G\epsilon} + \frac{CLe_n}{2W} + \frac{\sum (\Delta_e)}{2W}
\]

\[
C = \frac{1}{2} \left( \frac{1}{P_L} + \frac{1}{P_W} \right)
\]

- \(P_L\) is panel length
- \(P_W\) is panel width
- \(e_n\) is connector slip at diaphragm edge
Possible Modelling Approaches

Explicit model of CLT panel layout with connection in limited locations. Multi directional springs to model connections.

Different connection elements types per panel length. Few connection elements.

FEM Modeling for Design Work

- Semi-Rigid Analysis of Diaphragm in SAP 2000
- Modelled to match design example assumptions
- Concentrated Connection Model
  - 4 Springs per corner
  - With No Chord Slip, 4% difference in deflections
  - With Chord Slip, 11% difference in deflections
A Real Application: Framework 12 Story Project

Example Detail Conditions

CLT Panels Ends Supported on Beam

Typical CLT Span Direction
Example Modeled Diaphragm Deflections

East-West Loading

North-South Loading

WoodWorks Solutions Paper on CLT Modeling

June 2016 Structures Magazine Article

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Questions?

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Links to online resources at [www.woodworks.org](http://www.woodworks.org):