Mass Timber Structural Design: Engineering Modern Timber Structures

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Photo: Alex Schreyer
Bullitt Center
Seattle, WA

2x4 NLT roof deck
2x6 NLT floor deck

Floor assembly top to bottom:
3” concrete topping, acoustical mat, WSP, 2x6 NLT
### Glulam Design Values

**Bending About X-X Axis**

(Loaded Perpendicular to Wide Faces of Laminations)

<table>
<thead>
<tr>
<th>Combination</th>
<th>Species</th>
<th>Outer/ Core</th>
<th>$F_{bx}^+$ (psi)</th>
<th>$F_{bx}^-$ (psi)</th>
<th>$F_{c,\perp x}$ (psi)</th>
<th>$F_{vx}$ (psi)</th>
<th>$E_x$ ($10^6$ psi)</th>
<th>$E_{x\text{ min}}$ ($10^6$ psi)</th>
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<tbody>
<tr>
<td>24F-1.8E</td>
<td>2400</td>
<td>1450</td>
<td>650</td>
<td>650</td>
<td>265</td>
<td>1.8</td>
<td>0.95</td>
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<td>24F-V4</td>
<td>DF/DF</td>
<td>2400</td>
<td>1850</td>
<td>650</td>
<td>650</td>
<td>265</td>
<td>1.8</td>
<td>0.95</td>
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<td>24F-V8</td>
<td>DF/DF</td>
<td>2400</td>
<td>2400</td>
<td>650</td>
<td>650</td>
<td>265</td>
<td>1.8</td>
<td>0.95</td>
</tr>
<tr>
<td>24F-E4</td>
<td>DF/DF</td>
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<td>2400</td>
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<td>0.95</td>
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<td>DF/DF</td>
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<td>2400</td>
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<td>265</td>
<td>1.8</td>
<td>0.95</td>
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<td>0.95</td>
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<td>2400</td>
<td>740</td>
<td>740</td>
<td>300</td>
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<td>0.95</td>
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<td>300</td>
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<td>0.95</td>
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<tr>
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<td>SP/SP</td>
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<td>2400</td>
<td>805</td>
<td>805</td>
<td>300</td>
<td>1.9</td>
<td>1.00</td>
</tr>
</tbody>
</table>

Source: NDS supplement Table 5A
Mass timber design

Fire resistance

Glulam beam fire design:
- For unbalanced beams, Substitute 1 core lam for 1 tension lam for 1 hour rating, 2 core lams for 2 tension lams for 1.5 & 2 hour rating
- For balanced beams, match on compression side
NLT Structural Design

NLT shrinkage/expansion design:
Rule of thumb: leave gap between ½” and one ply wide per 8’-10’ wide panel
NLT Design Guide includes:

- Architecture
- Fire
- Structure
- Enclosure
- Supply and Fabrication
- Construction and Installation
- Erection engineering

Free download from www.thinkwood.com
Cross Laminated Timber

Considerations:

- Large light-weight panels
- Dimensionally stable
- Precise CNC machining available
- Recognized by IBC
- Dual Directional span capabilities
- Often architecturally exposed
- Fast on-site construction

Graphic Credit: StructureCraft
Building Code Acceptance of CLT

2015 International Building Code
Common CLT Layups

Most Designs
Least $/sf

- 3-ply 3-layer
- 5-ply 5-layer
- 7-ply 7-layer
- 9-ply 9-layer

7-ply 5-layer
9-ply 7-layer
## PRG 320 Defined Layups

### CLT Grade (basic)

### Layup

### Panel Properties

### Table A2: ASD Reference Design Values for Basic CLT Grades and Layups (for use in the U.S.)

<table>
<thead>
<tr>
<th>CLT Grade</th>
<th>Lamination Thickness (in.) in CLT Layup</th>
<th>Major Strength Direction</th>
<th>Minor Strength Direction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>(F,S)$_{adj}^{\perp,\parallel}$ (lbf-ft$^2$/ft of width)</td>
<td>(EI)$_{adj}^{\perp,\parallel}$ (10$^6$ lbf-in./ft of width)</td>
</tr>
<tr>
<td>E1</td>
<td>4 1/8 1 3/8 1 3/8 1 3/8</td>
<td>4,525 115 0.46 1,490</td>
<td>160 3.1 0.61 495</td>
</tr>
<tr>
<td></td>
<td>6 7/8 1 3/8 1 3/8 1 3/8 1 3/8 1 3/8</td>
<td>4,100 440 0.92 2,480</td>
<td>1,370 81 1.2 1,490</td>
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<tr>
<td></td>
<td>9 5/8 1 3/8 1 3/8 1 3/8 1 3/8 1 3/8 1 3/8</td>
<td>18,375 1,089 1.4 3,475</td>
<td>3,150 313 1.8 2,480</td>
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<tr>
<td>E2</td>
<td>4 1/8 1 3/8 1 3/8 1 3/8</td>
<td>3,825 102 0.53 1,980</td>
<td>165 3.6 0.56 660</td>
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<tr>
<td></td>
<td>6 7/8 1 3/8 1 3/8 1 3/8 1 3/8 1 3/8</td>
<td>8,825 389 1.1 3,300</td>
<td>1,440 95 1.1 1,980</td>
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<tr>
<td></td>
<td>9 5/8 1 3/8 1 3/8 1 3/8 1 3/8 1 3/8 1 3/8</td>
<td>15,600 963 1.6 4,625</td>
<td>3,300 364 1.7 3,300</td>
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<tr>
<td>E3</td>
<td>4 1/8 1 3/8 1 3/8 1 3/8</td>
<td>2,800 81 0.35 1,160</td>
<td>110 2.3 0.44 385</td>
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<tr>
<td></td>
<td>6 7/8 1 3/8 1 3/8 1 3/8 1 3/8 1 3/8</td>
<td>6,400 311 0.69 1,930</td>
<td>955 61 0.87 1,160</td>
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<td>9 5/8 1 3/8 1 3/8 1 3/8 1 3/8 1 3/8 1 3/8</td>
<td>11,025 769 1.0 2,700</td>
<td>2,210 234 1.3 1,930</td>
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<tr>
<td>E4</td>
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<td>4,525 115 0.50 1,820</td>
<td>140 3.4 0.62 605</td>
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<tr>
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<td>6 7/8 1 3/8 1 3/8 1 3/8 1 3/8 1 3/8</td>
<td>10,400 440 1.0 3,025</td>
<td>1,230 88 1.2 1,820</td>
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<tr>
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<td>9 5/8 1 3/8 1 3/8 1 3/8 1 3/8 1 3/8 1 3/8</td>
<td>18,400 1,089 1.5 4,225</td>
<td>2,850 338 1.9 3,025</td>
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<td>4 1/8 1 3/8 1 3/8 1 3/8</td>
<td>3,825 101 0.46 1,650</td>
<td>160 3.1 0.55 550</td>
</tr>
</tbody>
</table>
3rd Party Product Qualification of CLT

APA PRODUCT REPORT
DRJ Cross-Laminated Timber
Riddle Laminators, Inc.
Issued January 25, 2017

Products: DRJ Cross-Laminated Timber
Riddle Laminators, Inc.
P.O. Box 86
Riddle, OR 97878
(541) 874-8267
www.riddlewood.com

1. Basis of the product
   - 2015 International Laminated Timber (ILT)
   - 2012 and 2009 ILT
   - 2015 International Cross-Laminated Timber (CLT)
   - ANSI/SPR-12 PGR 12 Timber
   - SPUR PFR
   - Other qualification

2. Product description:
   - DRJ Cross-Laminated Timber
   - Manufactured by Riddle Laminators, Inc.

3. Design properties:
   - Structural performance
   - Fire resistance
   - Durability
   - Manufacture

4. Manufacturer:
   - Riddle Laminators, Inc.
   - P.O. Box 86
   - Riddle, OR 97878
   - (541) 874-8267

5. Additional information:
   - Testing and certification
   - Applications

APA PRODUCT REPORT
SmartLam Cross-Laminated Timber
Smartlam, LLC
August 18, 2017

Products: Smartlam Cross-Laminated Timber
Smartlam, LLC
1863 13th Street West
Columbia Falls, MT
(406) 652-0606
www.smartlam.com

1. Basis of the product
   - 2015 International Laminated Timber (ILT)
   - 2012 and 2009 ILT
   - 2015 International Cross-Laminated Timber (CLT)
   - ANSI/SPR-12 PGR 12 Timber
   - SPUR PFR
   - Other qualification

2. Product description:
   - Smartlam Cross-Laminated Timber
   - Manufactured by Smartlam, LLC

3. Design properties:
   - Structural performance
   - Fire resistance
   - Durability
   - Manufacture

4. Manufacturer:
   - Smartlam, LLC
   - 1863 13th Street West
   - Columbia Falls, MT
   - (406) 652-0606

5. Additional information:
   - Testing and certification
   - Applications

APA PRODUCT REPORT
Structurlam CrossLam
Structurlam Products LP
 Revised May 9, 2016

Products: Structurlam Cross-Laminated Timber
Structurlam Products LP
2176 Government Street
Penticton, British Columbia
(250) 492-8912
www.structurlam.com

1. Basis of the product
   - 2015 International Laminated Timber (ILT)
   - 2012 and 2009 ILT
   - 2015 International Cross-Laminated Timber (CLT)
   - ANSI/SPR-12 PGR 12 Timber
   - SPUR PFR
   - Other qualification

2. Product description:
   - Structurlam Cross-Laminated Timber
   - Manufactured by Structurlam Products LP

3. Design properties:
   - Structural performance
   - Fire resistance
   - Durability
   - Manufacture

4. Manufacturer:
   - Structurlam Products LP
   - 2176 Government Street
   - Penticton, British Columbia
   - (250) 492-8912

5. Additional information:
   - Testing and certification
   - Applications

APA PRODUCT REPORT
Nordic X-Lam
Nordic Structures
PR-L306
Revised May 29, 2016

Products: Nordic X-Lam
Nordic Structures
1100 Avenue d'Arts
Montreal, Quebec
(514) 871-8526
www.nordic.ca

1. Basis of the product
   - 2015 International Laminated Timber (ILT)
   - 2012 and 2009 ILT
   - 2015 International Cross-Laminated Timber (CLT)
   - ANSI/SPR-12 PGR 12 Timber
   - SPUR PFR
   - Other qualification

2. Product description:
   - Nordic X-Lam
   - Structures

3. Design properties:
   - Structural performance
   - Fire resistance
   - Durability
   - Manufacture

4. Manufacturer:
   - Nordic X-Lam
   - Structures
   - 1100 Avenue d'Arts
   - Montreal, Quebec
   - (514) 871-8526

5. Additional information:
   - Testing and certification
   - Applications

APA PRODUCT REPORT
Intertek
LISTING INFORMATION
KLH Massivholz GmbH – Massivholzplatten (solid wood slats) CLT
SPECIFIC 36204

KLH Massivholz GmbH
Katsch an der Mur 202
Tauplitz-Katsch, A-8442
Austria

1. Basis of the product
   - 2015 International Laminated Timber (ILT)
   - 2012 and 2009 ILT
   - 2015 International Cross-Laminated Timber (CLT)
   - ANSI/SPR-12 PGR 12 Timber
   - SPUR PFR
   - Other qualification

2. Product description:
   - KLH Massivholz GmbH
   - Massivholzplatten (solid wood slats)
   - CLT

3. Design properties:
   - Structural performance
   - Fire resistance
   - Durability
   - Manufacture

4. Manufacturer:
   - KLH Massivholz GmbH
   - Katsch an der Mur 202
   - Tauplitz-Katsch, A-8442
   - Austria

5. Additional information:
   - Testing and certification
   - Applications
FLATWISE Panel Loading

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

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

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

Span in **MAJOR** Strength Direction  
Span in **MINOR** Strength Direction

Reference & Source: ANSI/APA PRG 320
Flatwise Flexural Strength

Flexural Capacity Check (ASD)

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

per NDS

Commonly 1.0  Provided as combined value

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

Here and in the following, items in RED are provided CLT properties

Reference: NDS
Design Properties based on Extreme Fiber Model:

Shear Capacity Check (ASD):

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

Commonly 1.0

\[ V_a \leq (1.0) V_s \]

Note: Duration of Load Effects (Cd and \( \lambda \)) NOT applicable to Flatwise Shear Strength in the NDS

Reference: NDS & Product Reports
Uniform loading on one way slab:
Beam Analysis using
   Flexural Stiffness: $E_{I_{eff,0}}$
   Shear Stiffness: $G_{A_{eff,0}}$
Maximum Deflection @ Mid-Span

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

Note: 5/6 is shear deformation form factor for rectangular section from mechanics of materials.
See NDS C10.4.1, FPL “Wood Handbook”, etc.
Mass timber design

Fire resistance

CLT fire design:
- Lam thickness affects char depth
- Partially charred cross layers are typically neglected for structural checks
Structural Grid

Grids & Spans

• Consider Efficient Layouts
• Repetition & Scale
• Manufacturer Panel Sizing
• Transportation

24'-2"
24'-0"
30'-0"
30'-0"
Structural Grid

Member Sizes
- Impact of FRR on Sizing
- Impact of Sizing on Efficient Spans
- Consider connections – can drive member sizing

0 HR FRR: Consider 3-ply Panel
- Efficient Spans of 10-12 ft
- Grids of 20x20 (1 purlin) to 30x30 (2 purlins) may be efficient

Albina Yard, Portland, OR
20x20 Grid, 1 purlin per bay
3-ply CLT
Image: Lever Architecture
Structural Grid

Member Sizes
• Impact of FRR on Sizing
• Impact of Sizing on Efficient Spans
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0 HR FRR: Consider 3-ply Panel
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Structural Grid

Member Sizes
- Impact of FRR on Sizing
- Impact of Sizing on Efficient Spans
- Consider connections – can drive member sizing

1 or 2 HR FRR: Likely 5-ply Panel
- Efficient spans of 14-17 ft
- Grids of 15x30 (no purlins) to 30x30 (1 purlin) may be efficient

First Tech Credit Union, Hillsboro, OR
12x32 Grid, One-Way Beams
5-ply (5.5”) CLT
Image: Swinerton
Structural Grid

Member Sizes
• Impact of FRR on Sizing
• Impact of Sizing on Efficient Spans
• Consider connections – can drive member sizing

1 or 2 HR FRR: Likely 5-ply Panel
• Efficient spans of 14-17 ft
• Grids of 15x30 (no purlins) to 30x30 (1 purlin) may be efficient
Key Early Design Decisions

Typical MT Package Costs

- Project Overhead: 7%
- Labor: 14%
- Material: 64%
- Equipment: 15%

Source: Swinerton
Key Early Design Decisions

Panels are the biggest part of the biggest piece of the cost pie

Source: Swinerton
Key Early Design Decisions

Panel volume usually 65-80% of MT package volume

Type IIIA option 1
1-hr FRR
Purlin: 5.5”x28.5”
Girder: 8.75”x33”
Column: 10.5”x10.75”
Floor panel: 5-ply

Glulam volume = 118 CF (22% of MT)
CLT volume = 430 CF (78% of MT)
Total volume = 0.73 CF / SF

Source: Fast + Epp, Timber Bay Design Tool
Key Early Design Decisions

Panel volume usually 65-80% of MT package volume

Type IIIA option 2
1-hr FRR
Purlin: 5.5”x24”
Girder: 8.75”x33”
Column: 10.5”x10.75”
Floor panel: 5-ply

Glulam volume = 123 CF (22% of MT)
CLT volume = 430 CF (78% of MT)
Total volume = 0.74 CF / SF

Cost considerations: One additional beam (one additional erection pick), 2 more connections
Key Early Design Decisions

Panel volume usually 65-80% of MT package volume

Type IV-HT
0-hr FRR (min sizes per IBC)
Purlin: 5.5”x24” (IBC min = 5”x10.5”)
Girder: 8.75”x33” (IBC min = 5”x10.5”)
Column: 10.5”x10.75” (IBC min = 6.75”x8.25”)
Floor panel: 3-ply (IBC min = 4” CLT)

Glulam volume = 120 CF (32% of MT)
CLT volume = 258 CF (68% of MT)
Total volume = 0.51 CF / SF

Source: Fast + Epp, Timber Bay Design Tool
Key Early Design Decisions

Many ways to demonstrate connection fire protection: calculations, prescriptive NC, test results, others as approved by AHJ
Key Early Design Decisions

Steel hangers/hardware fully concealed within a timber-to-timber connection is a common method of fire protection.
Key Early Design Decisions

Connection FRR and beam reactions could impact required beam/column sizes
Key Early Design Decisions

2017 Glulam Beam to Column Connection Fire Tests under standard ASTM E119 time-temperature exposure

Photo: ARUP/SLB
Key Early Design Decisions

Softwood Lumber Board
Glulam Connection Fire Test
Summary Report

Issue | June 5, 2017

Full Report Available at:
Key Early Design Decisions

Member to member bearing also commonly used, can avoid some/all steel hardware at connection
Key Early Design Decisions

Member to member bearing also commonly used, can avoid some/all steel hardware at connection

Style of connection also impacts and is impacted by grid layout and MEP integration
Key Early Design Decisions

MASS TIMBER CONNECTIONS INDEX
A library of commonly used mass timber connections with designer notes and information on fire resistance, relative cost and load-acity.
Connections

Other connection design considerations:
• Structural capacity
• Shrinkage
• Constructability
• Aesthetics
• Cost

Credit: Alex Schreyer
Floor Vibration Design

“One might almost say that strength is essential and otherwise unimportant”

- Hardy Cross
None

Barely discussed in IBC, NDS, etc.
ASCE 7 Commentary Appendix C has some discussion, no requirements
Systems View of Vibration

Excitation Force(s) \rightarrow Structure \rightarrow Vibration Response
Vibrations vs Acoustics

**Structural Vibrations**
- 1 Hz – 100 Hz
- Transmitted through structure or through ground
- Physical effects

**Acoustic Vibrations**
- 20 Hz – 15,000 Hz
- Transmitted through air, walls, floors, windows
- Audible effects
Floor Vibration Dynamics

Natural Frequency

$$f_n = \frac{1}{2\pi} \sqrt{\frac{k}{m}}$$

Undamped Free Response

Period $T = \frac{1}{f_n}$ Frequency
# Walking Frequency $f_w$

The range of walking frequencies considered is an important consideration of vibration analysis.

<table>
<thead>
<tr>
<th>Walking Speed</th>
<th>Walking Frequency</th>
<th>Steps Per Minute</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very Slow</td>
<td>1.25 Hz</td>
<td>75 SPM</td>
</tr>
<tr>
<td>Slow</td>
<td>1.6 Hz</td>
<td>95 SPM</td>
</tr>
<tr>
<td>Moderate</td>
<td>1.85 Hz</td>
<td>110 SPM</td>
</tr>
<tr>
<td>Fast</td>
<td>2.1 Hz</td>
<td>126 SPM</td>
</tr>
<tr>
<td>Running</td>
<td>Up to 4.0 Hz</td>
<td>240 SPM</td>
</tr>
</tbody>
</table>

**Practical Tip** - walk to a metronome too understand the range.
Resonant vs Impulsive Response

Excitation Frequency not >> Natural Frequency
Excitation Creates Resonant Build-up of Vibration

Resonant Response

Resonance occurs when
walking frequency = natural frequency
\[ f_w = f_n \]

Also occurs when a harmonic of the walking frequency \( \sim \) natural frequency
\[ n f_w = f_n \]
For ‘n’ up to around 4

Walking at \( f_w = 2 \text{ Hz} \) creates resonance in
floor with natural frequency, \( f_n \), at

\[ 2 \text{Hz}, 4 \text{ Hz}, 6 \text{ Hz}, \text{ and } 8 \text{Hz} \]
Resonant vs Impulsive Response

Excitation creates Resonant build-up of vibration

Response decays out between load impulses

Resonant Response

Impulsive/Transient Response

For walking excitations

\[ f_n \sim< 8-10 \text{ Hz} \]
Limits of Human Perception of Vertical Acceleration

- Most sensitive to Acceleration around 4-8 Hz
- 0.05% g

Key:
- \( a \): acceleration (r.m.s.), m/s\(^2\)
- \( f \): frequency, Hz

ISO 10137:2007
Human Body Dynamics

Illustration: “Sven Jr.” by Sven-Olof Emanuelsson
Natural Frequency of Uniform Beam

Uniform simple span beam
• Span, L
• Flexural stiffness, EI
• Mass per length, m, or w/g

$$f_n = \frac{\pi}{2L^2} \sqrt{\frac{EI}{m}}$$

$$f_n = \frac{\pi}{2L^2} \sqrt{\frac{gEI}{w}}$$

*In floors, practical frequencies range from 5 Hz to 15+ Hz. Generally, the higher the frequency the better*

See Chopra “Dynamic of Structures”, etc for more information
Important Concepts

- No Code Requirements (good). No Precise Design Standard to Stand Behind (bad)

- Mass Effects – Increased mass decreases magnitude of response (good!) but decreases frequency of vibration (bad!)

Vibration Design Methods

Less:
- Design Effort
- Modelling and Analysis
- Judgement
- Flexibility
- Room for Innovation

More:
- Design Effort
- Modelling and Analysis
- Judgement
- Flexibility
- Room for Innovation
Vibration Design Methods

- Rules of Thumb
- Empirical Methods
- Simplified Analytical
- FEM/Modal Superposition
- FEM/Time History

\[ \Delta \leq \frac{L}{360} \text{ for floor live load} \]

IBC code limit on floor deflection

Wood Frame

Floor Joists:
\[ \Delta \leq \frac{L}{360} \text{ for } L < 15 \text{ ft} \]
\[ \Delta < 0.5'' \text{ for } L \geq 15 \text{ ft} \]

Floor Trusses:
\[ \Delta \leq \frac{L}{480} \text{ with strong-backs} \]

Woeste and Dolan
*Beyond Code: Preventing Floor Vibration.*
1998, Journal of Light Construction
Wood Frame

\[ f_n \geq 14 \text{ Hz for occupied (e.g. furnished) floors} \]
\[ f_n \geq 15 \text{ Hz for unoccupied floors} \]

Dolan, Murray, et al.  
*Preventing Annoying Wood Floor Vibration*  
1999, Journal of Structural Engineering

Proprietary rating systems from Joist Manufacturers
Vibration Design Methods

- Rules of Thumb
- Empirical Methods
- Simplified Analytical
- FEM/Modal Superposition
- FEM/Time History

**Mass Timber**

CLT Handbook Method

*U.S. CLT Handbook, 2013*
*Canadian CLT Handbook 2nd Ed., 2019*
*FPInnovations*
Recommended CLT Floor Span Limit (base value)

\[ L_{\text{lim}} \leq \frac{1}{12.05} \left( \frac{E_{\text{eff}}}{\bar{\rho}A} \right)^{0.293} \text{[ft]} \]

Where, for 12 in wide strip:

\[ E_{\text{eff}} = \text{effective flexural stiffness (lbf-in}^2) \]

\[ \bar{\rho} = \text{in-service specific gravity of the CLT, unitless} \]
\[ \text{e.g. weight normalized by weight of water} \]

\[ A = \text{the cross-section area (in}^2) = \text{thickness} \times 12 \text{ in} \]

Reference: US & Canadian CLT Handbooks, Chapter 7
Experimentally Derived Relationship

- **Fundamental Natural Frequency (Hz)**
- **Static Deflection (inch)**
  - Criterion: \( f/d^{0.7} > 125.1 \)
  - Unacceptable
  - Marginal
  - Acceptable

Research by Lin Hu, et al. at FPInnovations
CLT Handbook Method

Recommended CLT Floor Span Limit (base value)

\[ L_{\text{lim}} \leq \frac{1}{12.05} \left( \frac{E I_{\text{eff}}}{(\rho A)^{0.122}} \right)^{0.293} \]

2013 US CLT Handbook uses \( E I_{\text{app}} \)
2019 Canadian CLT Handbook uses \( E I_{\text{eff}} \)

Recommend using \( E I_{\text{eff}} \)

Easier to implement.
Less conservative.

Reference: Canadian CLT Handbook, Chapter 7
CLT Handbook Method

Excitation → Structure → Vibration Response

Normal Walking

Normal Human Sensitivities

Method NOT applicable to other Excitations or Sensitivities
## CLT Handbook Base Span Limit

For PRG 320-2019 Basic CLT Grades and Layups from Solid Sawn Lumber

<table>
<thead>
<tr>
<th>Grade</th>
<th>Layup</th>
<th>Thickness</th>
<th>Base Span Limit</th>
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<tbody>
<tr>
<td>E1</td>
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<td>22.7</td>
</tr>
<tr>
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<td>4 1/8&quot;</td>
<td>12.4</td>
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# CLT Handbook Base Span Limit

For PRG 320-2019 Basic CLT Grades and Layups from Solid Sawn Lumber

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<td>21.9</td>
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</table>

Approximate Base Span Limits:
- 4 1/8" 3-ply: ~12 to 13 ft
- 6 7/8" 5-ply: ~16 to 18 ft
- 9 5/8" 7-ply: ~20 to 22 ft

<table>
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<tr>
<th>Grade</th>
<th>Layup</th>
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<th>FPI Span Limit</th>
</tr>
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<tr>
<td></td>
<td>7ply</td>
<td>9 5/8&quot;</td>
<td>21.0</td>
</tr>
</tbody>
</table>

Limitations:
- Does not account for strength or deflections
- Does not account for beam flexibility
- Does not account for project specifics

Base Recommended Span Limit assumes:

- Single simply span CLT panel
- No heavy topping layer
- Rigid, pin supports (bearing walls)
Multi-Span Conditions?

- Check the longest span
- Recommend a 20% increase in the Basic Span Limit when non-structural elements are present which provide enhanced stiffening effect*
  *Partition walls, finishes, ceilings

Reference: 2019 Canadian CLT Handbook, Chapter 7
US Mass Timber Vibration Design Guide

Guide available for free download from WoodWorks.org

Project Team: WoodWorks, KPFF, Aspect, StructureCraft, & Fast+Epp
U.S. Mass Timber Floor Vibration Design Guide

Vibration Design Examples

Residential Bearing Wall Building with CLT

Open Office with NLT on Glulam Frame

High Performance Lab Space with CLT on Glulam Frame

Available for free from www.woodworks.org
Vibration Design Methods

- Rules of Thumb
- Empirical Methods
- Simplified Analytical
- FEM/Modal Superposition
- FEM/Time History

Mass Timber
- CLT Handbook Method

Steel
- AISC Design Guide 11

Concrete
- CCIP 016

Mass Timber
- U.S Mass Timber Floor Vibration Design Guide
Modal Superposition Method

FEA Model

Walking frequency, $f_w$
Walker weight
Walking location(s)
Observation location(s)
Damping
etc.

Modes of Vibration

Measures of Performance:
Accelerations for Resonant Low Frequency Floors
Velocities for Transient High Frequency Floors
The range of walking frequencies considered is an important aspect of vibration analysis.

<table>
<thead>
<tr>
<th>Walking Speed</th>
<th>Walking Frequency</th>
<th>Steps Per Minute</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very Slow</td>
<td>1.25 Hz</td>
<td>75 SPM</td>
</tr>
<tr>
<td>Slow</td>
<td>1.6 Hz</td>
<td>95 SPM</td>
</tr>
<tr>
<td>Moderate</td>
<td>1.85 Hz</td>
<td>110 SPM</td>
</tr>
<tr>
<td>Fast</td>
<td>2.1 Hz</td>
<td>126 SPM</td>
</tr>
<tr>
<td>Running</td>
<td>Up to 4.0 Hz</td>
<td>240 SPM</td>
</tr>
</tbody>
</table>

Practical Tip - walk to a metronome too understand the range
Beneficial to have a vibration specific structural analysis model. When considering low amplitude deflection to walking excitation, following AISC Design Guide 11 et al:

- Perimeter non-load bearing walls provide vertical restraint or stiffness
- “Gravity” connections often behave as rigid connections
- Use dynamic stiffness values where different that static stiffness value (Concrete)
- “Non-composite” components can have some composite behavior
Composite Behavior

Even if NOT designed as a composite for code required strength and stiffness, real systems can show partial composite action for vibrations.

Incidental Composite Behavior

\[ EI_{eff} > EI_1 + EI_2 \]
\[ GA_{eff} > GA_1 + GA_2 \]

Consider Composite for:

<table>
<thead>
<tr>
<th>Composite Behavior</th>
<th>Strength</th>
<th>Deflection</th>
<th>Vibration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Explicit</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Incidental</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
</tbody>
</table>

“What R Value Can I use?”
- Everybody
Mass Timber Design
Lateral framing systems

Light-frame wood shearwalls

Photo Credit: woodworks
Mass Timber Design
Lateral framing systems

Central Core – concrete shearwalls

Photo Credit: structurecraft
Exterior steel moment frame

Photo Credit: woodworks
Mass Timber Design
Lateral framing systems

interior steel moment frame

Photo Credit: woodworks
Mass Timber Design

Lateral framing systems

Steel Braced Frame

Photo Credit: john stamets
Mass Timber Design
Lateral framing systems

Mass Timber Shearwalls
Photo Credit: alex schreyer
CLT Panels have a significant in-plane shear strength.

**CLT in Lateral Force Resisting Systems**

<table>
<thead>
<tr>
<th>CLT Panel Designation</th>
<th>FACE LAMINATION ORIENTATION (psi)</th>
<th>FACE LAMINATION ORIENTATION (lb/ft of width)</th>
</tr>
</thead>
<tbody>
<tr>
<td>V2M1</td>
<td>99 V</td>
<td>175°</td>
</tr>
<tr>
<td></td>
<td>239 V</td>
<td>175°</td>
</tr>
<tr>
<td></td>
<td>309 V</td>
<td>175°</td>
</tr>
<tr>
<td>V2M1.1</td>
<td>105 V</td>
<td>270°</td>
</tr>
<tr>
<td></td>
<td>175 V</td>
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<td></td>
<td>245 V</td>
<td>270°</td>
</tr>
<tr>
<td></td>
<td>315 V</td>
<td>270°</td>
</tr>
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</table>

145 to 290 PSI Allowable Edgewise Shear

= 1.7 to 3.5 kips/ft (ASD) per inch of thickness!

Consult with the Manufacturers for Details

Multiply by $C_d = 1.6$ for short term loading
New Requirements for CLT Lateral Systems in SDPWS 2021!
Referenced from IBC 2021

Now with CLT shear wall and diaphragm requirements
2021 Special Design Provisions for Wind and Seismic

Top Changes Relevant to CLT Lateral Systems:
- New unified nominal shear capacity
- New CLT Shear Wall requirements (Appendix B)
- New CLT Diaphragm requirements

Available from awc.org

PowerPoint IS NOT the CODE!
CLT Shear Walls in SDPWS 2021

Platform Framed CLT Construction

applied load $v_u$

Section View

Elevation View
CLT Shear Walls in SDPWS 2021

Platform Frame CLT Construction

Section View

Elevation View

applied load $v_u$
CLT Shear Walls in SDPWS 2021

Platform Frame CLT Construction

Section View

Floor or Roof
Above Wall

Floor or Foundation
Below Wall

Elevation View

applied load $v_u$
CLT Shear Walls in SDPWS 2021

Platform Frame CLT Construction

- CLT Floor
- Floor or Roof
- Floor or Foundation
- CLT Wall
- Above Wall
- Below Wall

Section View

Elevation View

applied load $v_u$
CLT Shear Walls in SDPWS 2021

Platform Frame CLT Construction

CLT Floor

Floor or Roof
Above Wall

Floor or Foundation
Below Wall

CLT Wall

applied load $\nu$

Section View

Elevation View
CLT Shear Walls in SDPWS 2021

Platform Frame CLT Construction

Section View

Elevation View

applied load \( v_u \)
CLT Shear Walls in SDPWS 2021

Panel to Panel Connection

0.105” ASTM A653 Grade 33 Steel
(8) 16d box nails to each wall panel
3.5” long x 0.135”Ø shank with 0.344” Ø head

Panel to Platform Connection

Same steel plate and nails plus
5/8” Ø bolts or lag screws to roof, floor or foundation
Panel to Platform Connection

Nominal shear capacity

\( \nu_n = 2605 \ C_G \ \text{[lbs]} \) per angle connector

\( C_G \) adjusts for specific gravity, \( G \) of CLT

\( C_G = 1.0 \quad \text{for } G \geq 0.42 \)

\( = 0.86 \quad \text{for } G = 0.35 \)

\( = 1.0 - 2 \ (0.42 - G) \quad \text{for } 0.42 > G > 0.35 \)

Nominal unit shear capacity:

\( \nu_n = n \ (2605 / b_s) \ C_G \ \text{[lbs/ft]} \)
CLT Shear Walls in SDPWS 2021

CLT Shear Walls
not meeting Appendix B

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

CLT Shear Walls
meeting SDPWS 2021 Appendix B

Panel aspect ratios
\[ 2 \leq \frac{h}{b_s} \leq 4 \]

Panel aspect ratios
\[ \frac{h}{b_s} = 4 \]

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

Panel aspect ratios
\[ 2 \leq \frac{h}{b_s} \leq 4 \]
R Values for CLT Shear Walls in SDPWS 2021

CLT Shear Walls not meeting Appendix B

(\text{other})

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

In SDPWS 2021 4.6.3

CLT Shear Walls meeting SDPWS 2021 Appendix B

Panel aspect ratios
\[ 2 \leq h/b_s \leq 4 \]

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

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

* ASCE 7-22
CLT in the U.S. Building Code – Lateral in IBC 2021

New Requirements for CLT Lateral Systems!
(but R values for CLT Shear Walls not in ASCE 7-16)

SDPWS 2015

Now with CLT shear wall and diaphragm requirements

Where Seismic (R values) and Wind Systems are Referenced. No CLT

AWC SDPWS 2021

ASCE/SEI 7-16

2021 International Building Code
CLT in the U.S. Building Code – Lateral in the IBC 2024?

Future Full Recognition of CLT Lateral Systems

AWC SDPWS 2021

Now with CLT shear wall and diaphragm requirements

ASCE/SEI 7-22

Now with Platform Framed CLT Shear Walls

2024 IBC (in process)

To Be Made

2024
2021 Special Design Provisions for Wind and Seismic

Top Changes Relevant to CLT Lateral Systems:
- New unified nominal shear capacity
- New CLT Shear Wall requirements
- New CLT Diaphragm requirements

Available from awc.org

PowerPoint IS NOT the CODE!
Innovative Systems under continued research

Mass Timber Post-Tensioned Rocking Shear Walls
CLT Balloon Framed Shear Walls
CLT Diaphragms

Strength of Connections covered by NDS and Proprietary Fastener Evaluation Reports

Strength of CLT rarely governs.
• Detailing for performance and constructability
• Determination of diaphragm flexibility
• Calculation of diaphragm deflections
• Precalculated connection capacities
• Combination SDPWS $\gamma_D$ and ACSE 7 $\Omega_o$ and $\rho$

Available from woodworks.org
Pre-fabricated panels often pre-sheathed

Once installed, add splice strips, tape joint if applicable
NLT Diaphragm Design

Figure 4.7: Prefabricated Pre-sheathed Panels

Key
1. Field-installed Plywood/OSB
2. Plywood/OSB splice location with typical diaphragm nailing
3. Plywood/OSB splice location for high load diaphragm nailing
4. Shop-installed plywood/OSB diaphragm sheathing
5. Prefabricated NLT panel A
6. Prefabricated NLT panel B
7. NLT expansion gap location fire stopped as required
8. Self-tapping screw pairs crossing plywood/OSB splice location

Source: NLT Design & Construction Guide
This concludes The American Institute of Architects Continuing Education Systems Course

WoodWorks – Wood Products Council

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Questions?