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
Climate Change

Carbon Footprint – Climate Change

- Greenhouse Gases:
  - Water vapor
  - Carbon dioxide
  - Methane
  - Ozone

Natural or Anthropogenic?
(human activity)

Solar Radiation
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)
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
- Thick Orthotropic Plate

Glued Laminated Timber
- Beam-like member

Graphics provided by APA
 Graphics provided by WoodWorks
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 *


Photo provided by Next Portland
Outline

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- CLT intro IBC, NDS, ANSI/APA PRG-320
- Overall structural system approaches
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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**
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.

---

#### 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.
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>
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<tr>
<td>• 4-9 Products</td>
<td>• 4-10 Products +CLT</td>
</tr>
<tr>
<td>• 10-13 Connections</td>
<td>• 11-14 Connections</td>
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<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>

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### 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

New

10.1 General

10.1.1 Application

Chapter 10 applies to engineering design with performance-rated cross-laminated timber.

Design procedures, reference design values and other information in this chapter apply only to performance-rated cross-laminated timber produced in accordance with ANSI/APA PRG 320.

10.1.2 Definition

Cross-Laminated Timber (CLT) – 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.

10.1.3 Standard Dimensions

10.1.3.1 The net thickness of a lamination for all layers at the time of gluing shall not be less than 5/8 inch or more than 2 inches.

10.1.3.2 The thickness of cross-laminated timber shall not exceed 20 inches.

10.1.4 Specification

All required reference designations shall be specified.

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

4/11/2017
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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

https://www.apawood.org/cross-laminated-timber
Chapter 10 – Cross-Laminated Timber

CLT Manufacturing Standard

### 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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<tbody>
<tr>
<td></td>
<td>Load Factor</td>
<td>Material Factor</td>
<td>Temperature Factor</td>
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<tr>
<td>$F_a(S_{w}^A) = F_a(S_{w})$</td>
<td>$C_D$</td>
<td>$C_M$</td>
<td>$C_T$</td>
</tr>
<tr>
<td>$F_a(S_{p}^A) = F_a(S_{p})$</td>
<td>$C_D$</td>
<td>$C_M$</td>
<td>$C_T$</td>
</tr>
<tr>
<td>$F_a(S_{w}^B) = F_a(S_{w})$</td>
<td>$C_D$</td>
<td>$C_M$</td>
<td>$C_T$</td>
</tr>
<tr>
<td>$F_a(B_{w}Q)^A = F_a(B_{w}Q)^L$</td>
<td>$C_D$</td>
<td>$C_M$</td>
<td>$C_T$</td>
</tr>
<tr>
<td>$F_a(A_{p}^A) = F_a(A_{p})$</td>
<td>$C_D$</td>
<td>$C_M$</td>
<td>$C_T$</td>
</tr>
<tr>
<td>$F_a(A_{p}^B) = F_a(A_{p})$</td>
<td>$C_D$</td>
<td>$C_M$</td>
<td>$C_T$</td>
</tr>
<tr>
<td>$(EI)<em>{pp}^A = (EI)</em>{pp}$</td>
<td>$C_D$</td>
<td>$C_M$</td>
<td>$C_T$</td>
</tr>
<tr>
<td>$(EI)<em>{pp}^B = (EI)</em>{pp}$</td>
<td>$C_D$</td>
<td>$C_M$</td>
<td>$C_T$</td>
</tr>
</tbody>
</table>

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

### TABLE A1

<table>
<thead>
<tr>
<th>CLT Grades</th>
<th>$F_{s10}$ (ksi)</th>
<th>$F_{s1}$ (ksi)</th>
<th>$F_{s2}$ (ksi)</th>
<th>$F_{s3}$ (ksi)</th>
<th>$F_{s4}$ (ksi)</th>
<th>$F_{s5}$ (ksi)</th>
<th>$F_{s6}$ (ksi)</th>
<th>$F_{s7}$ (ksi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>E1</td>
<td>1.950</td>
<td>1.7</td>
<td>1.375</td>
<td>1.800</td>
<td>1.135</td>
<td>0.45</td>
<td>0.50</td>
<td>1.2</td>
</tr>
<tr>
<td>E2</td>
<td>1.650</td>
<td>1.5</td>
<td>1.020</td>
<td>1.700</td>
<td>1.180</td>
<td>0.60</td>
<td>0.525</td>
<td>1.4</td>
</tr>
<tr>
<td>E3</td>
<td>1.200</td>
<td>1.2</td>
<td>0.600</td>
<td>1.400</td>
<td>1.110</td>
<td>0.30</td>
<td>0.325</td>
<td>0.9</td>
</tr>
<tr>
<td>E4</td>
<td>1.950</td>
<td>1.7</td>
<td>1.375</td>
<td>1.800</td>
<td>1.175</td>
<td>0.55</td>
<td>0.575</td>
<td>1.4</td>
</tr>
<tr>
<td>Y1</td>
<td>0.900</td>
<td>1.6</td>
<td>0.575</td>
<td>1.250</td>
<td>1.180</td>
<td>0.60</td>
<td>0.525</td>
<td>1.4</td>
</tr>
<tr>
<td>V1</td>
<td>0.875</td>
<td>1.4</td>
<td>0.430</td>
<td>1.150</td>
<td>1.135</td>
<td>0.45</td>
<td>0.50</td>
<td>1.2</td>
</tr>
<tr>
<td>V2</td>
<td>0.975</td>
<td>1.6</td>
<td>0.550</td>
<td>1.450</td>
<td>1.175</td>
<td>0.55</td>
<td>0.575</td>
<td>1.4</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 listed in the section layout used in monitoring the CLT panel (see Table A.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:** 1950f-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:** 1950f-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. 1No. 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

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
2015 NDS Methodology

- Chapter 16 – Fire Design of Wood Members
- Mechanics Based Model
- Supported by empirical data
- NLT, GLT & CLT

Fire Design of Exposed Wood Members

Allowable Stress Design

Table 16.2.2 Adjustment Factors for Fire Design

<table>
<thead>
<tr>
<th>ASD</th>
<th>Design Stress in</th>
<th>Size Factor</th>
<th>Volume Factor</th>
<th>Flat Use Factor</th>
<th>Beam Stability Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bending Strength</td>
<td>F_b</td>
<td>x</td>
<td>2.85</td>
<td>C_F</td>
<td>C_V</td>
</tr>
<tr>
<td>Beam Buckling Strength</td>
<td>F_B</td>
<td>x</td>
<td>2.03</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Tensile Strength</td>
<td>F_T</td>
<td>x</td>
<td>2.85</td>
<td>C_F</td>
<td>-</td>
</tr>
<tr>
<td>Compressive Strength</td>
<td>F_C</td>
<td>x</td>
<td>2.58</td>
<td>C_F</td>
<td>-</td>
</tr>
<tr>
<td>Column Buckling Strength</td>
<td>F_C</td>
<td>x</td>
<td>2.03</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 rehomed cross-section dimensions.
Fire Design of Exposed Wood Members

Cross-laminated Timber - Effective Char Depth

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

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

\( h_{lam} \) = lamination thickness (in.)

\( n_{lam} \) = number of laminations charred (rounded to lowest integer)

\( t_{gi} \) = time for char front to reach glued interface (hr.)

\( t \) = exposure time (hr.)

---

Fire Design of Exposed Wood Members

CLT manufactured with laminations of equal thickness

<table>
<thead>
<tr>
<th>Required Fire Endurance (hr.)</th>
<th>Effective Char Depths, ( a_{char} ) (in.)</th>
<th>Effective Char Depths, ( n_{lam} ) (in.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-Hour</td>
<td>2.2 2.2 2.1 2.0 2.0 1.9 1.8 1.8</td>
<td>1.8 1.8 1.8 1.8 1.8 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</td>
<td>2.8 2.8 2.6 2.6 2.6 2.6 2.6 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</td>
<td>3.6 3.6 3.6 3.6 3.6 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

GLT and CLT Adhesives

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](http://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 strong-axis direction. The design loads are q_{ex} = 80 psf and q_{wall} = 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 strong-axis direction. The design loads are w_{ex} = 14,000 psf and w_{wall} = 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 caulking 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:
\[ P_{load} = P_{dead} + P_{live} = 6,150 \text{ psf} + 14,000 \text{ psf} = 20,150 \text{ lb/foot of width} \]

From PRG 320, select a 7-ply CLT panel made from 3/4 in x 3 1/2 inch lumber boards (CLT thickness of 9/16 inches). For CLT grade E1, tabulated properties are:

- Compression stress, \( f_{c1} = 1800 \text{ psi} \) (PRG 320 Annex A, Table A1)
- Bending moment, \( f_{b1} \cdot S_{eff} = 18,375 \text{ lb-ft/ft of width} \) (PRG 320 Annex A, Table A2)
- Bending stiffness, \( E_{eff} \cdot I_{eff} = 1.089 \times 10^7 \text{ lb-in^2/ft of width} \) (PRG 320 Annex A, Table A2)
- Shear stiffness, \( G_{eff} \cdot A_{eff} = 1.4 \times 10^6 \text{ lb-ft/ft of width} \) (PRG 320 Annex A, Table A2)

Recent Demonstration Fire Tests

[Images of fire tests]
Recent Demonstration Fire Tests

Heat Release Rate

Compartment Temperature

Recent Demonstration Fire Tests

Room after 60 minutes

Room after drywall removed following the three-hour test

CLT Test

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
Tall Wood

http://awc.org/tallwood

Resources

- www.awc.org
- Print versions
- PDF versions
Resources

- **Structure Magazine**
  - 2015 NDS
    - January 2015
  - 2015 SDPWS
    - July 2015
  - [www.awc.org](http://www.awc.org)
    - What's Changed?

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

Gravity Framing Styles

Lateral Force Systems
Mass Timber Framing Styles

Gravity Framing Styles

- Post & Beam
- Two-Way Panel Deck
- "Honeycomb"

ALBINA YARD
PORTLAND, OR

4 stories
16,000 sf
Green Roof

ARCHITECT: Lever Architecture
Photo: Scott Breneman

Copyright 2017 WoodWorks
• 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
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

Architect: Michael Green Architecture
Structural Engineer: Equilibrium Consulting
Contractor: PCL Constructors Westcoast
Photos: Ema Peter Photography
WIDC Floor System
Staggered 5 Ply over 3 Ply CLT Panels
Mass Timber Framing Styles

Gravity Framing Styles
- Post & Beam
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- “Honeycomb”

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

56' square kiosk
2 Layers of 3-ply, 4-1/8" CLT roof panels in opposite directions, each panel 8' x 56', creating 2 way spanning plate

Mass Timber Framing Styles

Gravity Framing Styles

Post & Beam
Two-Way Panel Deck
“Honeycomb”
Candlewood Suites
Redstone Arsenal, AL

- 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

Image Credit: Lend Lease & Schaefer
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:
  - DR 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 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)**

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

- \(F_b S_{eff}\) per NDS
- Commonly 1.0
- From Manufacturer

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

*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:**
\[
M_b = \frac{w L^2}{8} = \frac{(40+40\text{psf}) (16\text{ft})^2}{8} = 2560 \text{lb-ft/ft}
\]
Try 5 ply, (6 7/8 in thick) CLT Grade V2 Section

Design Example: Flexure

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 lb-ft/ft)

= 4675 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:

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

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

\[ F_s(IbQ_{\text{eff}})' = \text{adjusted shear strength} \]

*Reference: NDS 2015*

**Shear Strength**

Design Properties based on Extreme Fiber Model:

Shear Capacity Check (ASD):

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

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

*Commonly 1.0 From Manufacturer for Standard Sections*

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

Shear Analogy Method

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

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

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

Reference: *US CLT Handbook Chapter 3*
Flexural Stiffness

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

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

Structural Section Properties

Flexural Strength: \( F_{bS_{\text{eff},0}} \), \( F_{bS_{\text{eff},90}} \)
Flexural Stiffness: \( E_{I_{\text{eff},0}} \), \( E_{I_{\text{eff},90}} \)
Shear Strength: \( V_{s,0} \), \( V_{s,90} \)
Shear Stiffness: \( G_{A_{\text{eff},0}} \), \( G_{A_{\text{eff},90}} \)

Values in **RED** provided by CLT manufacturer

Reference: PRG 320 and CLT Product Reports
Deflection Calculations

General Purpose, 2 Way, Plate Action

Flexural Stiffness

\[ E_{I,0} \quad E_{I,90} \]

Shear Stiffness:

\[ \frac{5}{6} G_{A,0} \quad \frac{5}{6} G_{A,90} \]

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

Deflection Calculations

General Purpose: 1 Way, Beam Action

Stiffness: \[ E_{I,0} \quad \frac{5}{6} G_{A,0} \]

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

**Example Calculation:**

Uniform loading on one way slab:

Beam Analysis using

- Flexural Stiffness: $E_{i,0}$
- Shear Stiffness: $5/6 \, G_{A_{eff,0}}$

Maximum Deflection @ Mid-Span

\[
\Delta_{\text{max}} = \frac{5}{384} \cdot \frac{wL^4}{E_{i,0}} + \frac{1}{8} \cdot \frac{wL^2}{5/6 \, G_{A_{eff}}}
\]

Design Example:

\begin{align*}
&= 0.161 \text{ in} + 0.02 \text{ in} = 0.183 \text{ in} \\
&= \frac{L}{1050}
\end{align*}

Deflection Calculations

**Simplified Beam Deflections:**

Given load pattern and support conditions:

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

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

\[
E_{i,app} = \frac{E_{i,eff}}{1 + \frac{11.5E_{i,eff}}{G_{A_{eff}}L^2}}
\]

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:

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

US CLT Handbook & NDS 2015 Commentary

\[
EI_{app} = \frac{E I_{eff}}{1 + \frac{16K_s I_{eff}}{A_{eff} L^2}}
\]

NDS 2015

For Major Axis Spans:

\[
l_{eff} = \frac{E I_{eff}}{E_o}
\]

\[
A_{eff} = G A_{eff} / G_o
\]

\[
G_o = E_o / 16
\]


---

Deflection Calculations

Simplified Beam Deflections

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

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

\[
EI_{app} = \frac{E I_{eff}}{1 + \frac{16K_s I_{eff}}{A_{eff} L^2}}
\]

Apparent Flexural Stiffness depends on Span Length

\( EI_{app1} \neq EI_{app2} \)

\( L_1 = 20 \text{ foot} \)

\( L_2 = 16 \text{ foot} \)
Creep Factor

Deformation to Long Term Loads

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

- \( \Delta_{ST} \): Deflection due to short-term loading
- \( \Delta_{LT} \): Immediate deflection due to long term loading
- \( K_{cr} \): 2.0 for CLT in dry service conditions

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:

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

Where:

- \( E_{\text{app}} \): apparent stiffness for 1 foot strip, pinned supported, uniformly loaded, simple span (\( K_s = 11.5 \) (lb-in²))
- \( \rho \): specific gravity of the CLT
- \( A \): the cross section area (thickness x 12 inches) (in²)

Reference: US CLT Handbook, Chapter 7
Floor Vibration

CLT Handbook, Chapter 7 recommends,

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

and

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

Reference: US CLT Handbook, Chapter 7

Floor Vibration

CLT Handbook, Chapter 7 method:

Natural frequencies above 9 Hz and:

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

\( EI_{\text{app}} \) 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:

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

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:
- ≤ 16,000 µ-in/sec w/ moderate walking in living areas
- ≤ 8,000 µ-in/sec w/ slow walking pace in sleeping areas.

AISC DG 11 suggests approximate velocity limit of human perception:
8,000 µ-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

Connection Styles

**Floor Panel to Wall**

- Platform Frame With Only Screws
- Platform Frame with Double Brackets
- Platform Frame with Single Brackets
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.

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

Similar to Wood Structural Panel Shear Walls

Source: SDPWS 2008

Connections Determine Lateral Strength

Similar to Wood Structural Panel Shear Walls

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

Seismic Design

CLT Seismic Force Resisting Systems Not addressed In
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
Central Core – concrete shearwalls

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

State of Oregon Statewide Alternative

Statewide Alternate Method
January 2015

No. 15-01
Cross-Laminated Timber Provisions
(Bulletin 455, OSB-C)

Statewide Alternate Methods are approved by the Oregon Statewide Building Codes Division with the approval and consultation with the appropriate advisory board. The advisory board includes the technical and scientific staff of the state of Oregon's building official. In addition:

- Building permits may be issued when the alternate method is used.
- The discretion to use an alternate method is at the discretion of the building official.
- Statewide alternate methods do not limit the authority of the building official to consider other proposed alternate methods encompassing the same subject matter.

Code Section: OSSE Section 502.4 Type IV, Heavy Timber
Date: January 15, 2015
Initiated by: Building Codes Division
Subject: Cross-Laminated Timber
Background:

Cross-laminated timber (CLT) is an emerging wood product with applications in both residential
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

<table>
<thead>
<tr>
<th>Seismic Force-Resisting System</th>
<th>ASCE 7 Section Where Detailing Requirements Are Specified</th>
<th>Response Modification Coefficient, $R^*$</th>
<th>Overstrength Factor, $Q^*$</th>
<th>Deflection Amplification Factor, $C^*$</th>
<th>Structural System Limitations Including Structural Height, $H_s$, (ft) Limit $^t$</th>
<th>Seismic Design Category</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. BEARING WALL SYSTEMS</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Limits</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 1/2</td>
<td>3</td>
<td>4</td>
<td>NL</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 1/2</td>
<td>2</td>
<td>NL</td>
<td>NL</td>
</tr>
</tbody>
</table>

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?

Completed Panel to Panel Tests

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

Source: A Ceccotti in the US CLT Handbook
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:
- ICC, 2015 International Building Code
- ANSI/ULMA A2015 National Design Specification (NDS) for Wood Construction with Commentary
- AWS/SAPCA Special Design Provision for Wood and Composite Materials
- APA/AMPA R50 – 2012 Standard for Performance-rated Cross-Laminated Timber
- ASCE 7-10 Minimum Design Loads for Buildings and Other Structures
- AWC 56-02 Specification for Structural Wood Buildings

Diaphragm Design Example by Spickler et al.

3 Ply CLT Panels
Shear Wall

Lateral load, w
1000plf (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
    \[ \delta_{dia} = \frac{5vL^3}{8EAw} + \frac{vL}{4G_{w}t_{w}} + C\epsilon_{u} + \frac{\sum(\Delta U)}{2W} \]
    
    \[ C = \frac{1}{2} \left( \frac{1}{P_{L}} + \frac{1}{P_{W}} \right) \]

- \( P_{L} \) is panel length
- \( P_{W} \) is panel width
- \( \epsilon_{u} \) is connector slip at diaphragm edge

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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.

Discrete Panel with Corner Connections

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

CLT Panels Ends Supported on Beam
Example Modeled Diaphragm Deflections

East-West Loading

North-South Loading

WoodWorks Solutions Paper on CLT Modeling

Questions?

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Links to online resources at www.woodworks.org: