CLT Stands Up

A Look at Cross-laminated Timber Wall Design (DES442)

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DESCRIPTION

Even before cross-laminated timber (CLT) was recognized in the 2015 IBC, there was growing interest to use it in the US by designers seeking a sustainable construction product, with a reduced on-site construction time, all while exploiting the natural beauty of wood to provide a pleasing environment to occupants. Not only does CLT meet all of these attributes, but it also provides excellent thermal separation and can be designed to provide up to two hours of fire resistance and even more when protected. This presentation will provide a step-by-step design example of CLT used in a wall application to resist gravity loads as well as design for exposure to fire per the 2018 National Design Specification® (NDS®) for Wood Construction and AWC’s TR-10 – Calculating the Fire Resistance of Wood Members and Assemblies.

LEARNING OBJECTIVES

1. Discuss relevant CLT product manufacturing and design standards and identify where these standards are referenced in the IBC.

2. Describe how to design CLT walls for gravity loads.

3. Design a CLT wall for fire resistance and thermal separation.

4. Discuss existing state of in-plane CLT shear wall design provisions.
POLLING QUESTION

1. What is your profession?
   a. Architect
   b. Engineer
   c. Code Official
   d. Fire Service
   e. Builder/Manufacturer/Other

POLLING QUESTION

2. Where are you located given the map below?
   a. West (purple)
   b. North Central (green)
   c. Northeast (brown)
   d. Southeast (teal)
   e. South Central (mustard)
**POLLING QUESTION**

3. How familiar are you with CLT?
   a) Guru – designed or plan reviewed many CLT projects and can teach this course.
   b) Craftsman – designed or plan reviewed many projects with CLT.
   c) Apprentice – familiar with CLT but no design/review of projects.
   d) Novice – just started learning about CLT
   e) CLT whaaat?

---

**OUTLINE**

CLT Building Examples
CLT – IBC, NDS, ANSI/APA PRG-320
CLT Wall Structural & Fire Design Example
Resources
LIGHT WOOD FRAME CONSTRUCTION

UNITED KINGDOM – MASS TIMBER CONSTRUCTION

The Stadthaus
Hackney, London, U.K.
- 9 Stories (8 over 1)
- Mixed use
- Completed Jan. 2009

Developer:
Telford Homes

Architect:
Waugh Thistleton

General Contractor:
Ilford Homes

Structural Engineer:
Techniker Ltd
CANADIAN PROJECTS – MASS TIMBER

Brock Commons – Tallest Mass Timber Structure in North America

Vancouver, British Columbia, Canada

- 18 Stories (17 over 1)
- Mixed use student housing
- Completed Sept. 2017

Owner/Developer: University of British Columbia
Architect: Acton Ostry Architects, Inc.
General Contractor: Centura Building Systems Ltd.
Structural Engineer: Fast+Epp

Photo courtesy of Seagate Structures
CANADIAN PROJECTS – MASS TIMBER

The Arbora
Québec, Canada

- (3) 8 Stories (7 over 1)
- 434 Residential condo, townhouse and rental units

Developer: LSR GesDev and Sotramont
Architect: Lemay+CHA
Structural Engineer: Nordic Structures
CANADIAN PROJECTS – MASS TIMBER

Origine
Québec, Canada
- 12 over 1 Stories
- 92 Unit Residential condo

Developer: NÉB Group
Contractor: EBIC
Architect: Yvan Blouin Architect
Engineer: Groupe conseil SID Inc.
Mass Timber Source: Nordic Structures
Completed 2017
US PROJECTS – MASS TIMBER

Elementary School, Franklin, West Virginia — completed 2015

Owner: Pendleton County School District
Architect: MSES Architects
General Contractor: City Construction Company
Structural Engineer: Seagate Structures Ltd

Owner: Pendleton County School District
Architect: MSES Architects
General Contractor: City Construction Company
Structural Engineer: Seagate Structures Ltd

US PROJECTS – MASS TIMBER

Private Army Hotel
Redstone Arsenal Huntsville, AL
Completed 2016

Owner: Lendlease (US) Public Partnerships LLC
Architect: Leidos (now Benham)
General Contractor: Lendlease
Structural Engineer: Schaefer Structural Engineers

Owner: Lendlease (US) Public Partnerships LLC
Architect: Leidos (now Benham)
General Contractor: Lendlease
Structural Engineer: Schaefer Structural Engineers

Four stories 58,000 sq ft
Source: Lend Lease
US PROJECTS – MASS TIMBER

Albina Yard
Portland, Oregon
4 Story
Office, Retail
16,000SF
Completed Summer 2016

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

US PROJECTS – MASS TIMBER

CLT Stands Up
US PROJECTS – MASS TIMBER

Carbon 12
Portland, Oregon
8 Story (85 feet)
Condominiums/commercial
42,000SF
Completed Summer 2018

Developer: Ben Kaiser
Architect: PATH Architecture
General Contractor: Kaiser Group Inc.
Structural Engineer: DCI Engineers

CLT Stands Up
OUTLINE

CLT Building Examples

CLT – IBC, NDS, ANSI/APA PRG-320

CLT Wall Structural & Fire Design Example

Resources

BUILDING CODE
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 GLULAM

Glued Laminated Timber

Cross-Laminated Timber

Beam-like member

Thick Orthotropic Plate

Graphics provided by APA

Graphics provided by WoodWorks

BENDING MEMBERS – FLATWISE

- Design properties for out-of-plane (flatwise) loading – tabulated in PRG320
  - ASD bending moment \( (F_{b-S})_{eff,f} \)
  - Average bending stiffness \( (EI)_{eff,f} \)
  - ASD shear capacity \( (V_v) \)
  - Average shear stiffness \( (GA)_{eff,f} \)

Figure courtesy of APA (PRG320-18)
BENDING MEMBERS – EDGewise

• Properties for in-plane (edgewise) bending require qualification testing per PRG320
  • ASD bending moment ($F_{b,e}S_e$)
  • Average bending stiffness ($E_eI_e$)
  • ASD shear capacity ($F_{v,e}t_p$)
  • Average shear stiffness ($G_{v,e}t_p$)

Figure courtesy of APA (PRG 320-18)

TYPICAL CLT PANEL CONNECTORS
TYPICAL CLT PANEL CONNECTORS

CLT - TYPICAL CONSTRUCTION DETAILS

- Single surface spline
- Half-lapped
FIRE TESTS

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 2018?

Type IV Construction

2015 IBC

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. The details of Type IV construction shall comply with the provisions of this section and Section 2304.11. Exterior walls complying with Section 602.4.1 or 602.4.2 shall be permitted. Minimum solid sawn nominal dimensions are required for structures built using Type IV construction (HT). For glued-laminated members and structural composite lumber (SCL) members, the equivalent net finished width and depths corresponding to the minimum nominal width and depths of solid sawn lumber are required as specified in Table 602.4. Cross-laminated timber (CLT) dimensions used in this section are actual dimensions.

NEW: CLT and SCL

WHERE IS CLT ALLOWED IN IBC 2018?

<table>
<thead>
<tr>
<th>TABLE 2304.11</th>
<th>MINIMUM DIMENSIONS OF HEAVY TIMBER STRUCTURAL MEMBERS</th>
</tr>
</thead>
<tbody>
<tr>
<td>SUPPORTING</td>
<td>HEAVY TIMBER STRUCTURAL ELEMENTS</td>
</tr>
<tr>
<td></td>
<td>MINIMUM NOMINAL SOLID SAWN SIZE WIDTH, INCH DEPTH, INCH</td>
</tr>
<tr>
<td>Floor loads only or combined floor and roof loads</td>
<td>8 8 6/4 8/4 7 7/4</td>
</tr>
<tr>
<td>Columns, Framed sawn or glued-laminated timber arches that spring from the floor line; Framed timber trusses</td>
<td>8 8 6/4 8/4 7 7/4</td>
</tr>
<tr>
<td>Wood beams and girders</td>
<td>6 10 5 10/4 5/4 9/4</td>
</tr>
<tr>
<td>Roof loads only</td>
<td>6 8 5 8/4 5/4 7/4</td>
</tr>
<tr>
<td>Columns (roof and ceiling loads): Lower half of wood-frame or glued-laminated arches that spring from the floor line or from grade</td>
<td>6 8 5 8/4 5/4 7/4</td>
</tr>
<tr>
<td>Upper half of wood-frame or glued-laminated arches that spring from the floor line or from grade</td>
<td>6 6 5 6 5/4 5/4</td>
</tr>
<tr>
<td>Framed timber trusses and other roof framing: Framed or glued-laminated arches that spring from the top of walls or wall abutments</td>
<td>4 6 3 6/4 3/4 3/4</td>
</tr>
</tbody>
</table>

For SI: 1 inch = 25.4 mm.
a. Special members shall be permitted to be composed of two or more pieces not less than 3 inches nominal in thickness where blocked solidly throughout their intervening spaces or where spaces are tightly closed by a continuous wood cover plate of not less than 2 inches nominal in thickness secured to the underside of the members. Spline plates shall be not less than 3 inches nominal in thickness.
b. Where protected by approved automatic sprinklers under the roof deck, framing members shall be not less than 3 inches nominal in width.
TYPE IV CONSTRUCTION

All structural elements can be CLT

- Exterior walls – 6” total (actual)
  - FRTW or gypsum protection
- Floor – 4” (actual)
- Roof – 3” (actual)
- Interior walls – 4” (actual)

NLT structural elements

- Floor – 4” (nominal) on edge
- Roof – 3” (nominal) on edge

WHERE IS CLT ALLOWED IN IBC 2018?

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 and sheathing 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!
- Interior – any material permitted by code
- Roof
- Exterior Walls need to be non-combustible or FRT Wood (2 hour or less)

**WHERE IS CLT ALLOWED IN IBC 2018?**

**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.
TYPE V CONSTRUCTION

ALL structural elements can be CLT/NLT
- Exterior walls
- Floor
- Roof
- Interior walls

POLLING QUESTION

4. Which of the following is the tallest mass timber structure in North America?
   a) The Stadthaus
   b) Brock Commons
   c) The Arbora
   d) Origine
GOVERNING CODES FOR WOOD DESIGN

2018 IBC references 2018 NDS

Product Chapters

- Ch. 4 Sawn Lumber
- Ch. 5 Structural Glued Laminated Timber
- Ch. 8 Structural Composite Lumber
- Ch. 10 Cross-Laminated Timber
CHAPTER 10 – CROSS-LAMINATED TIMBER

10.1 General

10.1.1 Application

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 design values shall be specified in accordance with Section 10.2.

10.1.5 Service Conditions

Reference design values reflect dry service conditions, where the moisture content in service is less than
CLT MANUFACTURING STANDARDS

• 2018 IBC references ANSI/APA PRG 320-2017
• Applicable to current low- and mid-rise buildings using CLT
• Types III, IV, and V

• 2021 IBC references ANSI/APA PRG 320-2018
• Applicable to all CLT construction
• Types III, IV-HT, and V
• Types IV-A, IV-B, and IV-C
  • Tall mass timber
PRODUCT MARKING

Marks contain the following:

a) CLT layup qualified
b) CLT thickness or identification
c) Mill name or identification number
d) Approved agency name or logo
e) Reference product standard “ANSI/APA PRG 320”
f) “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 cross-laminated timber 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 cross-laminated timber 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: \( F_{u}(S_{u}), F_{u}(A_{u}), F_{u}(A_{u})\), \( F_{u}(S_{u}), F_{u}(A_{u}), F_{u}(A_{u})\), \( F_{l}(S_{l}), F_{l}(A_{l}), F_{l}(A_{l})\), \( F_{l}(S_{l}), F_{l}(A_{l}), F_{l}(A_{l})\) provided in 10.2 shall be multiplied by the adjustment factors specified in Table 10.3.1 to determine adjusted design values: \( F_{u}(S_{u}), F_{u}(A_{u}), F_{u}(A_{u})\), \( F_{u}(S_{u}), F_{u}(A_{u}), F_{u}(A_{u})\), \( F_{l}(S_{l}), F_{l}(A_{l}), F_{l}(A_{l})\), \( F_{l}(S_{l}), F_{l}(A_{l}), F_{l}(A_{l})\).

10.3.2 Load Duration Factor, \( c_{l} \) ( ASD only)

All reference design values except stiffness, \( E_{l} \), \( E_{l} \), and \( E_{l} \), rolling shear, \( F_{r}(S_{r})\), and compression perpendicular to grain, \( F_{u}(A_{u})\), shall be multiplied by load duration factors, \( c_{l} \), as specified in 2.3.2.

CLT PRODUCT REPORTS

https://www.apawood.org/cross-laminated-timber
## CHAPTER 10 – CROSS-LAMINATED TIMBER

### 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></td>
<td>Load Computation Factor</td>
<td>Service Factor</td>
<td>Ultimate Factor</td>
</tr>
<tr>
<td>$F_d(S_{nom}) = F_d(S_{net})$</td>
<td>$x$</td>
<td>$C_D$</td>
<td>$C_M$</td>
</tr>
<tr>
<td>$F_d(A_{nom}) = F_d(A_{net})$</td>
<td>$x$</td>
<td>$C_D$</td>
<td>$C_M$</td>
</tr>
<tr>
<td>$F_d(J) = F_d(J)$</td>
<td>$x$</td>
<td>$C_D$</td>
<td>$C_M$</td>
</tr>
<tr>
<td>$F_d(b'Q)<em>{a} = F_d(b'Q)</em>{b}$</td>
<td>$x$</td>
<td>-</td>
<td>$C_M$</td>
</tr>
<tr>
<td>$F_d(A_{nom})<em>{j} = F_d(A</em>{net})_{j}$</td>
<td>$x$</td>
<td>$C_D$</td>
<td>$C_M$</td>
</tr>
<tr>
<td>$F_c(t'AV) = F_c(t'AV)$</td>
<td>$x$</td>
<td>-</td>
<td>$C_M$</td>
</tr>
<tr>
<td>$(E)<em>{app} = (E)</em>{app}$</td>
<td>$x$</td>
<td>-</td>
<td>$C_M$</td>
</tr>
<tr>
<td>$(E)<em>{app</em>{max}} = (E)<em>{app</em>{max}}$</td>
<td>$x$</td>
<td>-</td>
<td>$C_M$</td>
</tr>
</tbody>
</table>
NDS – CHAPTER 12

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 7-16, FEMA P695, and FEMA P795 Quantification of Building Seismic Performance Factors; Component Equivalency Methodology
• Use a system prescribed in ASCE 7
IN-PLANE SHEAR FOR LATERAL LOADS

- No ASCE 7 R-value (earliest possible ASCE 7-22/2024 IBC)
- No standardized shear-through-thickness values (in-plane shear)
- No published standard design method
  - All present designs by alternative methods & materials
  - SDPWS 2021 being balloted now
- Design procedures per manufacturer’s specs
  - Based on tested assemblies
  - Not all manufacturers have design values/procedures
- Approval by alternate methods and materials

NDS CHAPTER 16 – FIRE (ASD)

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

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 not be otherwise used. The calculated fire resistance of concrete, concrete masonry and clay masonry assemblies shall be permitted in accordance with ACI 216.1/TMS 0216. The calculated fire resistance of steel assemblies shall be permitted in accordance with Chapter 5 of ASCE 29. The calculated fire resistance of exposed wood members and wood decking shall be permitted in accordance with Chapter 16 of ANSI/AWC National Design Specification for Wood Construction (NDS).
HEAVY TIMBER FIRE RESISTANCE RATING

PHOTO BY STRUCTURE MAGAZINE

FIRE PERFORMANCE GLULAM VS. STEEL

PHOTO BY STRUCTURE MAGAZINE
Fire resistance of exposed wood members may be calculated using the provisions of NDS Chapter 16.

2018 NDS METHODOLOGY

NDS Chapter 16 – Fire Design of Wood Members

- Mechanics Based Model
- Supported by empirical data
- NLT, Glulam & CLT
FIRE DESIGN OF EXPOSED WOOD MEMBERS

Allowable Stress Design

Table 16.2.2 Adjustment Factors for Fire Design

<table>
<thead>
<tr>
<th>Material Type</th>
<th>ASD</th>
<th>Design Stress to</th>
<th>Size Factor</th>
<th>Volume Factor</th>
<th>First Use Factor</th>
<th>Beam Stability Factor</th>
<th>Column Buckling Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bending Strength</td>
<td>$F_b$</td>
<td>2.85</td>
<td>$C_P$</td>
<td>$C_V$</td>
<td>$C_{BR}$</td>
<td>$C_L$</td>
<td>-</td>
</tr>
<tr>
<td>Beam Buckling Strength</td>
<td>$F_{be}$</td>
<td>2.03</td>
<td>-</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>
<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>-</td>
<td>$C_P$</td>
</tr>
<tr>
<td>Column Buckling Strength</td>
<td>$F_{ce}$</td>
<td>2.03</td>
<td>-</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 reduced cross-section dimensions.

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FIRE DESIGN OF EXPOSED WOOD MEMBERS

Technical Report No. 10
- Background on NDS provisions
- Design examples
- CLT provisions
NDS CHAPTER 16 – CALCULATED RESISTANCE

Revised

Cross-laminated Timber – Effective Char Depth

\[
a_{\text{char}} = n_{\text{lam}} \cdot h_{\text{lam}} + \beta_t \left( t - \left( n_{\text{lam}} \cdot t_g \right) \right)^{0.813} \tag{16.2-3}
\]

\[
t_g = \left( \frac{h_{\text{lam}}}{\beta_h} \right)^{1.23}
\]

\[
t_g = \text{time for char front to reach glued interface (hr.)}
\]

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

\[
n_{\text{lam}} = \frac{t}{t_g}
\]

\[
t_{\text{lam}} = \text{number of laminations charred (rounded to lowest integer)}
\]

\[
t = \text{exposure time (hr.)}
\]

\[
a_{\text{eff}} = 1.2a_{\text{char}} \quad (16.2-4)
\]

---

NDS CHAPTER 16 – CALCULATED RESISTANCE

CLT manufactured with laminations of equal thickness

<table>
<thead>
<tr>
<th>Required Fire Resistance (hr.)</th>
<th>Effective Char Depths, (a_{\text{eff}}) (in.)</th>
<th>lamination thicknesses, (h_{\text{lam}}) (in.)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5/8</td>
<td>3/4</td>
</tr>
<tr>
<td>1-Hour</td>
<td>2.2</td>
<td>2.2</td>
</tr>
<tr>
<td>1½-Hour</td>
<td>3.4</td>
<td>3.2</td>
</tr>
<tr>
<td>2-Hour</td>
<td>4.4</td>
<td>4.3</td>
</tr>
</tbody>
</table>
CLT Stands Up

NDS CHAPTER 16 – CALCULATED RESISTANCE

Table 16.2.1A  Char Depth and Effective Char Depth (for $\beta_0 = 1.5$ in./hr.)

<table>
<thead>
<tr>
<th>Required Fire Resistance (hr.)</th>
<th>Char Depth, $a_{\text{nom}}$ (in.)</th>
<th>Effective Char Depth, $a_{\text{eff}}$ (in.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-Hour</td>
<td>1.5</td>
<td>1.8</td>
</tr>
<tr>
<td>1½-Hour</td>
<td>2.1</td>
<td>2.5</td>
</tr>
<tr>
<td>2-Hour</td>
<td>2.6</td>
<td>3.2</td>
</tr>
</tbody>
</table>

For sawn lumber, structural glued laminated softwood timber, laminated veneer lumber, parallel strand lumber, and laminated strand lumber, assuming a nominal char rate, $\beta_0 = 1.5$ in./hr., the char depth, $a_{\text{nom}}$, and effective char depth, $a_{\text{eff}}$, are shown in Table 16.2.1A.

For cross-laminated timber manufactured with laminations of equal thickness and assuming a nominal char rate, $\beta_0$ of 1.5 in./hr., the effective char depth, $a_{\text{eff}}$, for each exposed surface is shown in Table 16.2.1B.

CLT Stands Up

NDS CHAPTER 16 – CALCULATED RESISTANCE

16.3 Wood Connections

Wood connections, including connectors, fasteners, and portions of wood members included in the connection design, shall be protected from fire exposure for the required fire resistance time. Protection shall be provided by wood, fire-rated gypsum board, other approved materials, or a combination thereof.
NDS CHAPTER 16 – CALCULATED RESISTANCE

- Char rate and char depth
- Modified char depth model
- Step-wise approach

FIRE DESIGN OF EXPOSED WOOD MEMBERS

Cross-section used for calculating capacity
Heated zone
Char layer
CALCULATED FIRE RESISTANCE?

Net section properties

Plan

Section

Typical one foot section

POLLING QUESTION

5. The following information may be found on a CLT product mark:
   a) Panel layup
   b) Panel thickness, width and length
   c) Mill Name
   d) Grade of laminations
   e) a. and c.
COMBINED BENDING AND AXIAL LOADING

A 10 ft CLT wall supports the following loads:
Dead load = 7500 plf (includes estimated self weight)
Live load = 15000 plf
Wind load = 25 psf

Design the wall using properties from PRG 320-18
**COMBINED BENDING AND AXIAL LOADING**

Select 3-ply CLT panel (each ply = 1-3/8”, total thickness = 4-1/8”) CLT grade E1 tabulated properties:

- $F_{c0} = 1800$ Reference compression stress, psi
- $F_{bSeff,f,0} = 4525$ Reference bending moment, ft-lb/ft of width
- $E_{Ieff,f,0} = 115 \times 10^6$ Reference bending stiffness, psi/ft of width
- $G_{Aeff,f,0} = 0.46 \times 10^6$ Reference shear stiffness, lb/ft of width

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**CLT MANUFACTURING STANDARD**

<table>
<thead>
<tr>
<th>Laminations Used in Major Strength Direction</th>
<th>Laminations Used in Minor Strength Direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>CLT</td>
<td>Layup</td>
</tr>
<tr>
<td>-----</td>
<td>-------</td>
</tr>
<tr>
<td>E1</td>
<td>1,950</td>
</tr>
<tr>
<td>E2</td>
<td>1,650</td>
</tr>
<tr>
<td>E3</td>
<td>1,200</td>
</tr>
<tr>
<td>E4</td>
<td>1,950</td>
</tr>
<tr>
<td>V1</td>
<td>900</td>
</tr>
<tr>
<td>V2</td>
<td>875</td>
</tr>
<tr>
<td>V3</td>
<td>750</td>
</tr>
</tbody>
</table>

For SI: 1 psi = 0.006895 MPa

a. See Section 4 for symbols.

b. Tabulated values are ASD reference design values and not permitted to be increased for the lumber size and flat use adjustment factors 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 A2).

c. Custom CLT layups that are not listed in this table shall be permitted in accordance with Table A2.

d. The tabulated $E$-values are published $E$ for lumber. For calculating the CLT design properties shown in Table A2, the transverse $E$ of the laminations is assumed to be $E/20$, the longitudinal $G$ of the laminations is assumed to be $E/16$, and the transverse $G$ of the laminations is assumed to be longitudinal $G/10$. 

---
TR-10 CLT WALL DESIGN EXAMPLE

See CLT manufacturer or ER for design values
Assume for this ex. PRG 320-18 design values

Excerpt from PRG 320-18 Table A2

<table>
<thead>
<tr>
<th>Major Strength Direction</th>
<th>Minor Strength Direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>((F_{Sv})_{v,H0}) (lbf-ft/ft of width)</td>
<td>((E_{I_{v,H0}})_{v,H0}) (10^6 lbf-ft/ft of width)</td>
</tr>
<tr>
<td>4,525</td>
<td>115</td>
</tr>
<tr>
<td>10,400</td>
<td>440</td>
</tr>
<tr>
<td><strong>18,325</strong></td>
<td><strong>1,089</strong></td>
</tr>
</tbody>
</table>

CLT MANUFACTURING STANDARD

CLT Layups

- **E1:** 1950I-1.7E Spruce-pine-fir MSR lumber in all longitudinal layers and No. 3 Spruce-pine-fir lumber in all transverse layers
- **E2:** 1600I-1.5E Douglas fir-Larch MSR lumber in all longitudinal layers and No. 3 Douglas fir-Larch lumber in all transverse layers
- **E3:** 1200I-1.2E Eastern Softwoods, Northern Species, or Western Woods MSR lumber in all longitudinal layers and No. 3 Eastern Softwoods, Northern Species, or Western Woods lumber in all transverse layers
- **E4:** 1950I-1.7E Southern pine MSR lumber in all longitudinal layers and No. 3 Southern pine lumber in all transverse layers
- **V1:** No. 2 Douglas fir-Larch lumber in all longitudinal layers and No. 3 Douglas fir-Larch lumber in all transverse layers
- **V2:** No. 1/No. 2 Spruce-pine-fir lumber in all longitudinal layers and No. 3 Spruce-pine-fir lumber in all transverse layers
- **V3:** No. 2 Southern pine lumber in all longitudinal layers and No. 3 Southern pine lumber in all transverse layers
COMBINED BENDING AND AXIAL LOADING

Effective Wall Compression Capacity

Area parallel to grain is 2 plies @ 1-3/8” thick

\[ A_{\text{parallel}} = 2 \times (1.375”) \times 12” = 33 \text{ in}^2 \text{ per foot of wall} \]

\[ P_c = F_{c0} \times A_{\text{parallel}} = 59,400 \text{ lb per foot of wall} \]

COMBINED BENDING AND AXIAL LOADING

Effective Wall Buckling Capacity

Use NDS Eqn. 10.4-1; \( K_s = 11.8 \) (pin-pin supports)

\[ EI_{\text{app}} = \frac{EI_{\text{eff0}}}{K_s \cdot EI_{\text{eff0}}} = 95 \times 10^6 \text{ psi/ft of wall} \]

Adjusted Buckling Capacity

\[ EI_{\text{appmin}} = 0.518 EI_{\text{app}} = 49 \times 10^6 \text{ psi/ft of wall (NDS C10.4.1)} \]
**COMBINED BENDING AND AXIAL LOADING**

**Adjusted Compression Capacity**

Live and dead loads only, so $C_D = 1.0$ (all other adjustment factors = 1.0)

\[ P_{cE} = \pi^2 \cdot \left(\frac{EI_{appmin}}{L^2}\right) = 34 \times 10^3 \text{ lb/ft of wall} \]

\[ P_{c*} = P_c \cdot C_D \cdot C_M \cdot C_t = 59.4 \times 10^3 \text{ lb/ft of wall} \]

\[ \alpha_c = \frac{P_{cE}}{P_{c*}} = 0.57 \]

\[ C_P := \frac{1 + \alpha_c}{2 \cdot c} - \sqrt{\left(\frac{1 + \alpha_c}{2 \cdot c}\right)^2 - \left(\frac{\alpha_c}{c}\right)} = 0.5 \]

\[ P'_c = P_{c*} \cdot (C_P) = 30.6 \times 10^3 \text{ lb/ft of wall} \]

---

**COMBINED BENDING AND AXIAL LOADING**

**Adjusted Bending Capacity**

Moment is due to applied wind load ($C_D = 1.6$)

\[ M = \left(\frac{w_{\text{wind}} \cdot L^2}{8}\right) = 312.5 \text{ ft-lb/ft of wall} \]

\[ C_L = 1.0 \ (d < b) \]

\[ F_b'S_{\text{eff0}} = F_b'S_{\text{eff0}} \cdot C_D \cdot C_M \cdot C_L \cdot C_t = 7240 \text{ ft-lb/ft of wall} \]
COMBINED BENDING AND AXIAL LOADING

Combined Capacity

Interaction check, Combined demand must be < 1.0

\[
Combined := \frac{P_{\text{total}}}{P_c} + \frac{M_{\text{max}}}{F_b S_{\text{eff}}' \left(1 - \frac{P_{\text{total}}}{P_{\text{cl}}}ight)} = 0.86
\]

NDS-CLT DESIGN

10.1.1 Application

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

10.1.1.2 Design procedures, reference design values and other information provided herein apply only to performance-rated cross-laminated timber produced in accordance with ANSI/APA PRG-220.

10.2.1 Reference Design Values

Reference design values for cross-laminated timber shall be obtained from the cross-laminated timber 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 cross-laminated timber manufacturer based on the actual layup used in the manufacturing process.

16.2.1.5 For cross-laminated timber, reduced section properties shall be calculated using equations provided by the cross-laminated timber manufacturer based on the actual layup used in the manufacturing process.
TR-10 CLT WALL DESIGN EXAMPLE

Given (cont.):
Adjustment factors:
Load duration factor $C_D = 1.0$
Moisture factor $C_M = 1.0$
Temperature factor $C_T = 1.0$

Calculate axial panel load (per foot of width):
$$P_{load} = (P_{dead} + P_{live}) = (6,150 \text{ plf} + 14,000 \text{ plf})(1\text{ ft width}) = 20,150 \text{ lb/ft of panel width}$$

TR-10 CLT WALL DESIGN EXAMPLE

• From PRG 320-18 select 7-ply CLT floor panel made from $1\frac{3}{8}$ in. x $3\frac{1}{2}$ in. lumber boards (CLT thickness of $9\frac{5}{8}$ in.)

Structural Check
• Calculate the effective wall compression capacity
  $$A_{parallel} = \text{bd of strong axis plies} = 4(12)(1.375)$$
  $$= 66 \text{ in}^2/\text{ft of width} \text{ (NDS 10.3.1)}$$
  $$P_c = F_{c,0} A_{parallel} = (1800)(66) = 118,800 \text{ lb/ft of width}$$
**TR-10 CLT WALL DESIGN EXAMPLE**

**Structural Check (cont.)**

- Calculate the apparent wall buckling capacity:

  NDS Equation 10.4-1, with PRG-320 assumption E/G = 16

  \[
  (EI)_{app} = \frac{E_{eff}}{1 + \frac{K_s E_{eff}}{G_{eff} L^2}}
  \]

  For pinned-pinned column buckling, \(K_s = 11.5\); therefore:

  \[
  (EI)_{app} = \frac{1,089 \times 10^6}{1 + \frac{11.8 (1,089 \times 10^6)}{(1.4 \times 10^6)(120)^2}} = 665 \times 10^6 \text{ lbs-in.}^2/\text{ft. of width}
  \]

  Using NDS Appendix H and the COV = 0.10 from PRG-320:

  \[
  (EI)_{app-min} = (665 \times 10^6)(1-1.645(0.10))(1.03)/1.66 = 345 \times 10^6 \text{ lb/in}^2/\text{ft of width (NDS 10.3.1)}
  \]

- Calculate the adjusted allowable column capacity:

  \[
  (EI)_{app-min}' = (EI)_{app-min} (CM)(Ct) = 345 \times 10^6(1.0)(1.0) = 345 \times 10^6 \text{ lb/in}^2/\text{ft of width (NDS 10.3.1)}
  \]

  Using the general form of the Euler buckling equation:

  \[
  P_c = \pi^2 \frac{(EI)_{app-min}}{L^2} = 236,500 \text{ lb/ft. of width (NDS C3.7.1.5)}
  \]

  \[
  P' c = P_c (C_o)(C_y)(C_t) = 118,800 \text{ lb/ft. of width (NDS C3.7.1.5)}
  \]

  Use \(c = 0.9\) for CLT

  \[
  \alpha_c = \frac{P_{ef}}{P_c} = 236,500/118,800 = 1.991
  \]

  \[
  C_p = \frac{1+\alpha_c}{2c} - \sqrt{\left(\frac{1+\alpha_c}{2c}\right)^2 - \frac{\alpha_c}{c}} = \frac{1+1.991}{2(0.9)} - \sqrt{\left(\frac{1+1.991}{2(0.9)}\right)^2 - \frac{1.991}{0.9}} = 0.9208
  \]

  \[
  P'_s = P'_c C_p = 118,800(0.9208) = 109,400 \text{ lb/ft of width}
  \]

  Structural Check: \(P'_s = P_{load} \geq 109,400 \text{ lb/ft} > 20,150 \text{ lb/ft}\)
TR-10 CLT WALL DESIGN EXAMPLE

Fire Check:
Mass loss due to charring is conservatively maximum induced moment is unchanged. 
\( A_{\text{eff}} = 3.8 \text{ inches} \)

The wall can be designed as an eccentrically-loaded 3-ply CLT column.

Table 16.2.1B  Effective Char Depths (for CLT with \( \beta_t = 1.5\text{ in./hr.)} \)

<table>
<thead>
<tr>
<th>Required Fire Resistance (hr.)</th>
<th>Effective Char Depth, ( A_{\text{eff}} ) (in.)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>lamination thicknesses, ( h_{\text{m}} ) (in.)</td>
</tr>
<tr>
<td>5/8</td>
<td>1/4</td>
</tr>
<tr>
<td>1-Hour</td>
<td>2.2</td>
</tr>
<tr>
<td>1 1/2-Hour</td>
<td>3.4</td>
</tr>
<tr>
<td>2-Hour</td>
<td>4.4</td>
</tr>
</tbody>
</table>

TR-10 CLT WALL DESIGN EXAMPLE

Fire Check (cont.)

Typical one foot section

CLT Stands Up
From PRG 320, select a 3-ply CLT panel made from the same 1-3/8 in x 3-1/2 in. lumber boards (CLT thickness of 4-1/8 inches) and the same CLT grade E1. The tabulated properties are:

- Reference compression stress, \( F_{c,0} \) = 1800 psi (Table A1)
- Reference bending moment, \( (F_bS)_{eff,f,0} \) = 4,545 lbf-ft/ft of width (Table A2)
- Reference bending stiffness, \( (EI)_{eff,f,0} \) = 115 x 10^6 lbf-in.^2/ft of width (Table A2)
- Reference shear stiffness, \( (GA)_{eff,f,0} \) = 0.46 x 10^6 lbf/ft of width (Table A2)

Calculate the effective wall compression capacity:

\[
A_{\text{parallel}} = bd \text{ of strong axis plies} = 2(12)(1.375) = 33 \text{ in}^2/\text{ft of width} \text{ (NDS 10.3.1)}
\]

\[
P_c = F_{c,0} A_{\text{parallel}} = (1800)(33) = 59,400 \text{ lb/ft of width} \text{ (NDS 10.3.1)}
\]

TR-10 CLT WALL DESIGN EXAMPLE

**Fire Check (cont.)**

Calculate the apparent wall buckling capacity

\[
(EI)_{app} = \frac{115 \times 10^6}{1 + \frac{11.8(115 \times 10^6)}{(0.46 \times 10^6)(120)^2}} = 95.4 \times 10^6 \text{ lbs-in.}^2/\text{ft. of width}
\]

\[
(EI)_{app-min} = (95.4 \times 10^6)(1-1.645(0.10))(1.03)/1.66
\]

\[
= 49.5 \times 10^6 \text{ lb/in}^2/\text{ft of width} \text{ (NDS 10.3.1)}
\]

Calculate the adjusted allowable column capacity (assuming \( C_0 = N/A \); \( C_w = N/A \); \( C_t = N/A \)):

\[
(EI)_{a-app-min} = 49.5 \times 10^6 \text{ lb/in}^2/\text{ft of width} \text{ (NDS 10.3.1)}
\]
**TR-10 CLT WALL DESIGN EXAMPLE**

**Fire Check (cont.)**

Calculate the adjusted allowable column capacity (cont.)

Using the general form of the Euler buckling equation:

\[
P_{ce,f} = 2.03 \frac{\pi^2 (EI)_{app - min}}{L^2} = 2.03 \frac{\pi^2 (49.5 \times 10^6)_{app - min}}{120^2} = 68,900 \text{ lb/ft. of width} \quad \text{(NDS C3.7.15)}
\]

\[
P_{*c,f} = 2.58 P_c = 2.58(59,400) = 153,300 \text{ lb/ft. of width} \quad \text{(NDS C3.7.1.5)}
\]

Use \( c = 0.9 \) for CLT

\[
\alpha_c = \frac{P_{ce,f}}{P_{*c,f}} = 68,900 / 153,300 = 0.4494
\]

\[
C_p = \frac{1 + \alpha_c}{2e} - \sqrt{\frac{1 + \alpha_c}{2e}}\frac{\alpha_c}{\pi} = \frac{1 + 0.4494}{2(0.9)} - \sqrt{\frac{1 + 0.4494}{2(0.9)}}\frac{0.4494}{0.9} = 0.4192
\]

\[
P'_f = P'_c C_p = 153,300 (0.4192) = 64,250 \text{ lb/ft of width}
\]

Fire Check: \( P'_f = P_{load} \geq 64,250 \text{ lb/ft} > 20,150 \text{ lb/ft} \)

---

**TR-10 CLT WALL DESIGN EXAMPLE**

**Fire Check (cont.)**

**Eccentricity**

\[
e = \frac{(d_7 - p_{ly} - d_3 - p_{ly})}{2} = \frac{(9.625 - 4.125)}{2} = 2.75''
\]

Eccentricity moment (assuming \( C_D = N/A; C_W = N/A; C_t = N/A; C_L = 1.0 \))

\[
M'_f = (2.85) F_b (S_{eff})(C_L) = 2.85(4,525)(1.0)
\]

\[
= 12,900 \text{ ft-lb/ft of width} \quad \text{(NDS 16.2.2)}
\]
**TR-10 CLT WALL DESIGN EXAMPLE**

**Fire Check (cont.)**

Based on NDS Equation 15.4-3:

\[
\left(\frac{P_{\text{Load}}}{P'_f}\right)^2 + \frac{(P_{\text{Load}} e)[1 + 0.234(P_{\text{Load}}/P_{\text{Ce}})]}{M'_f[1 - (P_{\text{Load}}/P_{\text{Ce}})]} \leq 1.0
\]

Fire Check:

\[
\left(\frac{20.150}{64.250}\right)^2 + \frac{(20.150)(2.75)[1 + 0.234(20.150/68.900)]}{(12.900)\left(\frac{12.900}{12.900}\right)[1 - (20.150/68.900)]} = 0.64 \leq 1.0
\]

---

**TR-10 CLT WALL DESIGN EXAMPLE**

**Fire Check (cont.)**

There is conservatism in this example due to the simplifying assumption that the remaining cross-section after two hours is a 3-ply CLT wall. The conservatism can be estimated by back-calculating the time required for the first 3 laminations (includes 2 strong-axis and 1 weak-axis laminations) to char. The time required to char each lamination can be calculated using the equations in NDS 16.2-2 as:

\[
t_{\text{gl}} = \left(\frac{h_{\text{lam}}}{\beta_t}\right)^{\frac{1.23}{1.5}} = \left(\frac{1.375}{1.5}\right)^{\frac{1.23}{1.5}} = 0.90 \text{ hrs}
\]

\[
t = n_{\text{lam}}t_{\text{gl}}/1.2 = 3(0.90)/1.2 = 2.25 \text{ hrs}
\]

Note that, while the structural contribution of the fourth lamination, (a crossing ply), was ignored in these calculations, it does protect the last 3 laminations in the CLT so the fourth lamination could also be added:

\[
t = 4(0.90)/1.2 = 3 \text{ hrs}
\]

In fact, this CLT wall would be expected to have similar structural fire resistance from 2.25 to 3 hrs. A more rigorous analysis would demonstrate that the expected fire resistance of this CLT wall under these loading conditions is about 3 hours.
TR-10 CLT WALL DESIGN EXAMPLE

Thermal Separation

ASTM E119 average temp increase on unexposed surface < 250°F Estimated time to burn-through, \( t_{bt} \) is calculated using TR10 Section 4.4.1.1:

\[
t_{bt} = 60 \left( \frac{d-0.6}{1.5} \right)^{1.23} + 17 = 60 \left( \frac{9.625-0.6}{1.5} \right)^{1.23} + 17 = 562 \text{ minutes}
\]  

(TR10 4.4.1.1)

\[t_{ts} = 0.85 \ times \ t_{bt} = 0.85 \times 562 = 478 \text{ minutes} \quad \text{(TR10 4.4.1.2)} \]

Thermal Separation Check: \( t_{ts} > FRR \)  478 minutes > 120 minutes

POLLING QUESTION

6. Which of the following is true for CLT wall systems?
   a) Manufacturer or code ER provide ref. design values
   b) The deflection criteria in the IBC is the same as the NDS
   c) Exposed CLT may be designed for 2 hrs. of fire-resistance
   d) All of the above
   e) a) and c)
OUTLINE

CLT Building Examples
CLT – IBC, NDS, ANSI/APA PRG-320
CLT Wall Structural & Fire Design Example

Resources

RESOURCES

www.awc.org
• Print versions
• PDF versions
RESOURCES

E-courses

2018 NDS Changes - National Design Specification® for Wood Construction (STD120)

Taking Wood to the Next Level – CLT as a Floor or Roof Element (DES441-1)

Outcomes of ICC Tall Wood Ad Hoc Committee: Proposals and Discussion (DES605)

http://awc.org/education/ecourses

RESOURCES

Structure Magazine

2018 NDS
2018 WFCM
2015 SDPWS
www.awc.org

What's Changed?
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