An Engineer's Guide to Mass Timber Structures: Simplifying Design Steps and Connection Details

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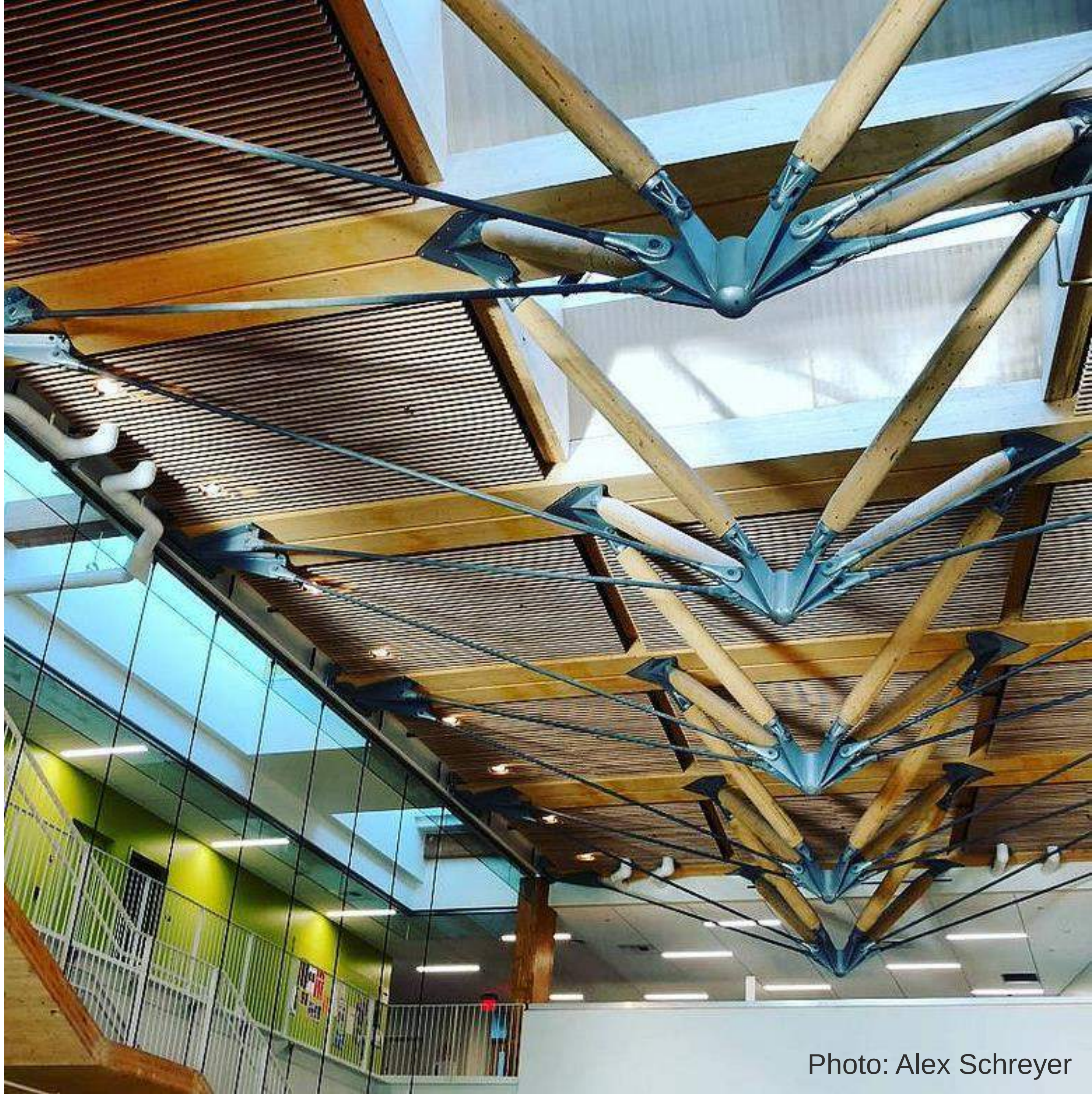

Photo: Alex Schreyer

Mass Timber Framing Systems

Mass Timber Framing Systems

- Gravity Framing Styles
  - Post & Beam
  - Two-Way Panel Deck
  - Hybrid Light-Frame & Mass Timber
  - Mass Timber Walls “Honeycomb”

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- Gravity Framing Styles
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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

Photo Credit: John Stamets

Framework

Portland, OR

Photo: joshua jay elliot


HUDSON BUILDING
VANCOUVER, WA
DEVELOPER: Killian Pacific and Mackenzie
PHOTO CREDIT: WoodWorks

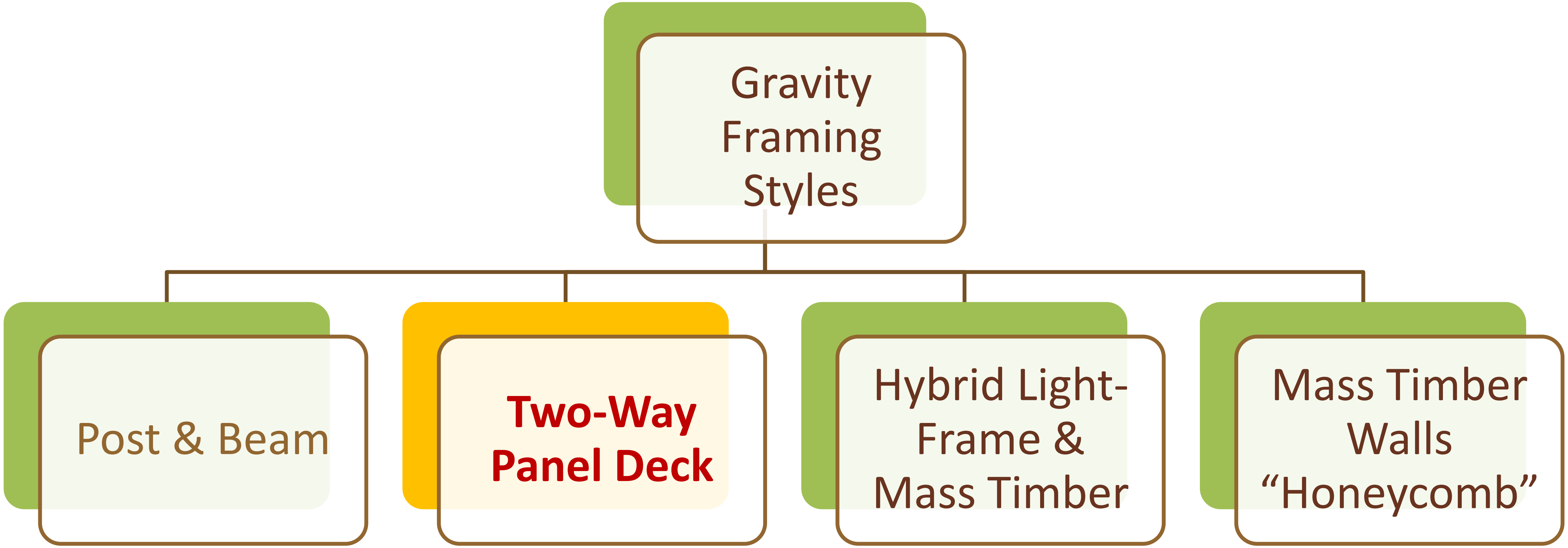
T3 Minneapolis

Minneapolis, MN

Image Credit: Blaine Brownell


UMass Design Building
Amherst, MA
Photo Credit: alex schreyer

Mass Timber Framing Systems



BROCK COMMONS

VANCOUVER, BC

5 PLY CLT PANELS, 2-WAY SPAN
~9'X13' GRID OF COLUMNS

Images: acton ostry architects

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

Photo Credit: Tom Harris

International Community Health Services Shoreline, WA

Photo Credit: Andrew Pogue Photography

Cooley Landing Education Center

East Palo Alto, CA

Mass Timber Framing Systems

Gravity Framing Styles

- Post & Beam
- Two-Way Panel Deck
- **Hybrid Light-Frame & Mass Timber**
- Mass Timber Walls “Honeycomb”

Virtuoso, Vancouver, BC

Image: Adera

Image: Seagate Structures

Cheney Park Apartments
CLT floor on Panelized
Light Frame Walls

Photo Credit: WoodWorks

CrossFit Center
Spokane, WA

Photo Credit: WoodWorks

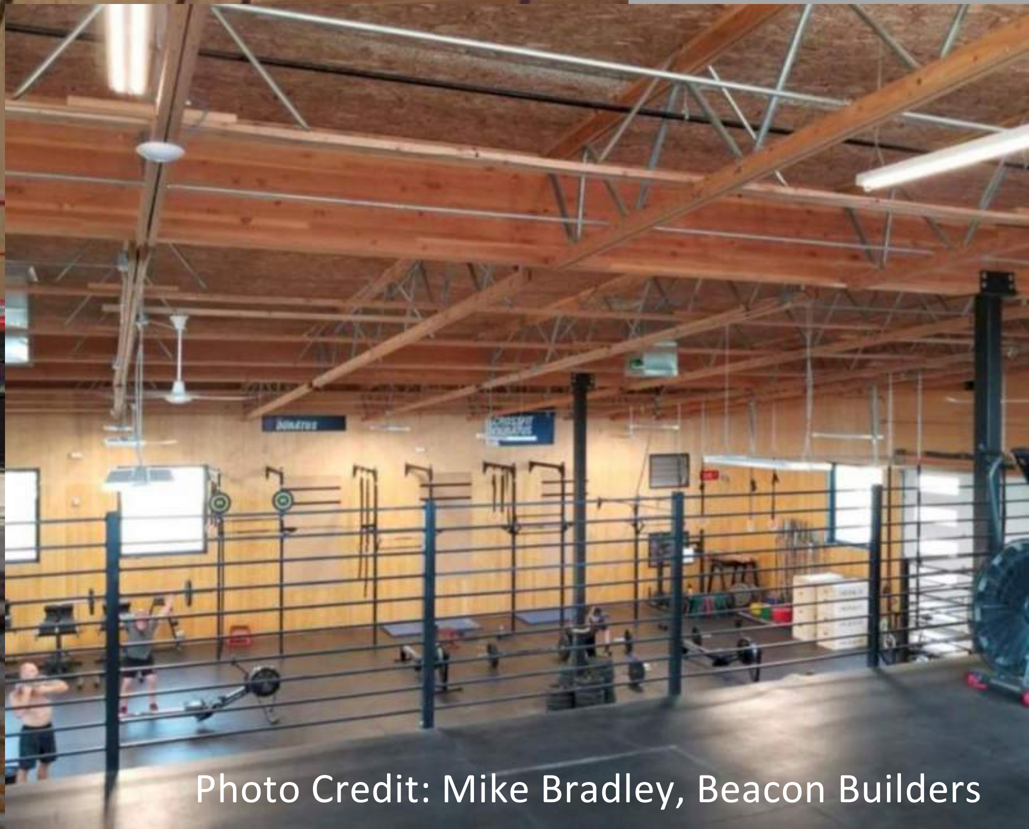


Photo Credit: Mike Bradley, Beacon Builders

Mass Timber Framing Systems

- Gravity Framing Styles
  - Post & Beam
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Candlewood Suites

Redstone Arsenal, AL

- 62,600 SF, 4 story hotel, 92 private rooms
- CLT utilized for walls, roof panels, and floor panels

Image Credit: Lend Lease

Redstone Arsenal Hotel
Huntsville, AL

Image Credit: Lend Lease

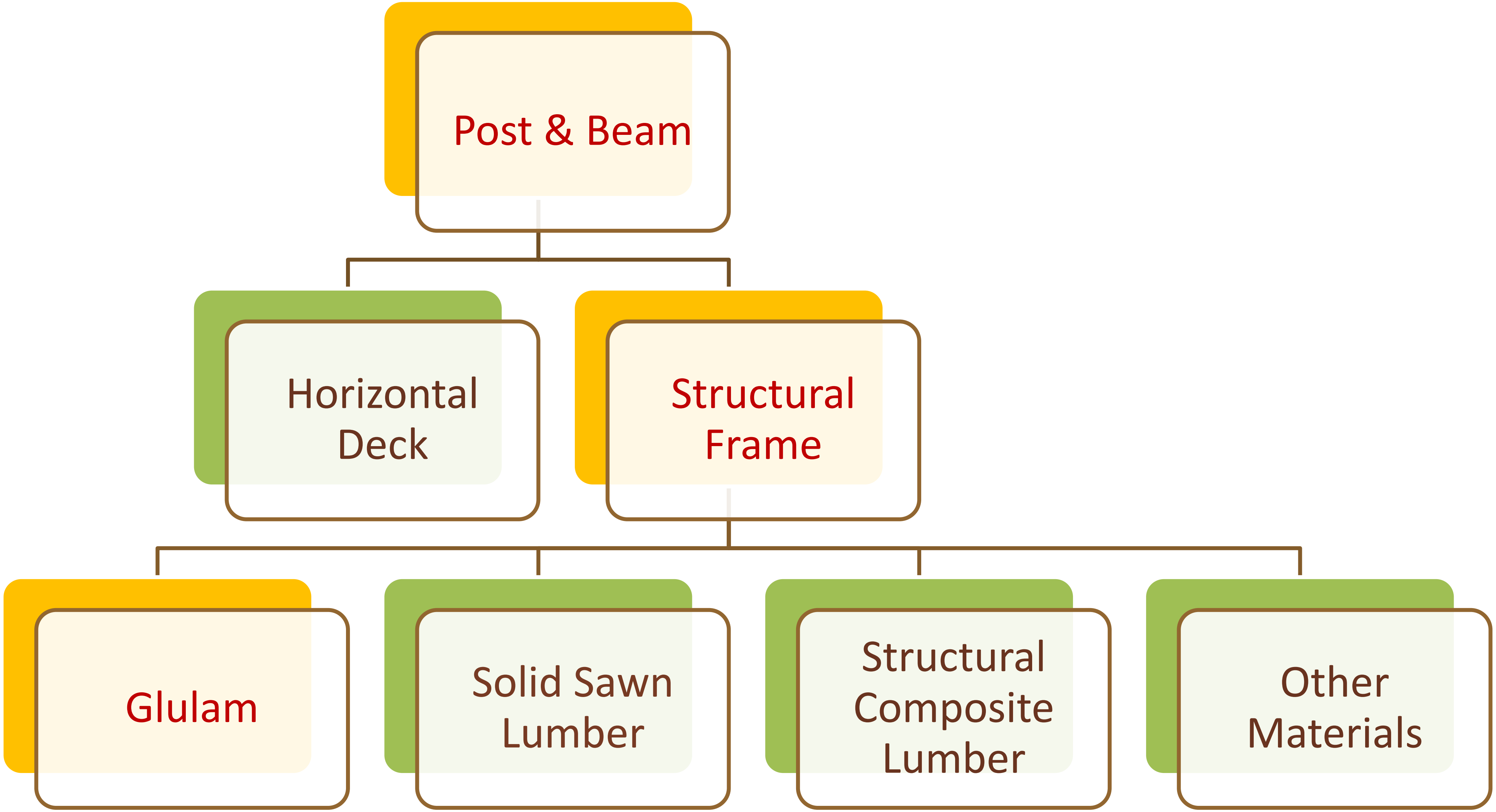
Photo Credit: IHG® Army Hotels

Candlewood Suites

Redstone Arsenal, AL

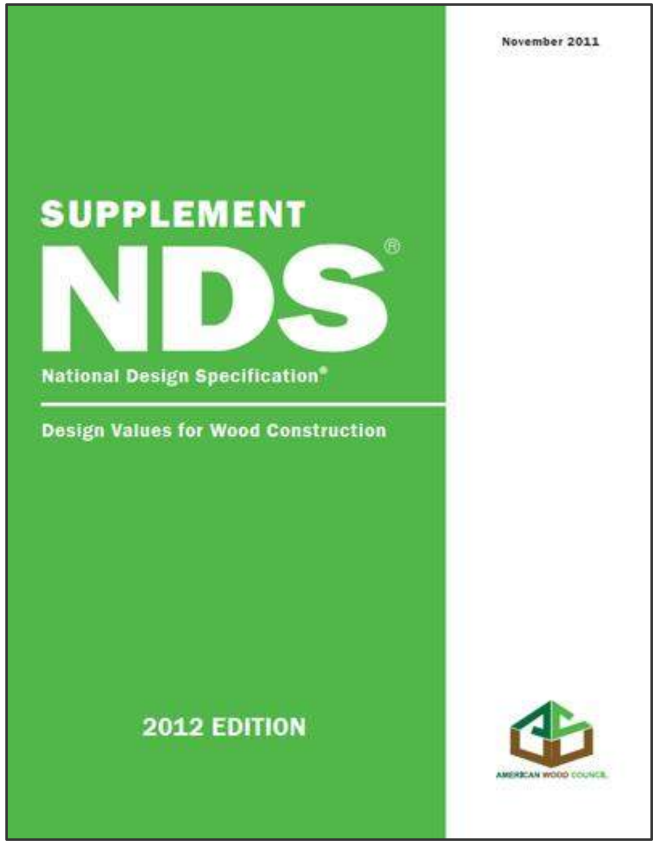
Photo Credit: Lendlease

Mass Timber Framing Systems



Glulam Design Values

Combination Symbol	Species Outer/ Core	Bending About X-X Axis (Loaded Perpendicular to Wide Faces of Laminations)						
		Bending		Compression Perpendicular to Grain		Shear Parallel to Grain	Modulus of Elasticity	
		Bottom of Beam Stressed in Tension (Positive Bending)	Top of Beam Stressed in Tension (Negative Bending)	Tension Face	Compression Face		For Deflection Calculations	For Stability Calculations
		F_{bx}^{+} (psi)	F_{bx}^{-} (psi)	$F_{c\perp x}$ (psi)		F_{vx} (2) (psi)	E_x (10^6 psi)	$E_{x\,min}$ (10^6 psi)
24F-1.8E		**2400**	**1450**	**650**		**265**	**1.8**	**0.95**
24F-V4	DF/DF	2400	1850	650	650	265	1.8	0.95
24F-V8	DF/DF	2400	2400	650	650	265	1.8	0.95
24F-E4	DF/DF	2400	1450	650	650	265	1.8	0.95
24F-E13	DF/DF	2400	2400	650	650	265	1.8	0.95
24F-E18	DF/DF	2400	2400	650	650	265	1.8	0.95
24F-V3	SP/SP	2400	2000	740	740	300	1.8	0.95
24F-V8	SP/SP	2400	2400	740	740	300	1.8	0.95
24F-E1	SP/SP	2400	1450	805	650	300	1.8	0.95
24F-E4	SP/SP	2400	2400	805	805	300	1.9	1.00



Source: NDS supplement Table 5A

Mass Timber and Steel Framing?

Barracuda Condos
Madison WI

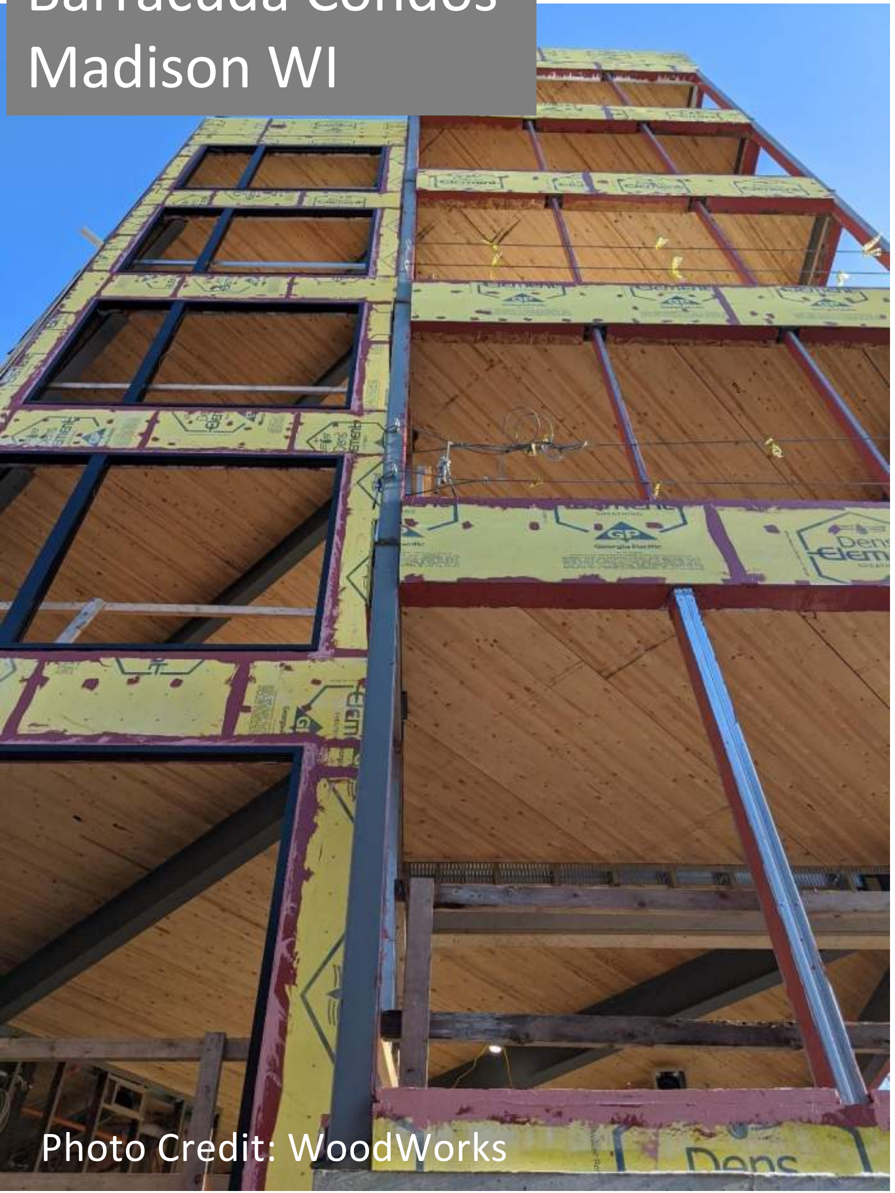
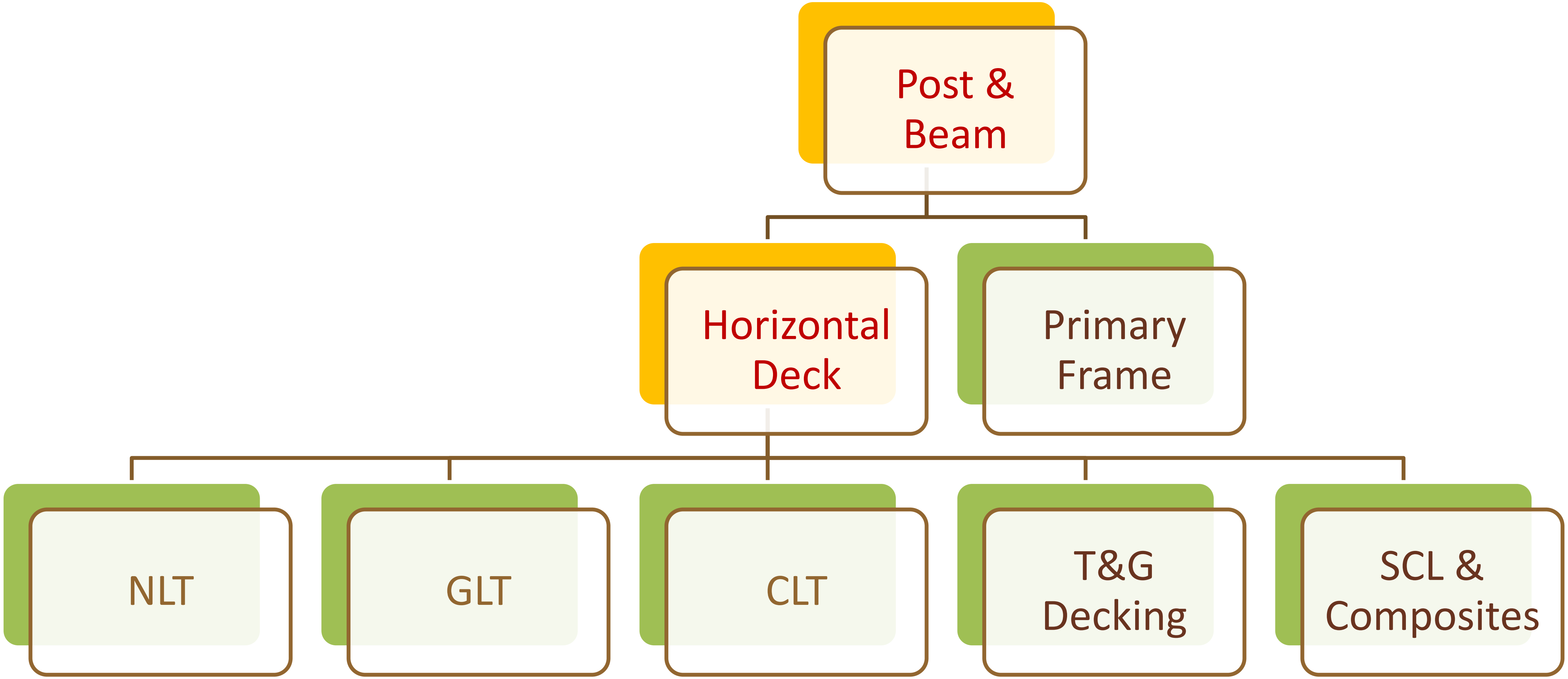


Photo Credit: WoodWorks

Public Library
Brentwood CA

Mass Timber Framing Systems



Mass Timber Products

Nail-Laminated Timber (NLT)

Cross-Laminated Timber (CLT)

Horizontal Framing

Glue-Laminated Timber (GLT)

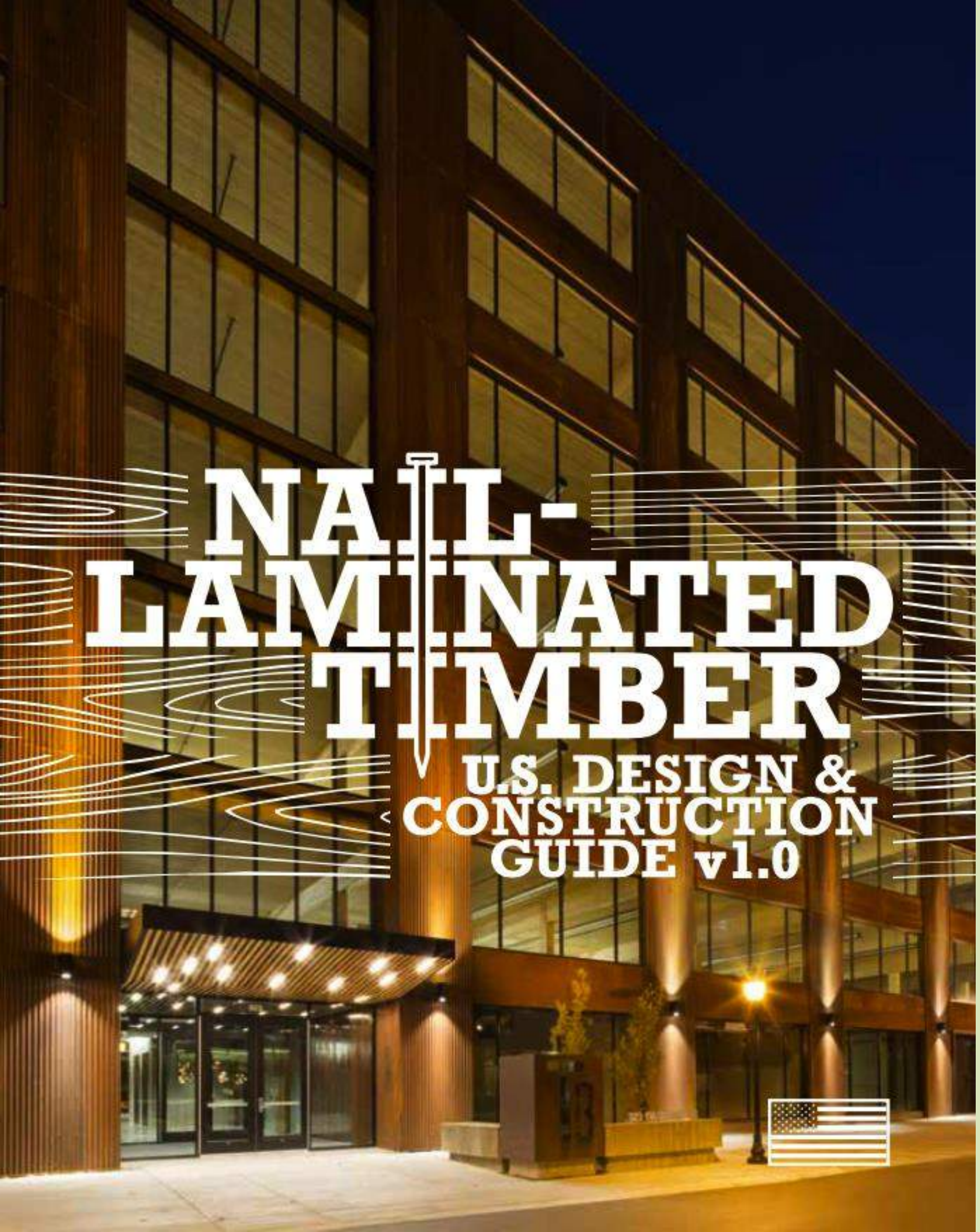
Tongue & groove decking (T&G)

Timber concrete composite

Structural Composite Lumber

Image source: StructureCraft

NLT Structural Design



NLT Design Guide includes:

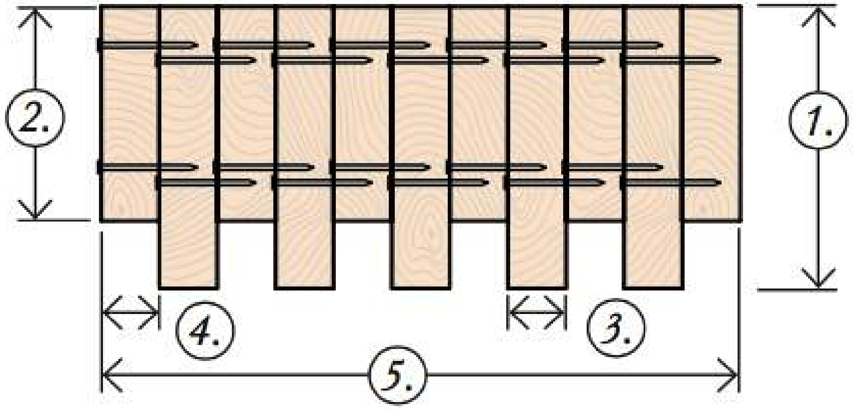
- Architecture
- Fire
- Structure
- Enclosure
- Supply and Fabrication
- Construction and Installation
- Erection engineering

Free download from www.thinkwood.com

NLT Structural Design

NLT shrinkage/expansion design:

Rule of thumb: leave gap between ½” and one ply wide per 8’-10’ wide panel



6. $x_i = \frac{n_i b_{lam\ i}}{b_{panel}}$

Figure 4.3: *Staggered NLT Cross Section*

Key

1. *NLT deep lamination depth (d_1)*
2. *NLT shallow lamination depth (d_2)*
3. *NLT deep lamination thickness (b_{lam1})*
4. *NLT shallow lamination thickness (b_{lam2})*
5. *NLT panel width (b)*
6. *Ratio of lamination depths (x_i), where n_i = the number of laminations of depth d_i*

Fluted NLT Design

STIFFNESS ($K_{section.E}$)	BENDING ($K_{section.b}$)	SHEAR ($K_{section.v}$)
$K_{section.E} = X_1 + X_2\left[\frac{d_2}{d_1}\right]^3$	$K_{section.b} = X_1 + X_2\left[\frac{d_2}{d_1}\right]^3$	$K_{section.v} = X_1$

$K_{section}$ is always <1 and applied assuming full panel depth of x_1

Example: 2x4 and 2x6 alternating lams

$$x_1 = x_2 = 0.5$$

$$K_{section,b} = 0.5 + 0.5\left[\frac{3.5}{5.5}\right]^3 = 0.63$$

See NLT Design & Construction Guide for Details

Cross-Laminated Timber

Cross Laminated Timber

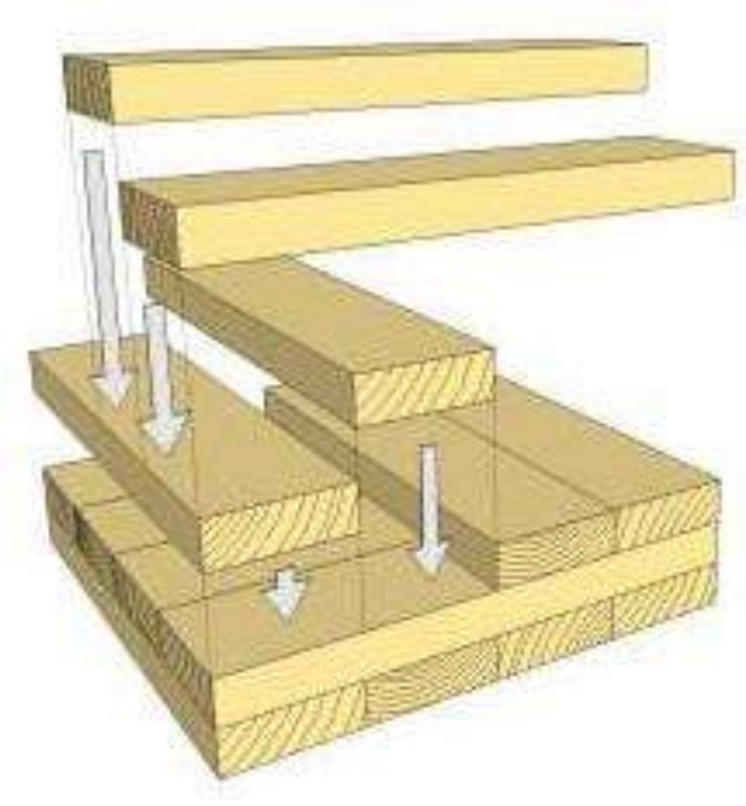
Considerations:

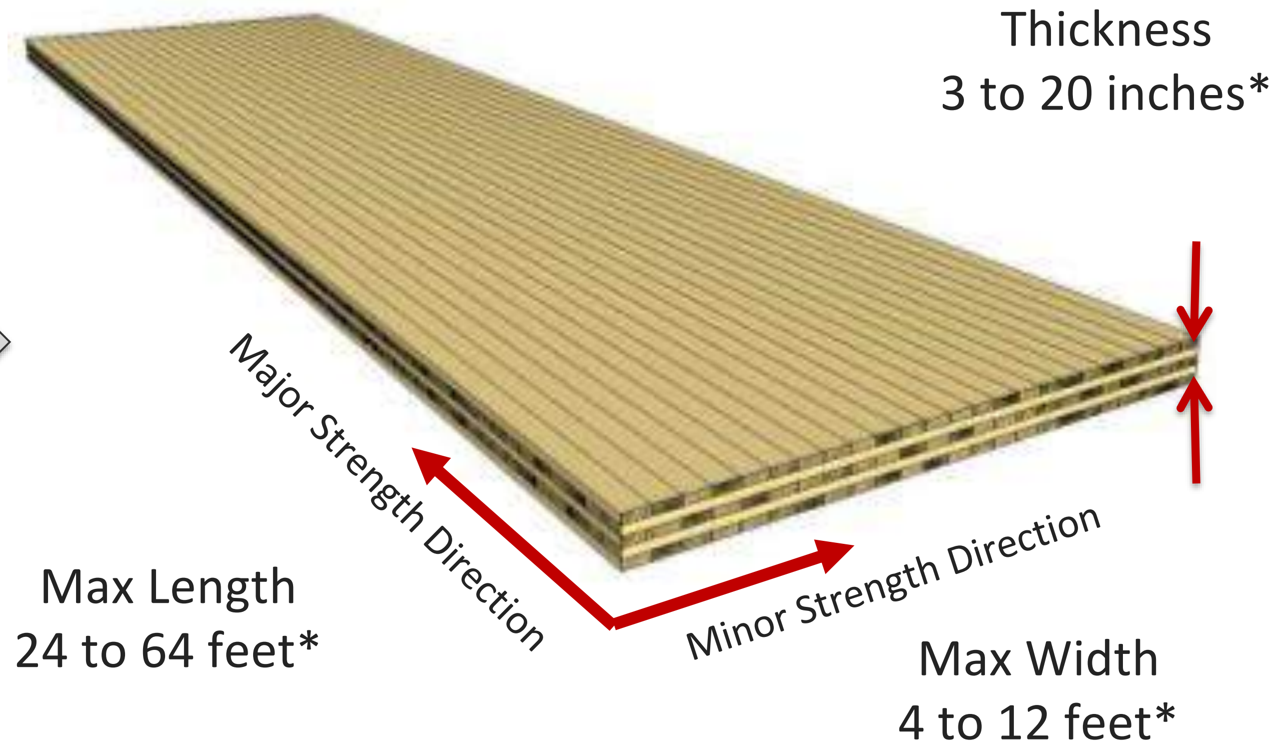
- Large light-weight panels
- Dimensionally stable
- Precise CNC machining available
- Recognized by IBC
- Dual Directional span capabilities
- Often architecturally exposed
- Fast on-site construction

Graphic Credit: StructureCraft

What is CLT?

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





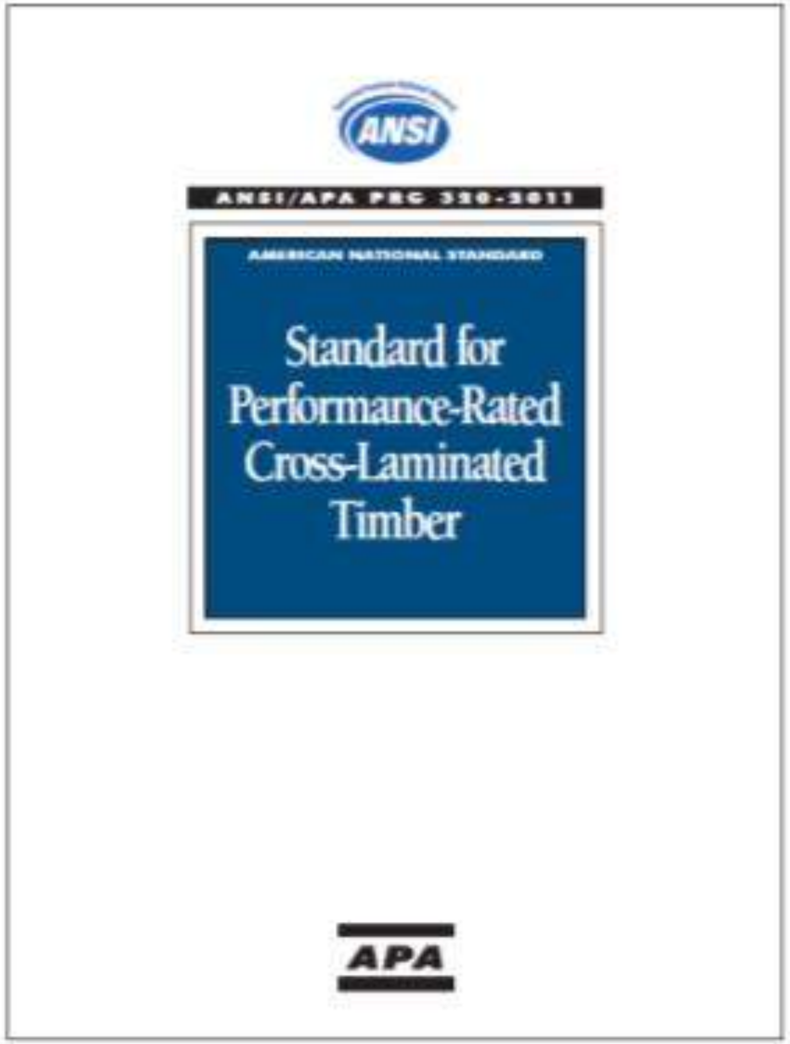
*All dimensions are approximate.
Consult with manufacturers


First Tech Credit Union
Hillsboro, Oregon
Photo Credit: Structurlam Products

Building Code Acceptance of CLT

2015 International Building Code

North American CLT Product Standard



ANSI/APA PRG 320 Standard for Performance-Rated Cross-Laminated Timber

The Standard Covers:

- U.S. and Canada Use
- Panel Dimensions and Tolerances
- Component Requirements
- Structural Performance Requirements
- Panel and Manufacturing Qualification
- Marking (Stamping)
- Quality Assurance

CLT Basic Stress Grades

Stress Grade	Major Strength Direction	Minor Strength Direction
E1	1950f-1.7E MSR SPF	#3 Spruce Pine Fir
E2	1650f-1.5E MSR DFL	#3 Doug Fir Larch
E3	1200f-1.2E MSR Misc	#3 Misc
E4	1950f-1.7E MSR SP	#3 Southern Pine
E5	1650f-1.5E MSR Hem-Fir	#3 Hem-Fir
V1	#2 Doug Fir Larch	#3 Doug Fir Larch
V2	#1/#2 Spruce Pine Fir	#3 Spruce Pine Fir
V3	#2 Southern Pine	#3 Southern Pine
V4	#2 Spruce Pine Fir (South)	#3 Spruce Pine Fir (South)
V5	#2 Hem-Fir	#3 Hem-Fir

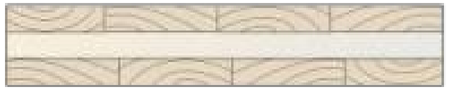
Basic solid sawn CLT stress grade in PRG 320-2019.

Other custom stress grades including structural composite lumber (SCL) permitted

Common CLT Layups

Most Designs
Least $/sf

3-ply 3-layer



5-ply 5-layer

7-ply 7-layer

7-ply 5-layer

9-ply 9-layer

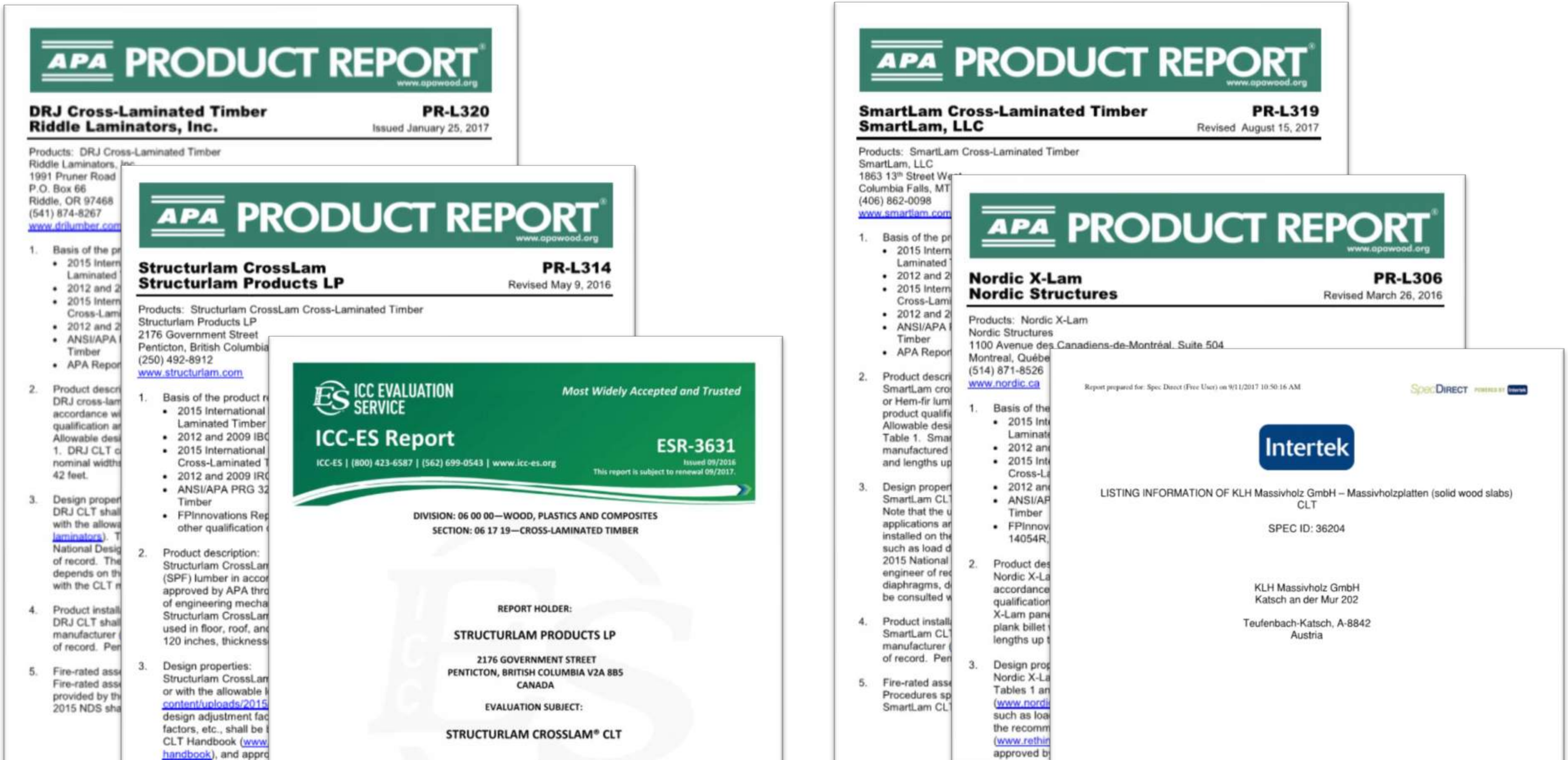
9-ply 7-layer

PRG 320 Defined Layups

TABLE A2.
THE ALLOWABLE BENDING CAPACITIES[a,b,c] FOR CLT LISTED IN TABLE A1 (FOR USE IN THE U.S.)

CLT Grade	CLT t (in.)	Lamination Thickness (in.) in CLT Layup							Major Strength Direction			Minor Strength Direction		
		=	⊥	=	⊥	=	⊥	=	$F_bS_{eff,0}$ (lbf-ft/ft)	$EI_{eff,0}$ (10^6 lbf-in.²/ft)	$GA_{eff,0}$ (10^6 lbf/ft)	$F_bS_{eff,90}$ (lbf-ft/ft)	$EI_{eff,90}$ (10^6 lbf-in.²/ft)	$GA_{eff,90}$ (10^6 lbf/ft)
E1	4 1/8	1 3/8	1 3/8	1 3/8					4,525	115	0.46	160	3.1	0.61
	6 7/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8			10,400	440	0.92	1,370	81	1.2
	9 5/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8	18,375	1,089	1.4	3,125	309	1.8
E2	4 1/8	1 3/8	1 3/8	1 3/8					3,825	102	0.53	165	3.6	0.56
	6 7/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8			8,825	389	1.1	1,430	95	1.1
	9 5/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8	15,600	963	1.6	3,275	360	1.7
E3	4 1/8	1 3/8	1 3/8	1 3/8					2,800	81	0.35	110	2.3	0.44
	6 7/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8			6,400	311	0.69	955	61	0.87
	9 5/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8	11,325	769	1.0	2,180	232	1.3
E4	4 1/8	1 3/8	1 3/8	1 3/8					4,525	115	0.53	180	3.6	0.63
	6 7/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8			10,425	441	1.1	1,570	95	1.3
	9 5/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8	18,400	1,090	1.6	3,575	360	1.9
V1	4 1/8	1 3/8	1 3/8	1 3/8					2,090	108	0.53	165	3.6	0.59
	6 7/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8			4,800	415	1.1	1,430	95	1.2
	9 5/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8	8,500	1,027	1.6	3,275	360	1.8
V2	4 1/8	1 3/8	1 3/8	1 3/8					2,030	95	0.46	160	3.1	0.52
	6 7/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8			4,675	363	0.91	1,370	81	1.0
	9 5/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

3rd Party Product Qualification of CLT



CLT Product Reports

CLT Grade (basic or custom)

Layup

Panel Properties

Table 1. Allowable Design Properties[a] for Lumber Laminations Used in SmartLam CLT (for Use in the U.S.)

CLT Grade	Major Strength Direction						Minor Strength Direction					
	$F_{b,0}$ (psi)	E_0 (10^6 psi)	$F_{t,0}$ (psi)	$F_{c,0}$ (psi)	$F_{v,0}$ (psi)	$F_{s,0}$ (psi)	$F_{b,90}$ (psi)	E_{90} (10^6 psi)	$F_{t,90}$ (psi)	$F_{c,90}$ (psi)	$F_{v,90}$ (psi)	$F_{s,90}$ (psi)
SL-V4	775	1.1	350	1,000	135	45	775	1.1	350	1,000	135	45

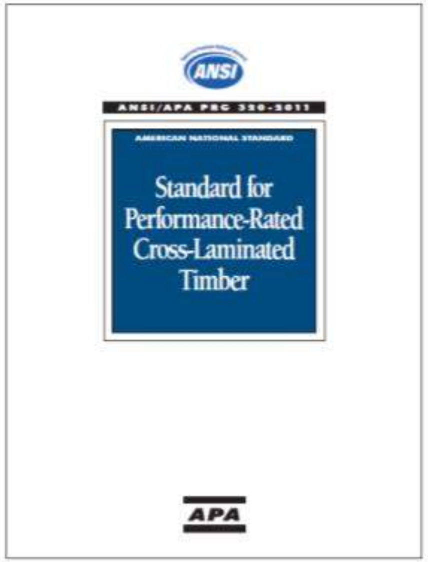
For SI: 1 psi = 0.006895 MPa

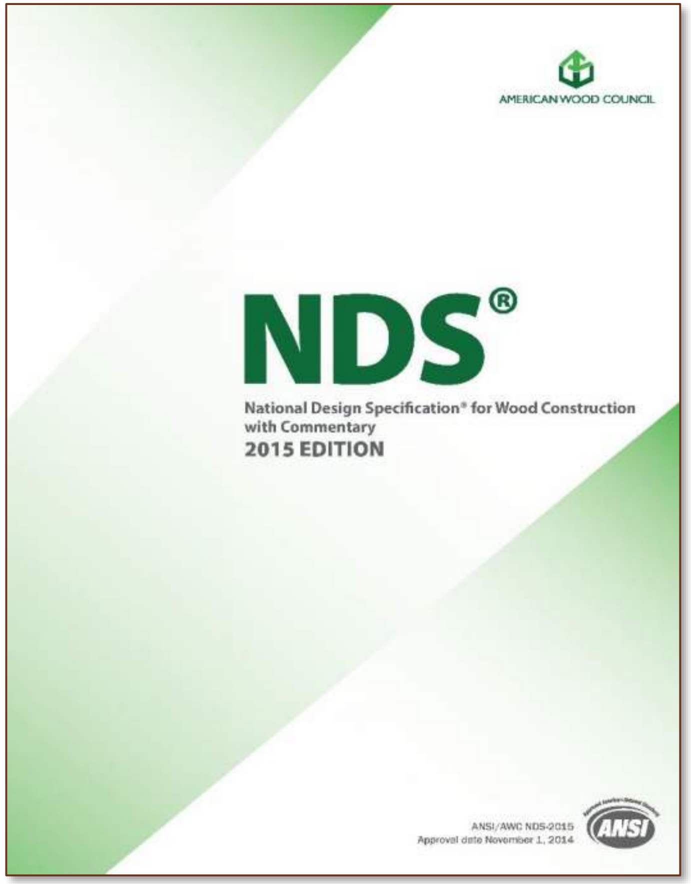
[a] Tabulated values are allowable design values and not permitted to be increased for the lumber flat use or size factor in accordance with the NDS. The design values shall be used in conjunction with the section properties provided by the CLT manufacturer based on the actual layup used in manufacturing the CLT panel (see Tables 2 and 3).

Table 2. Allowable Design Capacities[a] for SmartLam Balanced CLT (for Use in the U.S.)

CLT Grade	Layup #	Thick-ness (in.)	Lamination Thickness (in.) in CLT Layup									Major Strength Direction				Minor Strength Direction			
			=	⊥	=	⊥	=	⊥	=	⊥	=	$F_bS_{eff,0}$ (lbf-ft/ft)	$EI_{eff,0}$ (10^6 lbf-in.²/ft)	$GA_{eff,0}$ (10^6 lbf/ft)	$V_{s,0}$ (lbf/ft)	$F_bS_{eff,90}$ (lbf-ft/ft)	$EI_{eff,90}$ (10^6 lbf-in.²/ft)	$GA_{eff,90}$ (10^6 lbf/ft)	$V_{s,90}$ (lbf/ft)
SL-V4[b]	3-alt	4 1/8	1 3/8	1 3/8	1 3/8							1,800	74	0.41	1,430	245	2.9	0.41	495
	4-maxx	5 1/2	1 3/8	1 3/8 x 2	1 3/8							2,925	161	0.49	1,740	975	23	0.85	990
	5-alt	6 7/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8					4,150	286	0.83	1,980	2,120	74	0.83	1,430
	5-maxx	6 7/8	1 3/8 x 2	1 3/8	1 3/8 x 2							5,150	355	1.4	2,460	245	2.9	0.86	495
	6-maxx	8 1/4	1 3/8 x 2	1 3/8 x 2	1 3/8 x 2							7,200	596	1.2	2,875	975	23	1.3	990
	7-alt	9 5/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8			7,325	707	1.2	2,500	4,825	283	1.2	1,960
	7-maxx	9 5/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8					9,425	909	1.7	3,200	2,120	74	1.3	1,430

Structural Design Standardization





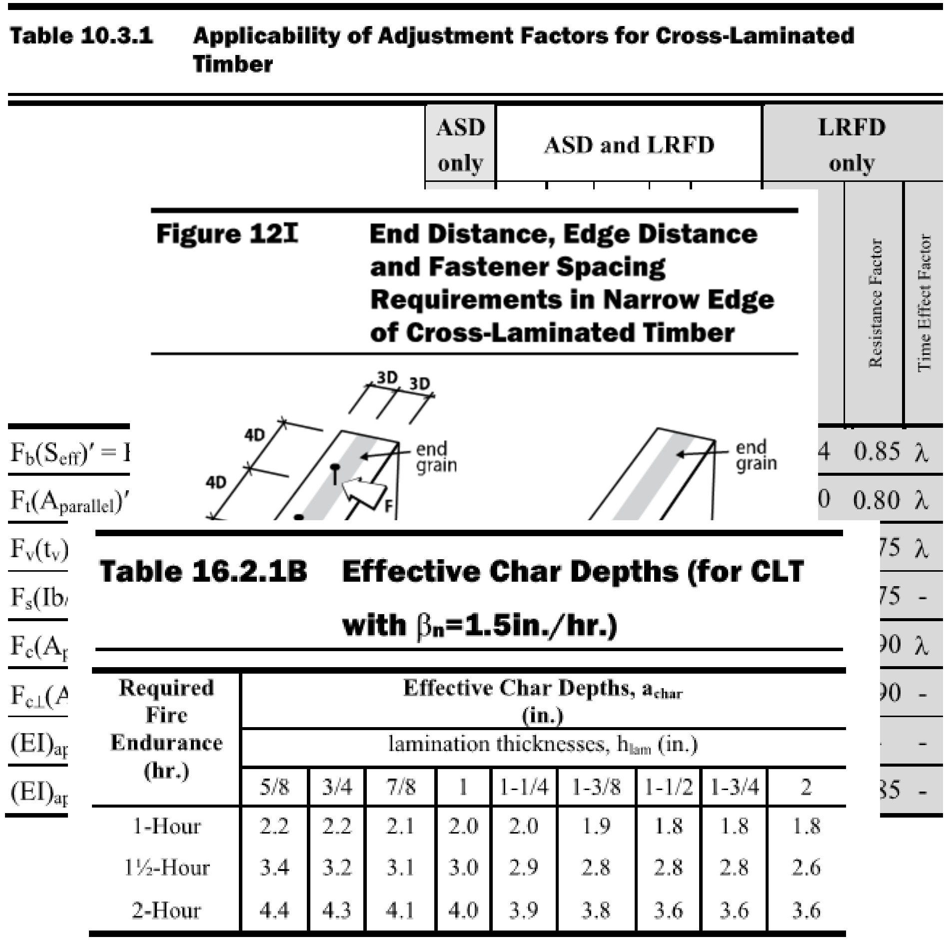


Table 10.3.1 Applicability of Adjustment Factors for Cross-Laminated Timber

	ASD only	ASD and LRFD	LRFD only	
			Resistance Factor	Time Effect Factor
$F_b(S_{eff})' = F$			0.85	λ
$F_t(A_{parallel})'$			0.80	λ
$F_v(t_v)$			75	λ
$F_s(Ib$			75	-
$F_c(A_p$			90	λ
$F_{c\perp}(A$			90	-
$(EI)_{ap}$				-
$(EI)_{ap}$			85	-

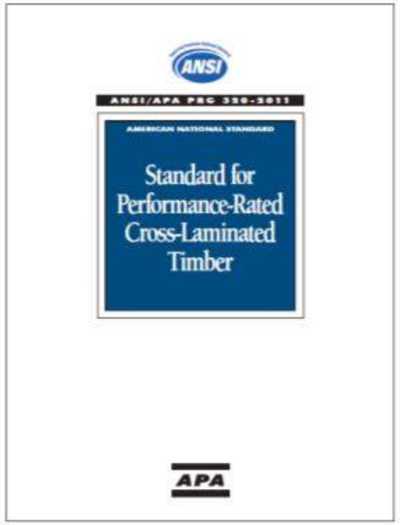
Figure 12I End Distance, Edge Distance and Fastener Spacing Requirements in Narrow Edge of Cross-Laminated Timber

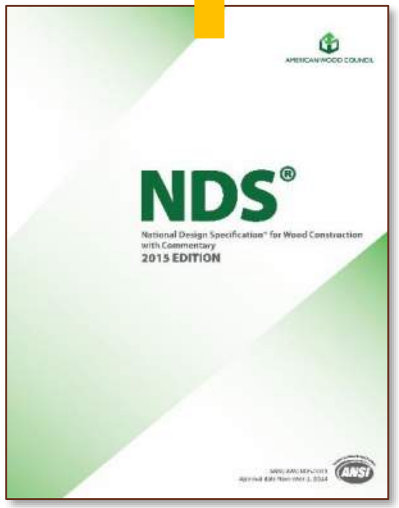
Table 16.2.1B Effective Char Depths (for CLT with β_n=1.5in./hr.)

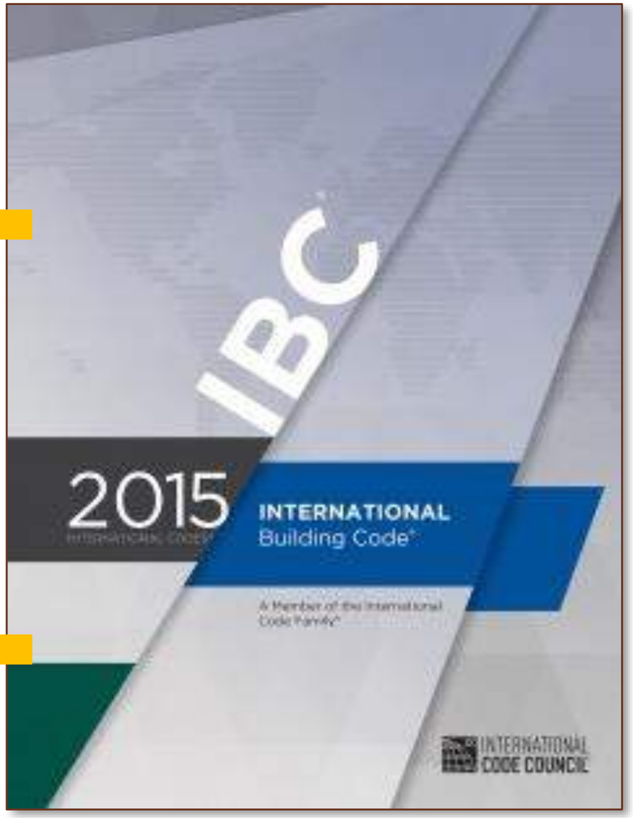
Required Fire Endurance (hr.)	Effective Char Depths, a_{char} (in.)								
	lamination thicknesses, h_{lam} (in.)								
	5/8	3/4	7/8	1	1-1/4	1-3/8	1-1/2	1-3/4	2
1-Hour	2.2	2.2	2.1	2.0	2.0	1.9	1.8	1.8	1.8
1½-Hour	3.4	3.2	3.1	3.0	2.9	2.8	2.8	2.8	2.6
2-Hour	4.4	4.3	4.1	4.0	3.9	3.8	3.6	3.6	3.6

National Design Specification for Wood Construction
2015 & 2018 Edition

Model Building Code Acceptance







2015 International Building Code

Highlights of CLT Provisions in IBC 2015

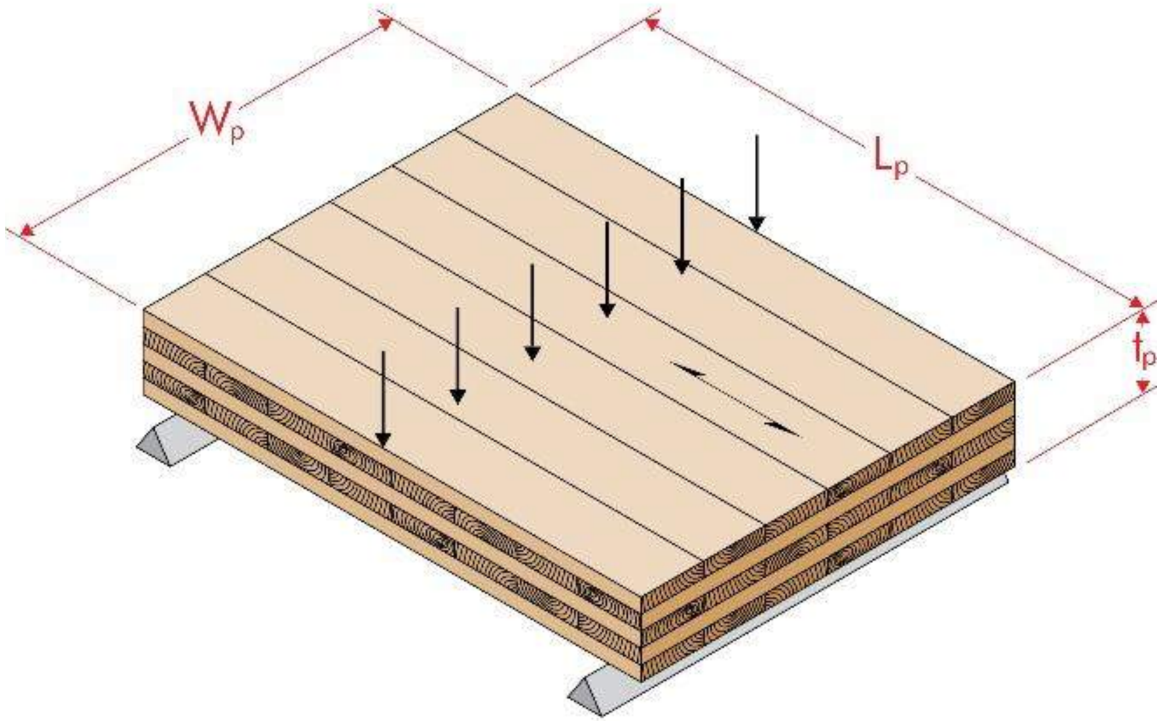
- CLT is generally available for use in Type III, IV and V construction.

- IBC 2015 Chapter 6 Defines Dimensions of CLT to qualify as Heavy Timber (Type IV Construction)
  - 4” Interior walls
  - 4” Floors
  - 3” Roofs
  - Non Fire-Retardant Treated CLT allowed in Exterior Walls of Type IV construction in many conditions. (IBC 2015 602.4)

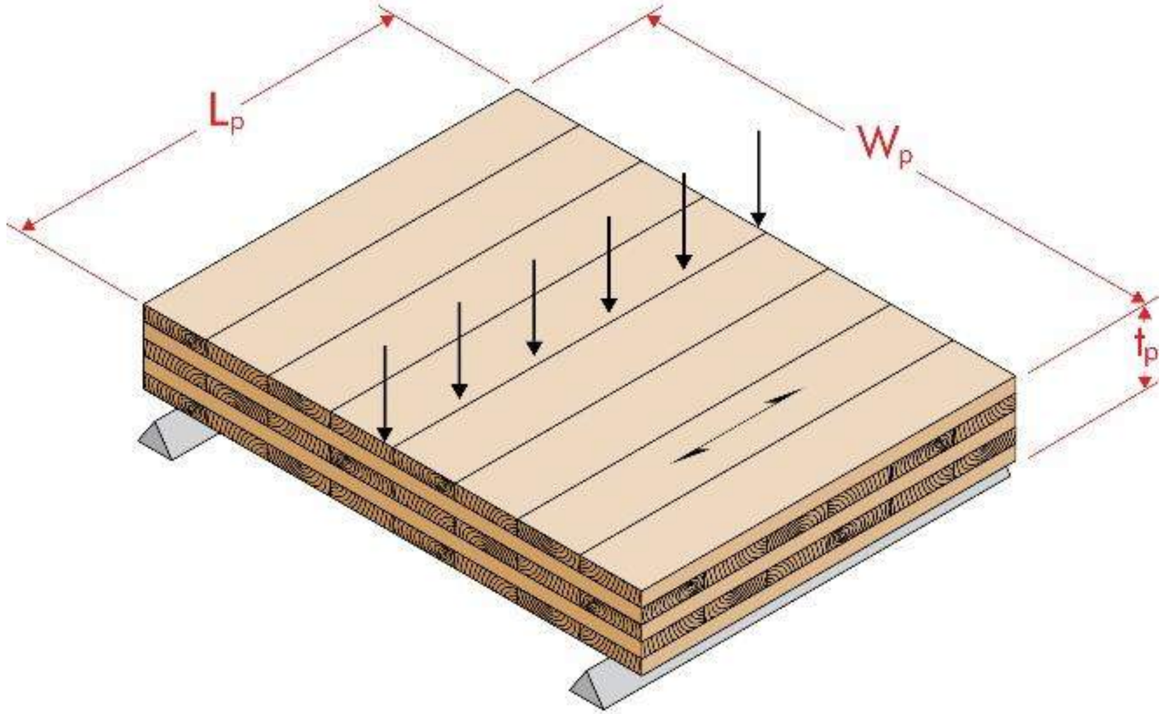
The Heavy Timber construction size requirements only apply to Type IV Construction

Flatwise Properties

FLATWISE Panel Loading



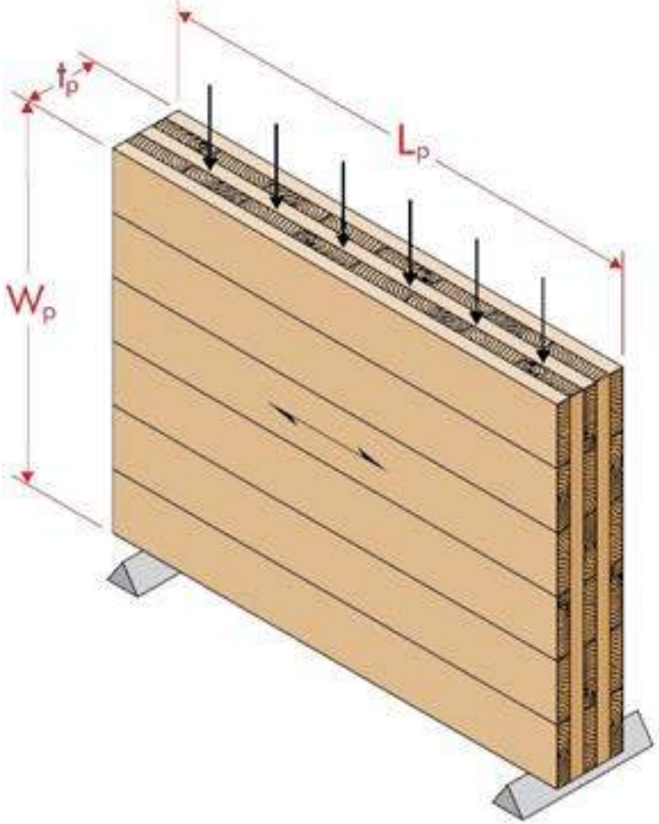
Span in MAJOR Strength Direction
"Parallel" Direction



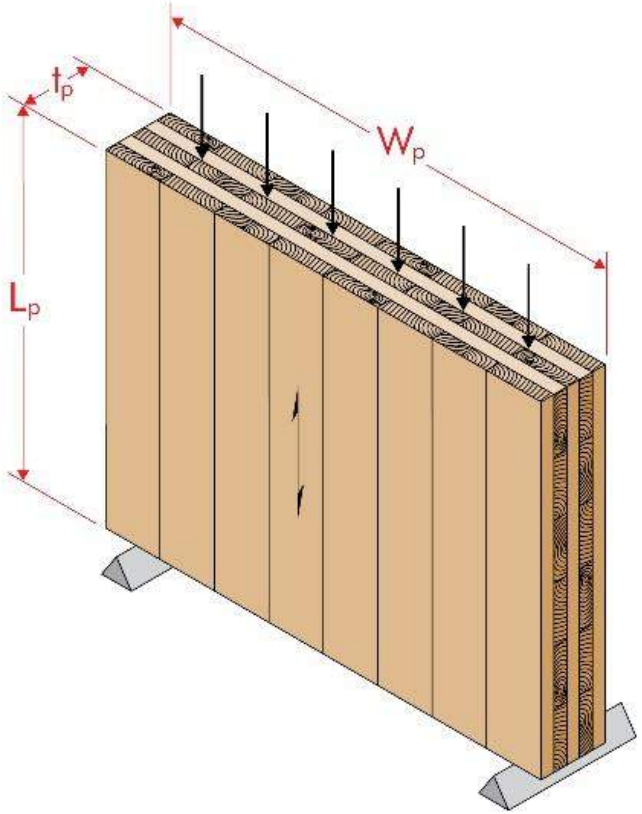
Span in MINOR Strength Direction
"Perpendicular" Direction

Reference & Source: ANSI/APA PRG 320

EDGEWISE Panel Loading



Span in MAJOR Strength Direction



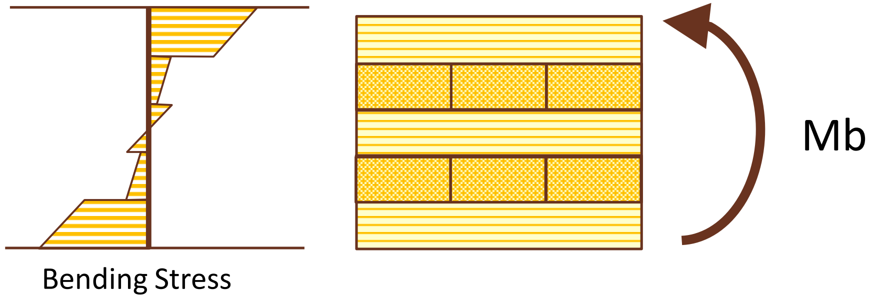
Span in MINOR Strength Direction

Reference & Source: ANSI/APA PRG 320

Flatwise Flexural Strength

Design properties based on an Extreme Fiber Model:

Flexural Capacity Check:



$$M_b \leq (F_b S_{eff})'$$

M_b = applied bending moment

$(F_b S_{eff})'$ = adjusted bending capacity

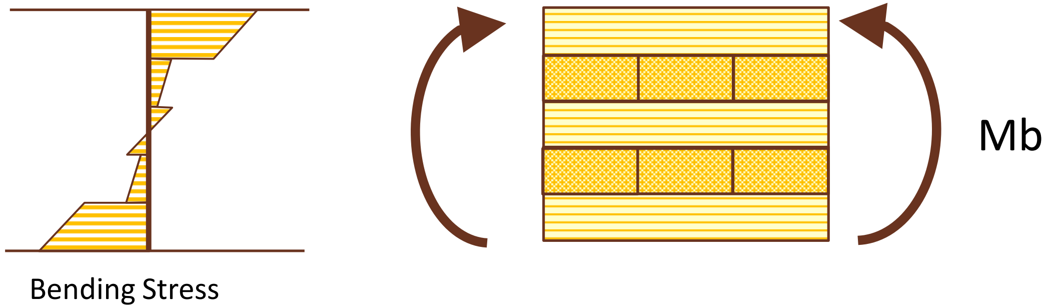
S_{eff} = effective section modulus

F_b = reference bending design stress of outer lamination

Reference: NDS 2015

Flatwise Flexural Strength

Flexural Capacity Check (**ASD**)



$$(F_b S_{eff})' = C_D \underbrace{C_M \, C_t \, C_L}_{\text{Commonly 1.0}} \underbrace{(F_b S_{eff})}_{\text{Provided as combined value}}$$

per NDS

$$M_b \leq C_D \, (1.0) \, (F_b S_{eff})$$

Reference: NDS 2015

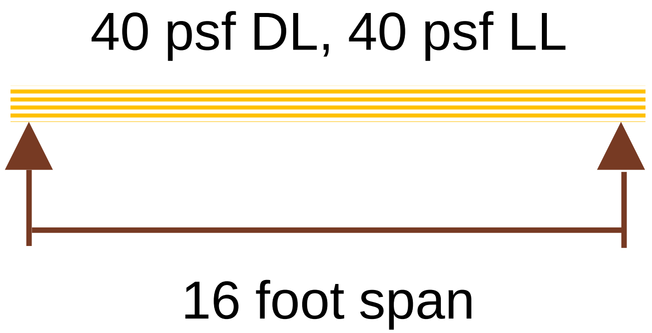
Flatwise Flexural Strength Design Example

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

Analysis of a 1 ft strip of panel as beam

Calculate ASD Applied Moment (1.0D + 1.0L)

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

Flatwise Flexural Strength Design Example

Look for Acceptable CLT Grade from PRG 320: $F_b S_{eff,0}$ > 2560 lb-ft/ft

TABLE A2.
THE ALLOWABLE BENDING CAPACITIES[a,b,c] FOR CLT LISTED IN TABLE A1 (FOR USE IN THE U.S.)

CLT Grade	CLT t (in.)	Lamination Thickness (in.) in CLT Layup =	⊥	=	⊥	=	⊥	=	Major Strength Direction $F_b S_{eff,0}$ (lbf-ft/ft)	$EI_{eff,0}$ (10^6 lbf-in.²/ft)	$GA_{eff,0}$ (10^6 lbf/ft)	Minor Strength Direction $F_b S_{eff,90}$ (lbf-ft/ft)	$EI_{eff,90}$ (10^6 lbf-in.²/ft)	$GA_{eff,90}$ (10^6 lbf/ft)
	4 1/8	1 3/8	1 3/8	1 3/8					2,090	108	0.53	165	3.6	0.59
V1	6 7/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8			4,800	415	1.1	1,430	95	1.2
	9 5/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8	8,500	1,027	1.6	3,275	360	1.8
	4 1/8	1 3/8	1 3/8	1 3/8					2,030	95	0.46	160	3.1	0.52
V2	6 7/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8			4,675	363	0.91	1,370	81	1.0
	9 5/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8	8,275	898	1.4	3,125	309	1.6

Select 5-Ply 6 7/8” Thick V1 Panel with $F_b S_{eff,0}$ = 4800 lb-ft/ft

Reference: ANSI/APA PRG 320-2012

Flatwise Flexural Strength Design Example

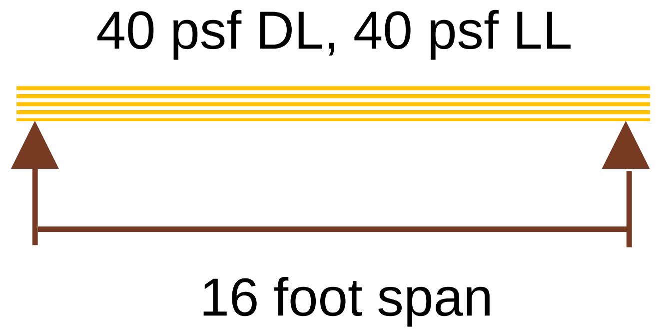
ASD Flexural Capacity:

Dead + Live load, $C_D = 1.0$

$$(F_bS_{eff})' = C_D\,(1.0)\,(F_bS_{eff})$$

$$= 1.0\,(1.0)\,(4800\text{ lb-ft/ft})$$

$$= 4800\text{ lb-ft/ft}$$



$$M_b = 2560\text{ lb-ft/ft} \le (F_bS_{eff})' = 4800\text{ lb-ft/ft}$$

Flexural Strength OK

Flatwise Shear Strength

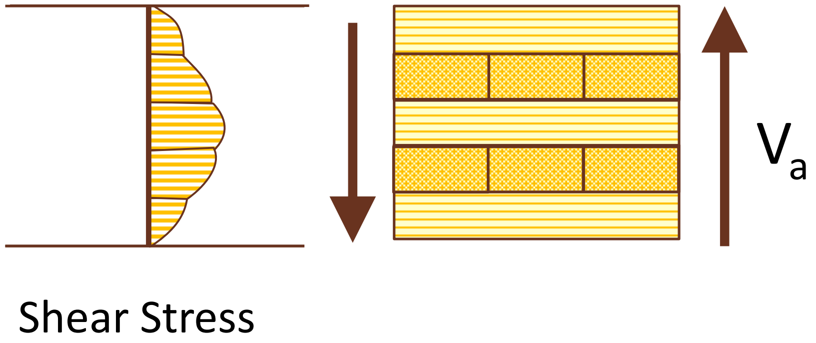
Design Properties based on Extreme Fiber Model:

Shear Capacity Check:

$$V_a \leq F_s(Ib/Q)_{eff}'$$

V_a = applied shear

$F_s(IbQ_{eff})'$ = adjusted shear strength



Jargon Alert! AKA "Planar Shear", "Out-of-Plane Shear", or "Rolling Shear" Strength

Wood Structural Panel Term

Structural Engineering Term

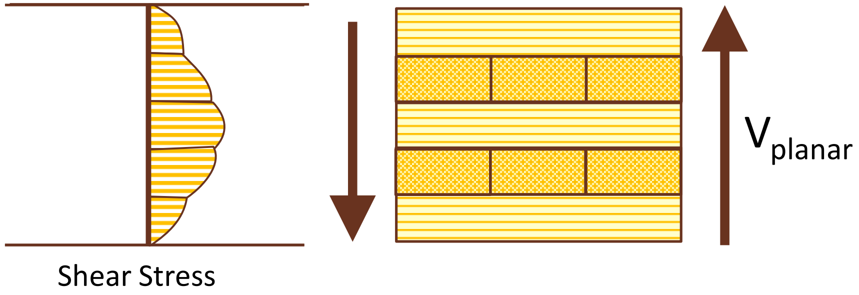
CLT Term

Reference: NDS 2015

Flatwise Shear Strength

Design Properties based on Extreme Fiber Model:

Shear Capacity Check (ASD):



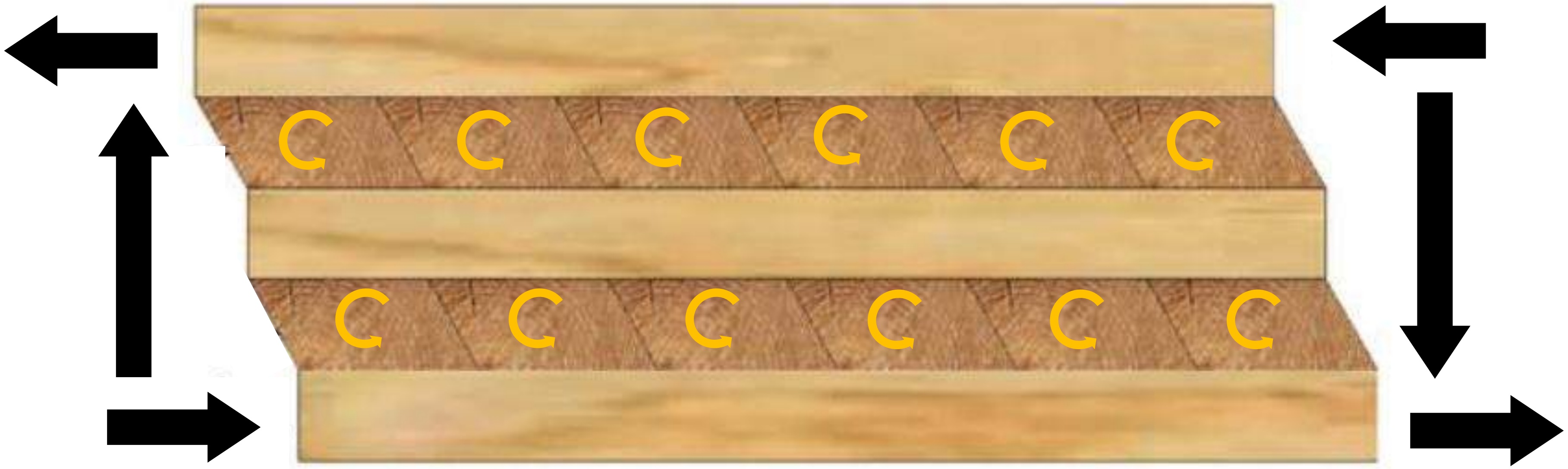
$$F_s(I_bQ)_{eff}' = \underbrace{C_M\,C_t}_{\text{Commonly } 1.0}\,\underbrace{(F_s(I_bQ)_{eff})}_{\text{From Manufacturer}} = C_M\,C_t\,\underbrace{V_s}$$

$$V_{planar} \leq (1.0)\,V_s$$

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

Reference: NDS 2015 & Product Reports

Flatwise Shear Strength

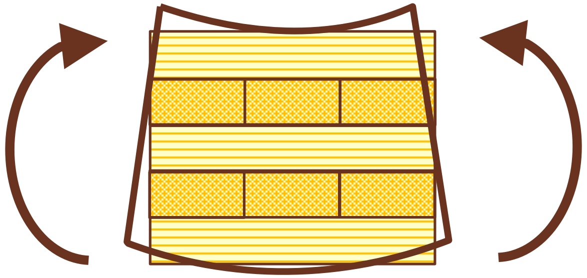


Rolling Shear

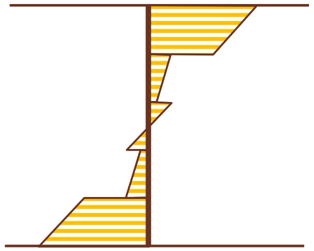
Source: CSA O86-14, 2016 Supplement

Flatwise Flexural Stiffness

Shear Analogy Method



EI_{eff}



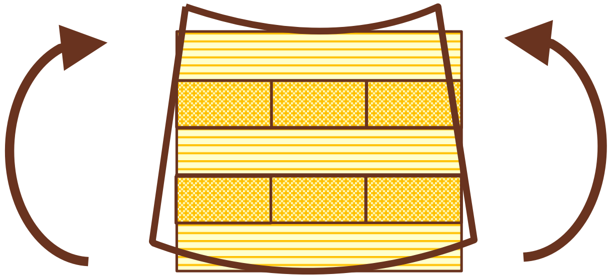
Bending Stress

$$(EI)_{eff,f,0} = \sum_{i=1}^{n} E_i b_0 \frac{t_i^3}{12} + \sum_{i=1}^{n} E_i b_0 t_i z_i^2$$

$$S_{eff,f,0} = \frac{(EI)_{eff,f,0}}{E_{major}} \frac{2}{t_p};$$

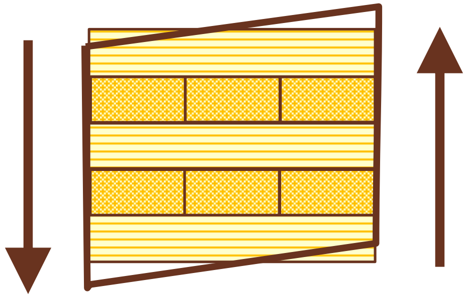
Reference: ANSI/APA PRG 320 2019 Appendix X3.

Flatwise Flexural Stiffness



EI_{eff}

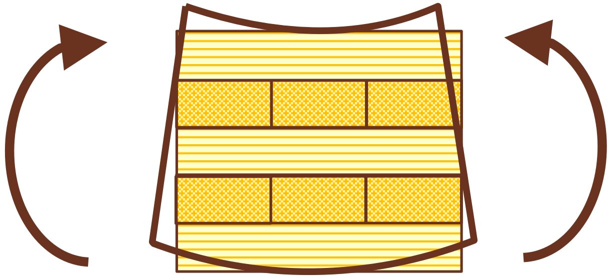
$$(EI)_{eff,f,0} = \sum_{i=1}^{n} E_i b_0 \frac{t_i^3}{12} + \sum_{i=1}^{n} E_i b_0 t_i z_i^2$$



GA_{eff}

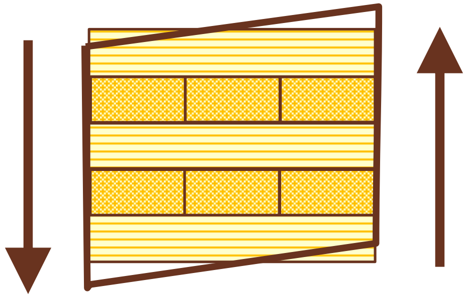
$$(GA)_{eff,f,0} = \frac{\left(t_p - \frac{t_1}{2} - \frac{t_n}{2}\right)^2}{\left[\left(\frac{t_1}{2G_1 b_0}\right) + \left(\sum_{i=2}^{n-1} \frac{t_i}{G_i b_0}\right) + \left(\frac{t_n}{2G_n b_0}\right)\right]}$$

Flatwise Flexural Stiffness



$$(EI)_{eff,f,0} = \sum_{i=1}^{n} E_i b_0 \frac{t_i^3}{12} + \sum_{i=1}^{n} E_i b_0 t_i z_i^2$$

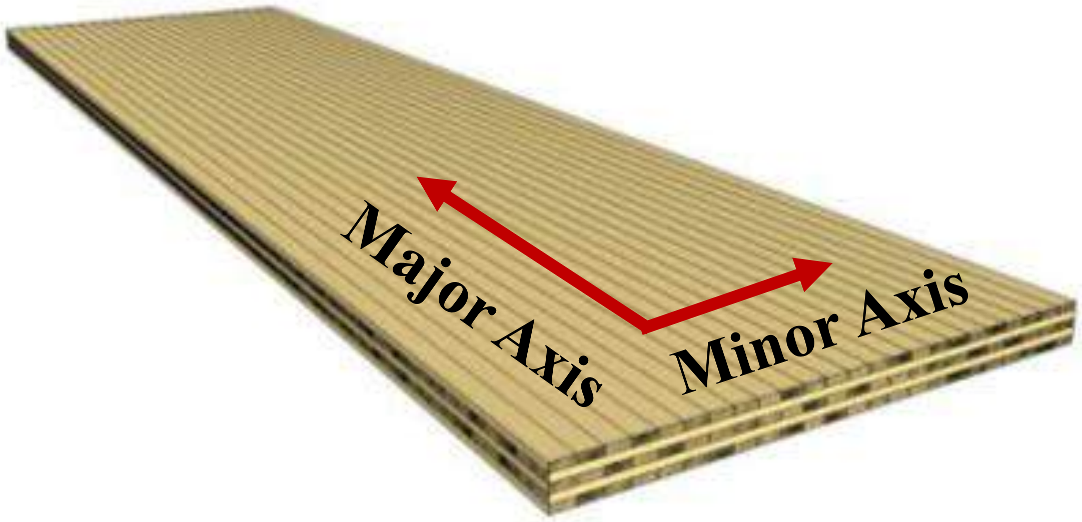
Important to develop properties of new CLT Sections.
Not to use standard CLT Sections



GA_{eff}

$$(GA)_{eff,f,0} = \frac{(t_p - \frac{t_1}{2} - \frac{t_n}{2})^2}{\left[\left(\frac{t_1}{2G_1 b_0}\right) + \left(\sum_{i=2}^{n-1} \frac{t_i}{G_i b_0}\right) + \left(\frac{t_n}{2G_n b_0}\right)\right]}$$

Flatwise CLT Panel Section Properties



Flexural Strength:	$F_bS_{eff,0}$	$F_bS_{eff,90}$
Flexural Stiffness:	$EI_{eff,0}$	$EI_{eff,90}$
Shear Strength:	$V_{s,0}$	$V_{s,90}$
Shear Stiffness:	$GA_{eff,0}$	$GA_{eff,90}$

Values in RED provided by CLT manufacturer

Reference: PRG 320 and CLT Product Reports

Deflection Calculations

General Purpose: 1 Way, Beam Action

Needed Stiffness: $EI_{eff,0}$ $GA_{eff,0}$

Can model multiple spans, cantilevers, etc.

Flatwise Deflection Example

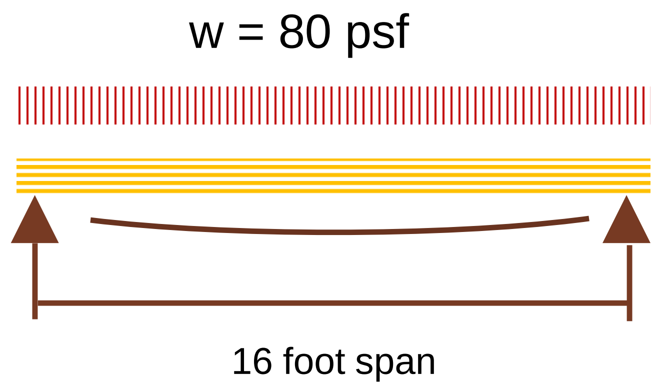
Uniform loading on one way slab:

Beam Analysis using

Flexural Stiffness: $EI_{eff,0}$

Shear Stiffness: $5/6\ GA_{eff,0}$

Maximum Deflection @ Mid-Span



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

From Manufacturer

Flatwise Deflection Example

For selected 6 7/8” 5-Ply V1, lookup major strength stiffness values

TABLE A2.
THE ALLOWABLE BENDING CAPACITIES[a,b,c] FOR CLT LISTED IN TABLE A1 (FOR USE IN THE U.S.)

		Lamination Thickness (in.) in CLT Layup							Major Strength Direction			Minor Strength Direction		
CLT Grade	CLT t (in.)	=	⊥	=	⊥	=	⊥	=	$F_bS_{eff,0}$ (lbf-ft/ft)	$EI_{eff,0}$ (10^6 lbf-in.^{2}/ft)	$GA_{eff,0}$ (10^6 lbf/ft)	$F_bS_{eff,90}$ (lbf-ft/ft)	$EI_{eff,90}$ (10^6 lbf-in.^{2}/ft)	$GA_{eff,90}$ (10^6 lbf/ft)
	4 1/8	1 3/8	1 3/8	1 3/8					2,090	108	0.53	165	3.6	0.59
V1	6 7/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8			4,800	*415*	*1.1*	1,430	95	1.2
	9 5/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8	8,500	1,027	1.6	3,275	360	1.8
	4 1/8	1 3/8	1 3/8	1 3/8					2,030	95	0.46	160	3.1	0.52
V2	6 7/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8			4,675	363	0.91	1,370	81	1.0
	9 5/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8	8,275	898	1.4	3,125	309	1.6

Reference: ANSI/APA PRG 320-2012

Flatwise Deflection Example

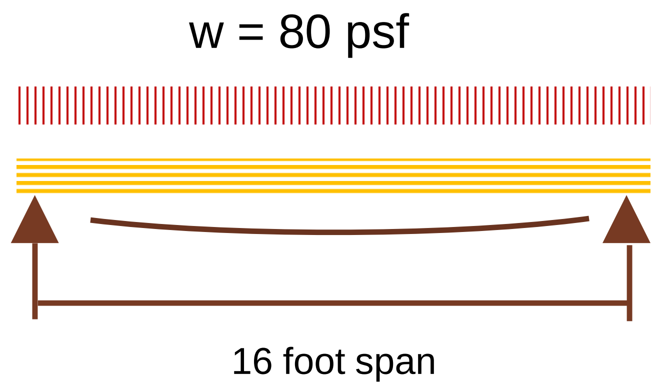
Uniform loading on one way slab:

Beam Analysis using

Flexural Stiffness: $EI_{eff,0}$

Shear Stiffness: $5/6\ GA_{eff,0}$

Maximum Deflection @ Mid-Span



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

$$= \frac{5}{385} \cdot \frac{80\ \text{psf}\ (16\ \text{ft})^4}{415 \times 10^6\ \text{lbf in}^2/\text{ft}} \cdot \left(\frac{12\ \text{in}}{1\ \text{ft}}\right)^3 + \frac{1}{8} \cdot \frac{80\ \text{psf}\ (16\ \text{ft})^2}{{}^5/_6\ 1.1 \times 10^6\ \text{lbf/ft}} \cdot \frac{12\ \text{in}}{1\ \text{ft}}$$

= 0.284 in + 0.034 in = 0.318 in

= L / 604

Deflection Creep Factor

Deformation to Long Term Loads

$$\Delta_T = K_{cr}\,\Delta_{LT} + \Delta_{ST}$$ NDS Eq 3.5-1

Δ_{ST} Deflection due to short-term loading

Δ_{LT} Immediate deflection due to long term loading

K_{cr} 2.0 for CLT in dry service conditions

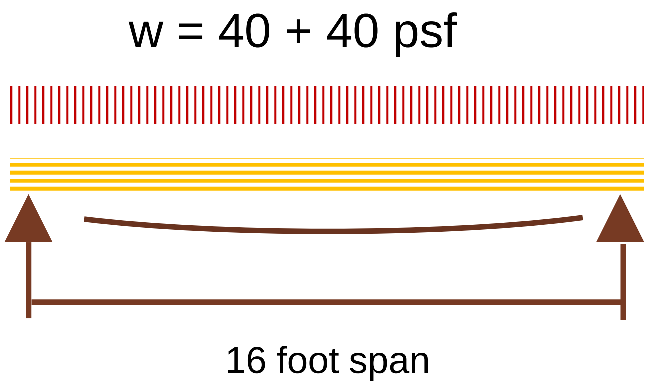
Design Example:

Δ_{ST} from 40psf = 0.159 in (assuming long term = dead)

Δ_{LT} from 40psf = 0.159 in

Δ_T = 2.0 (0.159) + 0.159 = 0.477 in

= L / 403

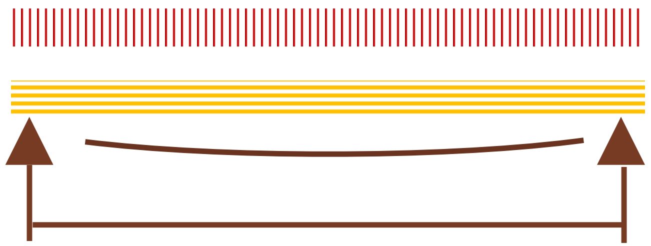


Reference: NDS 2015

Deflection Calculations

Simplified Beam Deflections:

For single span, simply supported uniform load



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

What is ***Apparent*** Flexural Stiffness, EI_{app}, such that

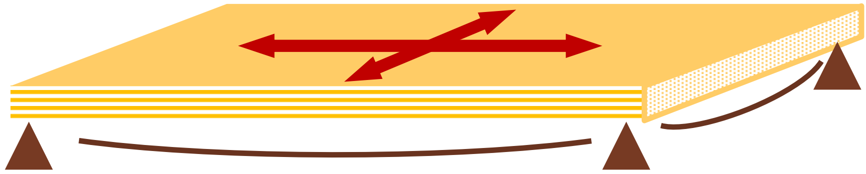
$$\Delta_{max} = \frac{5}{384} \cdot \frac{wL^4}{EI_{app}}$$

Set equal to each other and solve for EI_{app} →

$$EI_{app} = \frac{EI_{eff}}{1 + \dfrac{11.5 EI_{eff}}{GA_{eff} L^2}}$$

Reference: US CLT Handbook & NDS

Deflection Calculations



General Purpose, 2 Way, Plate Action

Flexural Stiffness

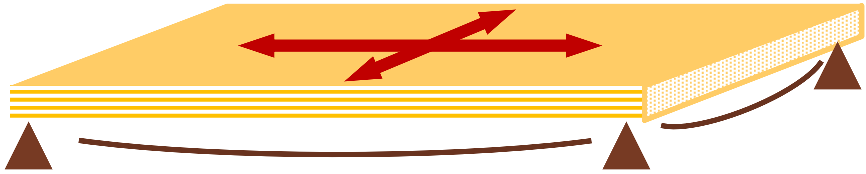
$EI_{eff,0}$ $EI_{eff,90}$

Shear Stiffness:

$5/6\ GA_{eff,0}$ $5/6\ GA_{eff,90}$

5/6 from A′ = 5/6 A shape factor for rectangular sections

Point Supported Plates



Possible, however not common.

Structural design issues include:

- Compression perp to grain at support points
- Bi-directional bending stress interactions
- Punching shear

Not covered in NDS

Using PRG 320 Standard Grades for Design?

TABLE A2.
THE ALLOWABLE BENDING CAPACITIES[a,b,c] FOR CLT LISTED IN TABLE A1 (FOR USE IN THE U.S.)

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E1	4 1/8	1 3/8	1 3/8	1 3/8					4,525	115	0.46	160	3.1	0.61
	6 7/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8			10,400	440	0.92	1,370	81	1.2
	9 5/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8	18,375	1,089	1.4	3,125	309	1.8
E2	4 1/8	1 3/8	1 3/8	1 3/8					3,825	102	0.53	165	3.6	0.56
	6 7/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8			8,825	389	1.1	1,430	95	1.1
	9 5/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8	15,600	963	1.6	3,275	360	1.7
E3	4 1/8	1 3/8	1 3/8	1 3/8					2,800	81	0.35	110	2.3	0.44
	6 7/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8			6,400	311	0.69	955	61	0.87
	9 5/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8	11,325	769	1.0	2,180	232	1.3
E4	4 1/8	1 3/8	1 3/8	1 3/8					4,525	115	0.53	180	3.6	0.63
	6 7/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8			10,425	441	1.1	1,570	95	1.3
	9 5/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8	18,400	1,090	1.6	3,575	360	1.9
V1	4 1/8	1 3/8	1 3/8	1 3/8					2,090	108	0.53	165	3.6	0.59
	6 7/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8			4,800	415	1.1	1,430	95	1.2
	9 5/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8	8,500	1,027	1.6	3,275	360	1.8
V2	4 1/8	1 3/8	1 3/8	1 3/8					2,030	95	0.46	160	3.1	0.52
	6 7/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8			4,675	363	0.91	1,370	81	1.0
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

PRG 320 includes pre-defined Stress Grades, Layups and related Design Properties

Is doesn't tell you what CLT grades and layups are available.

Coordinate with manufacturers availability and information

Working with CLT: Know Your Supply Chain

- CLT Manufactures different CLT grades and maximum panel sizes
- CLT Manufacturers have specific CNC capabilities
- 3rd Party Fabricators can have additional CNC capabilities

Photo: DR Johnson

Photo: Sauter Timber

Floor Vibration Design

"One might almost say that **strength is essential** and **otherwise unimportant**"

- Hardy Cross

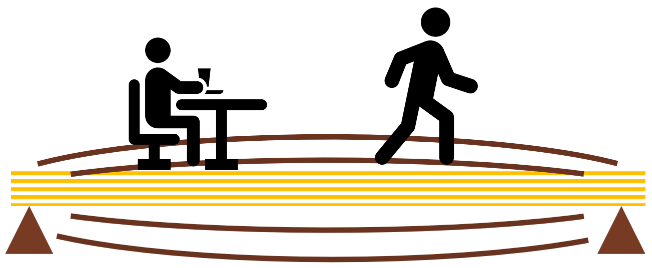
US Building Code Requirements for Vibration

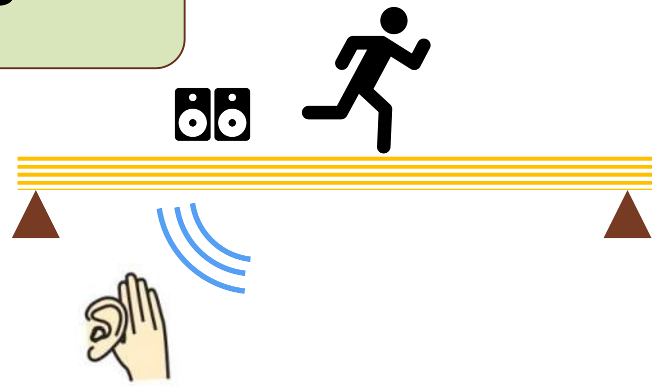
None

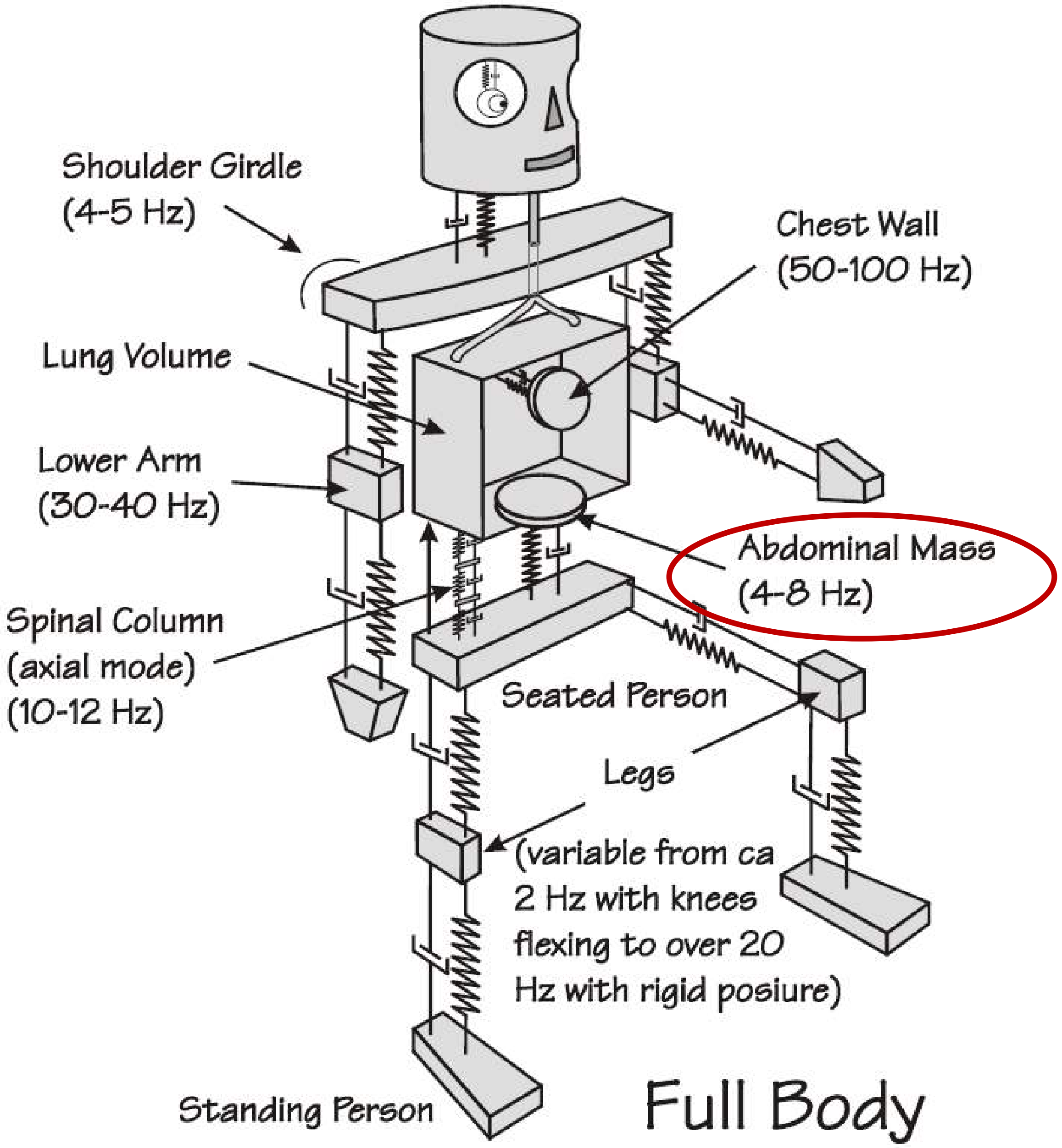
Barely discussed in IBC, NDS, etc.
ASCE 7 Commentary Appendix C has some discussion, no requirements

Vibrations vs Acoustics

Structural Vibrations	Acoustic Vibrations
1 Hz – 100 Hz	20 Hz – 15,000 Hz
Transmitted through structure or through ground	Transmitted through air, walls, floors, windows
Physical effects	Audible effects







Human Body Dynamics

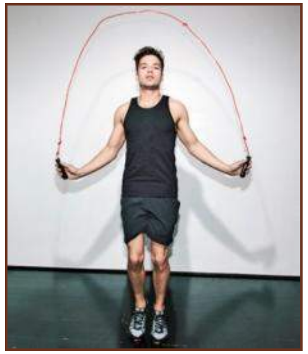
Illustration: “Sven Jr.” by Sven-Olof Emanuelsson

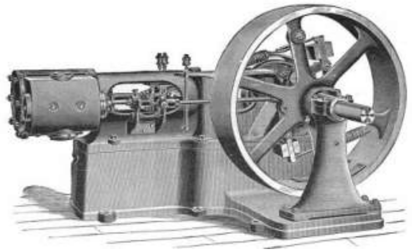
Common Vibration Sources for Buildings

Vibration sources are complex:

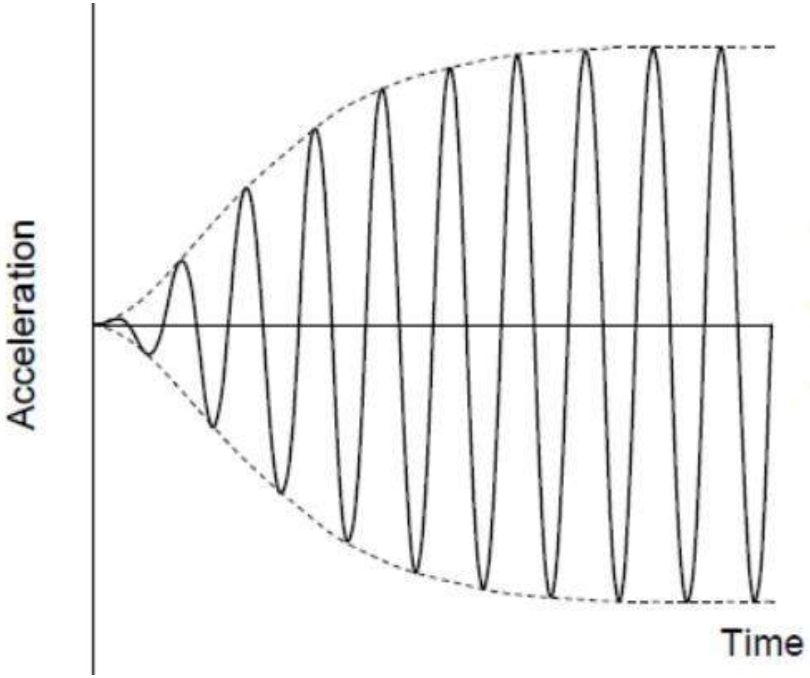
- Footfall, running, aerobics, etc.
- Machinery and equipment
- Vehicular traffic, rail traffic, forklifts
- Ground-borne, structure-borne, air-borne
- Steady-state, episodic, periodic
- Harmonic, pulse, random
- Moving, stationary





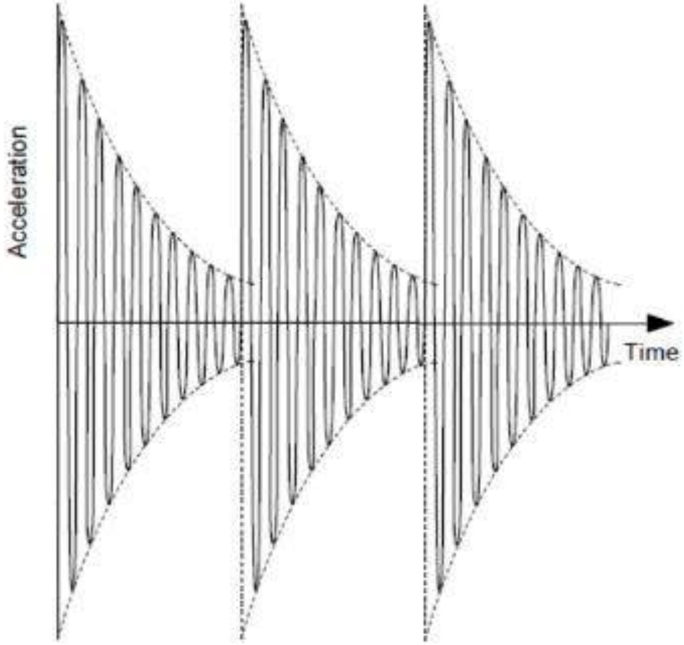


Resonant vs Impulsive Response



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

<u>Low Frequency Floor</u>



Excitation Frequency >> Natural Frequency
Responses decays out between load cycles

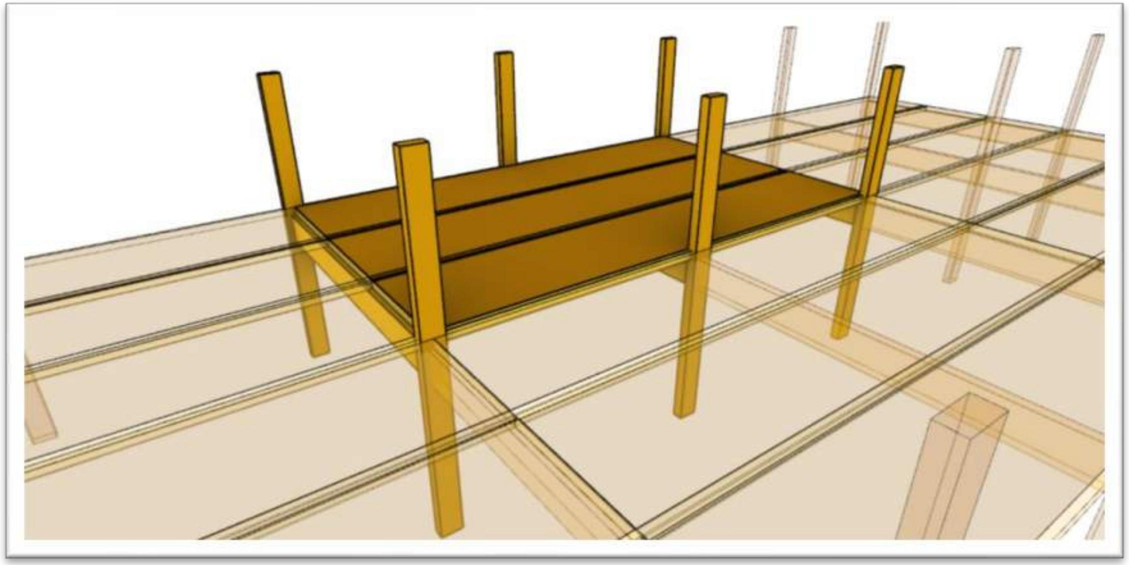
<u>High Frequency Floor</u>

f_n ~< 8 Hz For Walking Excitation f_n ~> 8 Hz

Framing Materials Properties for Vibration

Material	Floor Weight (psf)	Damping	Material Stiffness (10^6 psi)	Material Mass (pcf)	Example Floor System
Concrete	100-150	1-5%	3.2-5.8	120-150	2-way slab on columns
Steel	50-100	0.5-5%	30	490	Concrete on metal deck on purlins and girders
Mass Timber	15-65	1-6%	1.2-1.8	30-40	Beam *or* wall supported
Wood Frame	10-40	2-12%	1.2-2.0	30-40	Wall supported

Beam vs Wall Supported Floors



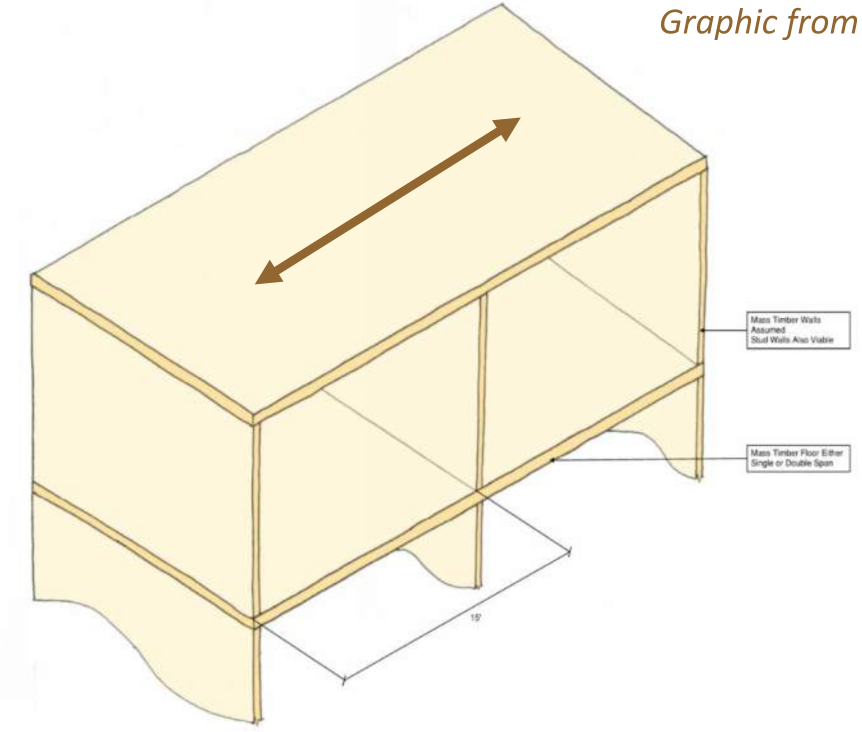
Graphic from StructureCraft

Mass Timber Panels on Grid of Beams.
Frequency of Floor < Frequency of Panel
Vibration of Floor > Vibration of Panel
Vibration Design Depends on Beams

<u>Low Frequency Floor?</u>

Maybe

Graphic from ASPECT



Mass Timber Panels on Bearing Walls

<u>High Frequency Floor?</u>

At all but longer floor spans

Vibration Design Methods

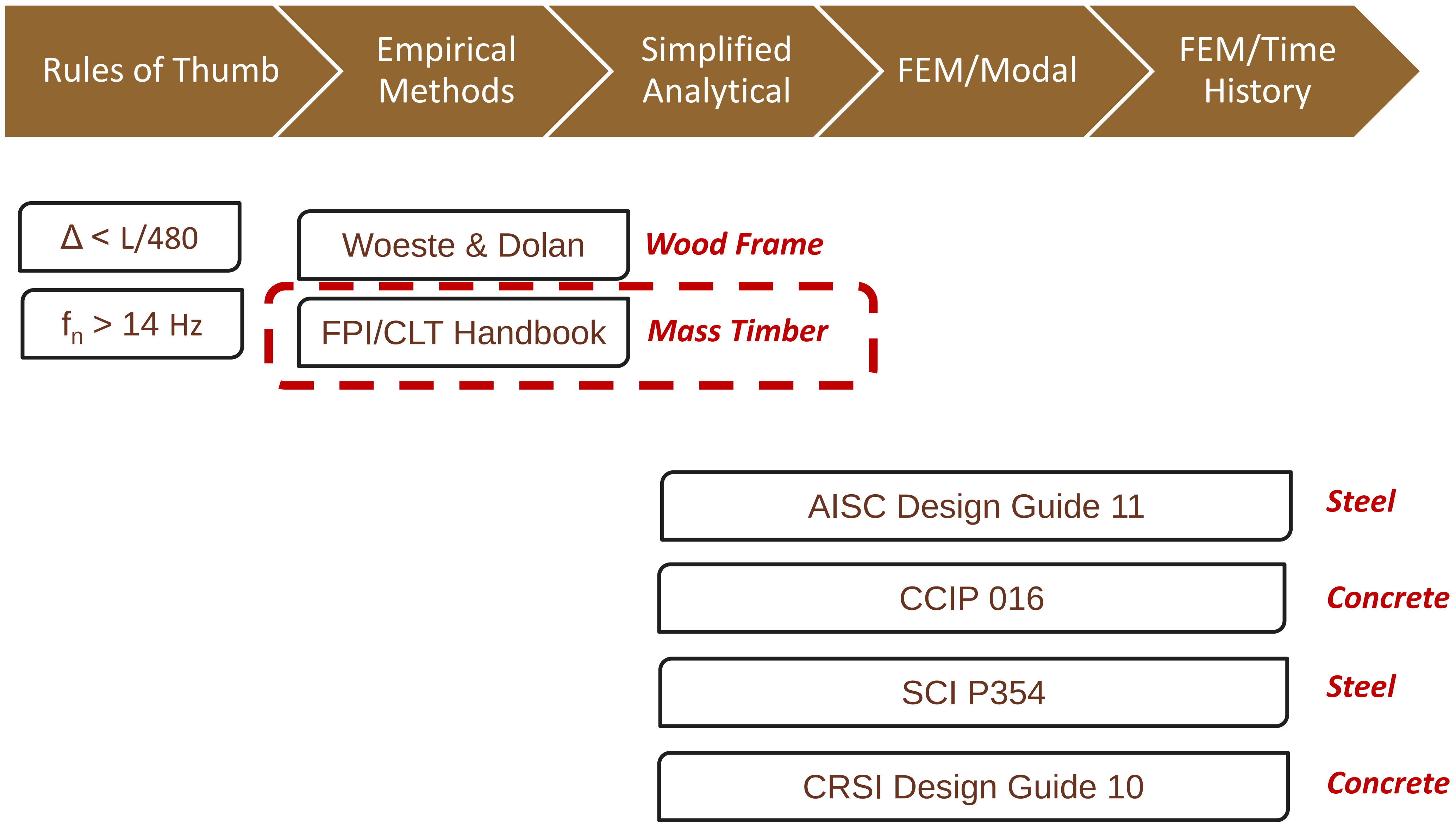
Rules of Thumb → Empirical Methods → Simplified Analytical → FEM/Modal → FEM/Time History

Rules of Thumb
- $\Delta < L/480$
- $f_n > 14$ Hz

Empirical Methods
- Woeste & Dolan — ***Wood Frame***
- FPI/CLT Handbook — ***Mass Timber***

Simplified Analytical
- AISC Design Guide 11 — ***Steel***
- CCIP 016 — ***Concrete***
- SCI P354 — ***Steel***
- CRSI Design Guide 10 — ***Concrete***

Vibration Design Methods



Vibration Design Methods

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

- $\Delta < L/480$
- $f_n > 14$ Hz

Woeste & Dolan	***Wood Frame***
FPI/CLT Handbook	***Mass Timber***
Mass Timber Design Guide (in development)	***Mass Timber***
AISC Design Guide 11	***Steel***
CCIP 016	***Concrete***
SCI P354	***Steel***
CRSI Design Guide 10	***Concrete***

Floor Vibration

One approach: US CLT Handbook, Chapter 7 (FPI Method)

Calculated natural frequency of simple span of bare CLT:

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

Where:

EI_{app} = apparent stiffness for pinned supported, uniformly loaded, simple span (K_s = 11.5) (lb-in^2)

ρ = specific gravity of the CLT

A = the cross section area (thickness x 12 inches) (in^2)

Reference: US CLT Handbook, Chapter 7

Floor Vibration-FPI Method

Limit CLT Floor Span such that

$$\text{Span } L \leq \frac{1}{12.05}\frac{(EI_{app})^{0.293}}{(\rho A)^{0.122}}$$

Based on:
- Un-topped CLT
- Single, Simple span
- Bearing wall supports.

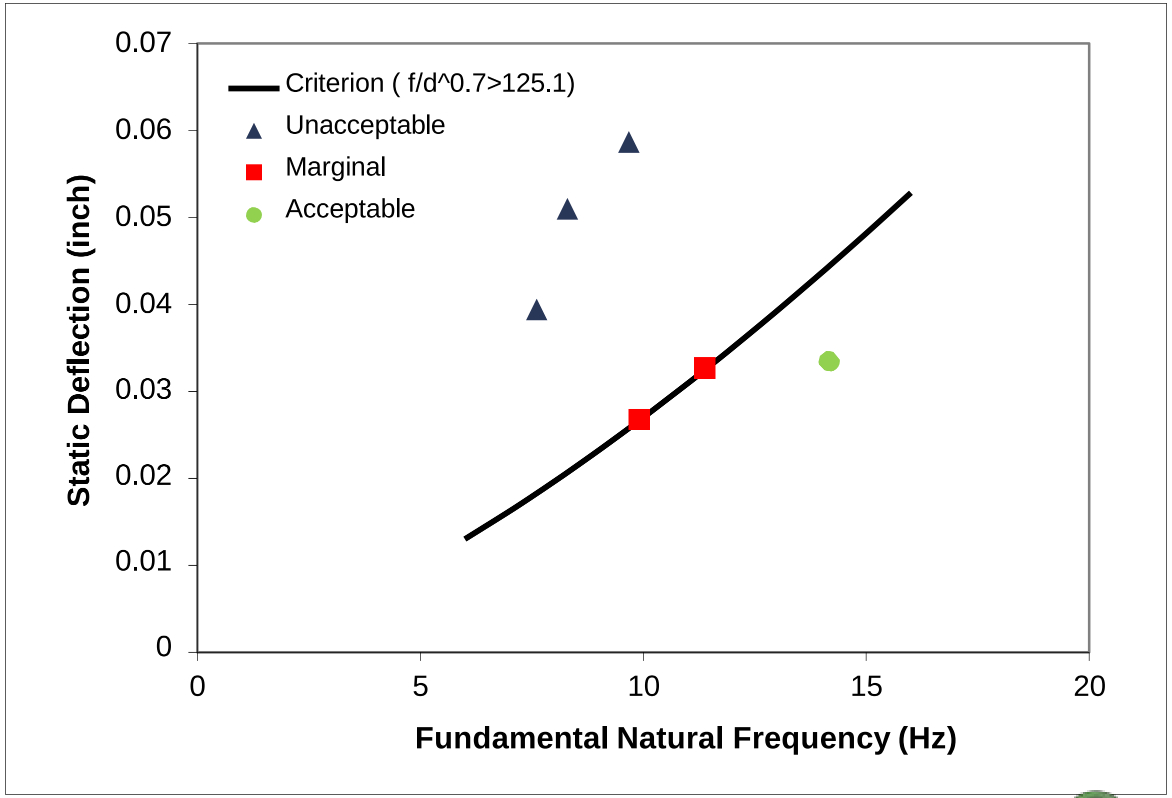
Does not account for:
- Supporting beam flexibility
- Multi-span conditions
- Additional floor mass (topping slab, etc)

Reference: US CLT Handbook, Chapter 7

Floor Vibration-FPI Method

CLT Handbook, Chapter 7 Recommendations

Experimental Verification – Results



Research by Lin Hu, et al. at FPInnovations

FPI Span Limit for Basic CLT Grades / Layups

Grade	Layup	Thickness	FPI Span Limit
E1	3ply	4 1/8”	12’ 5”
	5ply	6 7/8”	17’ 4”
	7ply	9 5/8”	21’ 8”
E2	3ply	4 1/8”	12’ 0”
	5ply	6 7/8”	16’ 8”
	7ply	9 5/8”	20’ 10”
E3	3ply	4 1/8”	11’ 7”
	5ply	6 7/8”	16’ 1”
	7ply	9 5/8”	20’ 1”
E4	3ply	4 1/8”	12’ 2”
	5ply	6 7/8”	17’ 0”
	7ply	9 5/8”	21’ 3”

Grade	Layup	Thickness	FPI Span Limit
V1	3ply	4 1/8”	12’ 2”
	5ply	6 7/8”	17’ 0”
	7ply	9 5/8”	21’ 3”
V2	3ply	4 1/8”	11’ 11”
	5ply	6 7/8”	16’ 8”
	7ply	9 5/8”	20’ 10”
V3	3ply	4 1/8”	12’ 0”
	5ply	6 7/8”	16’ 9”
	7ply	9 5/8”	21’ 0”

Approximate FPI Span Limits:

3-ply: 11 to 12 ft
5-ply: 16 to 17 ft
7-ply: 20 to 21 ft

Limitations:

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

CLT Handbook In Practice

- Experience shown it consistently produces well performing floors

- Does not consider
  - Multi-span panels
  - Flexibility of supports, e.g. beams
  - Impact of topping slabs

Improves Performance

Lowers Performance

Performance??

- Recommend 20% increase in acceptable span length OK for multi-span panels with non-structural elements that are considered to provide an enhanced stiffening effect, including partition walls, finishes and ceilings, etc.

US Mass Timber Vibration Design Guide

USDA Wood Innovations Grant funded project in progress

US Mass Timber Floor Vibration Design Guide

Approximate Outline

1 Introduction
- 1.1 Preface
- 1.2 Scope of this Guide
- 1.3 Terminology
- 1.4 Symbols
- 1.5 Vibration Characteristics of Floor Structures
- 1.6 Building Codes and Standards

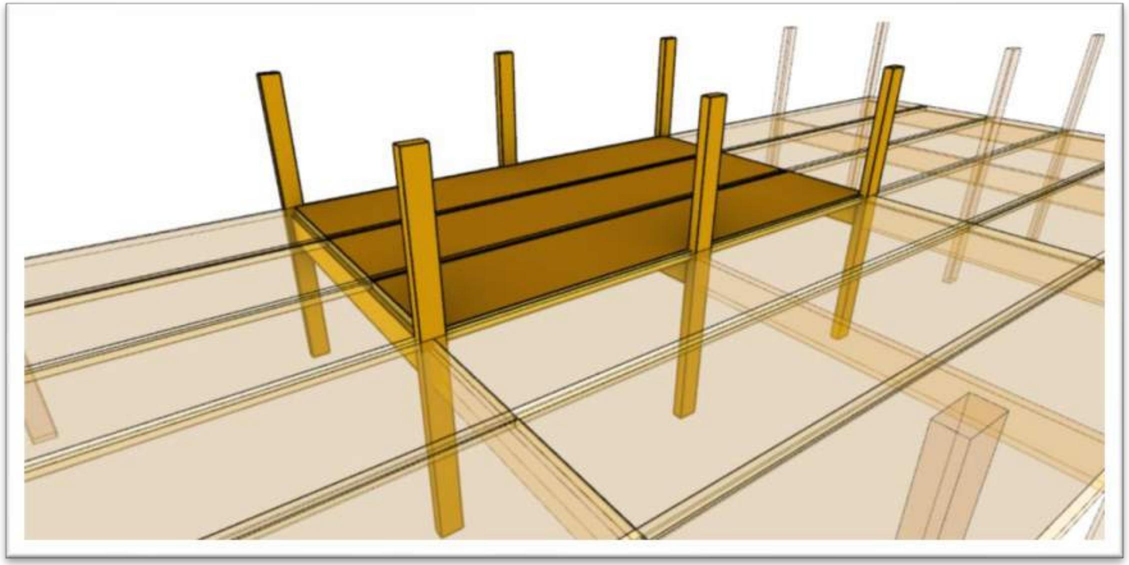
2 Understanding Floor Vibration
- 2.1 Structural Response to Footfall Forces
- 2.2 Vibration Background
- 2.3 Methods for Evaluating Vibration
- 2.4 Human Perception of Vibration

3 Vibration Design Considerations
- 3.1 Floor Loading / Mass
- 3.2 Damping
- 3.3 Component Stiffness
- 3.4 Composite Behavior
- 3.5 Structural and Floor Configurations
- 3.6 Excitation Parameters
- 3.7 Floor Vibration Performance Targets

Guide to be published by WoodWorks Later in 2020

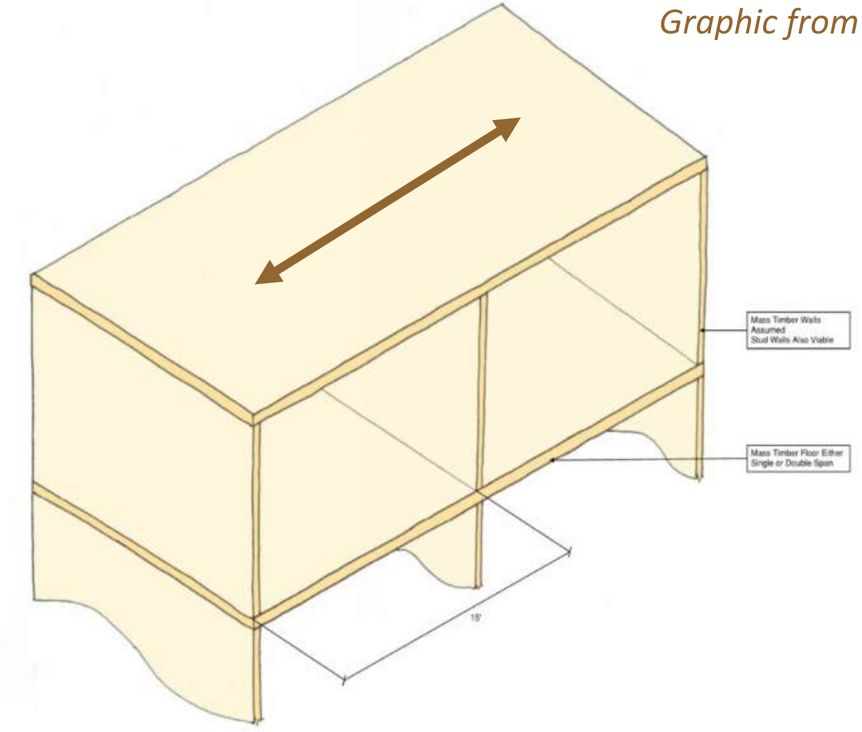
Project Team: WoodWorks, KPFF, Aspect, StructureCraft, & Fast+Epp

Preliminary Recommendations



Graphic from StructureCraft

Graphic from ASPECT



Mass Timber Panels on Grid of Beams:
- **Modal Analysis based methods valid**
  - **- AISC Design Guide 11**
  - **- CCIP 0-16**

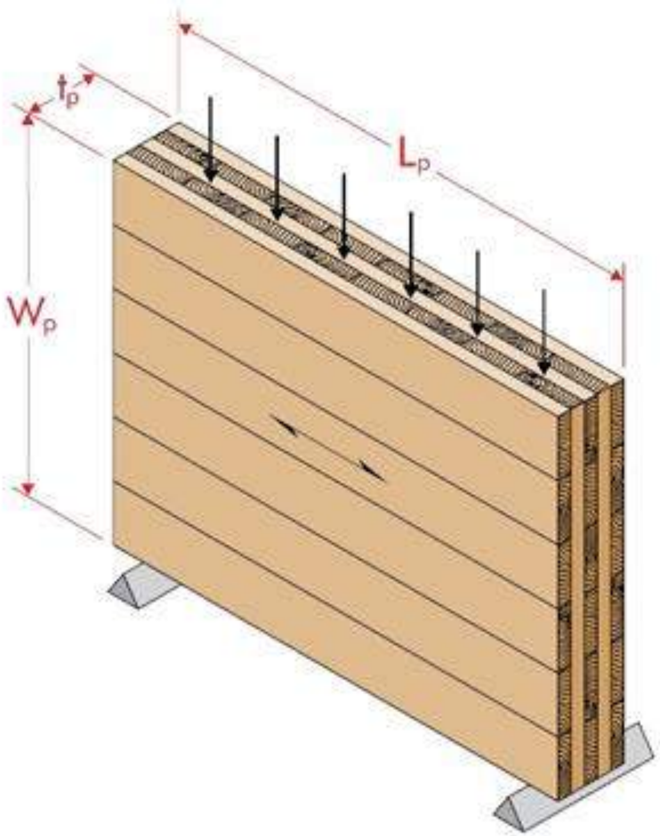
Mass Timber Modeling Guidelines:
- **- Incidental composite action.**

CLT Panels on Bearing Walls:
- **FPI Method simple to implement**
- **Conservative for typical residential**

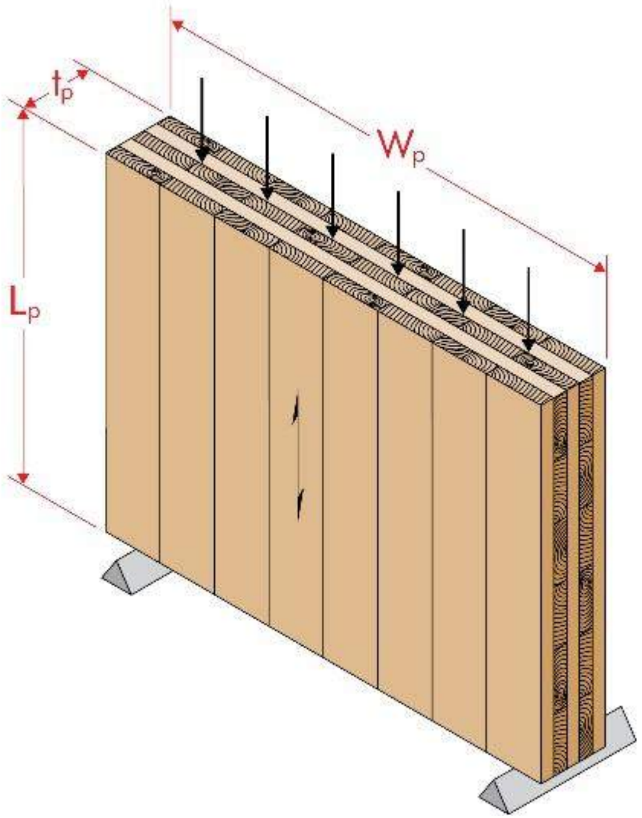
Other Mass Timber Panels not covered

Edgewise Structural Properties

EDGEWISE Panel Loading



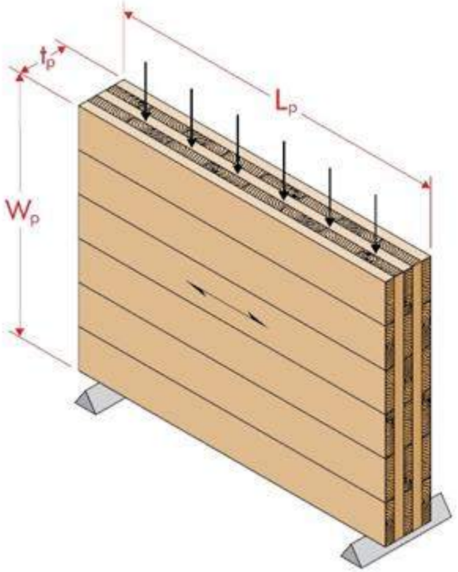
Span in MAJOR Strength Direction



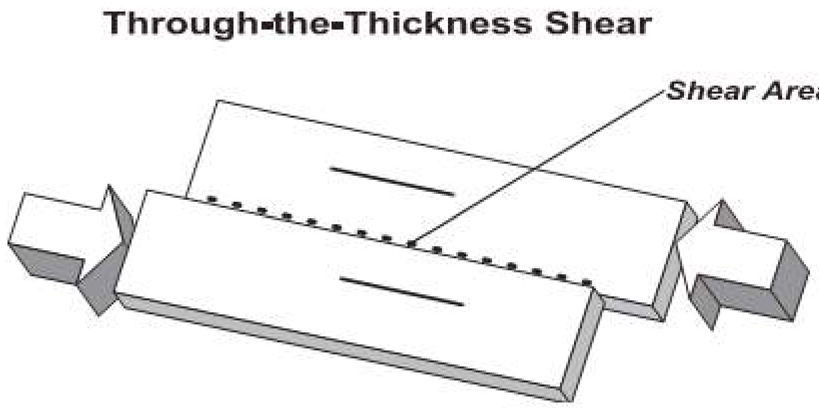
Span in MINOR Strength Direction

Reference & Source: ANSI/APA PRG 320-2017

Shear Force Terminology & Jargon



Source: ANSI/APA PRG 320-2017



Source: NDS 2015 Manual

Through-the-Thickness Shear
In-plane Shear Forces
EDGEWISE Shear in PRG 320-2017

NDS 2015: $F_v(t_v)$
PRG 320-2017: $F_{v,e,0}\,t_p$ & $F_{v,e,90}\,t_p$

CLT in Lateral Force Resisting Systems

CLT Panels have a significant in-plane shear strength.

TABLE 3—REFERENCE DESIGN VALUES FOR IN-PLANE SHEAR OF THE STRUCTURLAM CROSSLAM® CLT PANELS[1]

GRADE	LAYUP DESIGNATION	FACE LAMINATION ORIENTATION (psi)	
		=[2]	⊥[2]
V2M1.1	105V	130	195
	175V	180	195[4]
	245V	180[3]	195[4]
	315V	180[3]	195[4]

Source: ICC-ES *ESR 3631*

Table 3. Allowable In-Plane Shear (psi) for Nordic X-Lam[(a)] (for use in the U.S.)

CLT Grade	Layup #	Thickness (in.)	Allowable In-Plane Shear Stress (psi), $F_{v,\ in\text{-}plane}$, with Face Lamination Orientation of	
			=	⊥
E1	78-3s	3 1/8	105[(b)]	130[(b)]
	89-3s	3 1/2	75	130[(b)]
	105-3s	4 1/8	105	130
	131-5s	5 1/8	125[(c)]	150[(c)]
	140-4s	5 1/2	105[(b)]	130[(b)]
	143-5s	5 5/8	105[(b)]	150[(c)]
	175-5s	6 7/8	125	150
	197-7s	7 3/4	105[(b)]	150[(c)]
	213-7l	8 3/8	125[(c)]	150[(c)]
	220-7s	8 5/8	125[(c)]	150[(c)]
	244-7s	9 5/8	125[(c)]	150[(c)]
	244-7l	9 5/8	125[(c)]	150[(c)]
	267-9l	10 1/2	105[(b)]	150[(c)]
	314-9l	12 3/8	125[(c)]	150[(c)]

Source: *APA Product Report PR-L306*

~75 to 195+ PSI Allowable Edgewise Shear

~900 to 2300 PLF *per Inch of Thickness.*

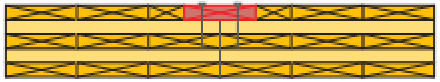
Consult with the Manufacturers for Details

Standard test method defined using ASTM D198

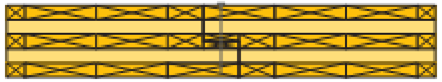
Connection Details

Connection Styles

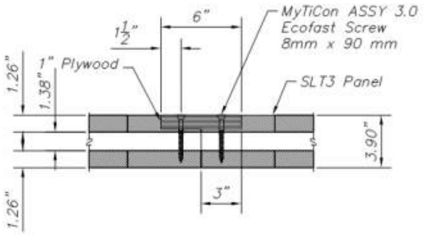
Panel to Panel at floors, roofs or walls

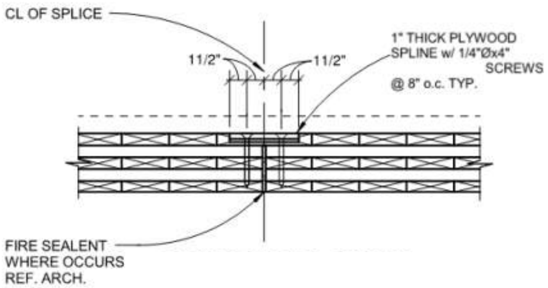


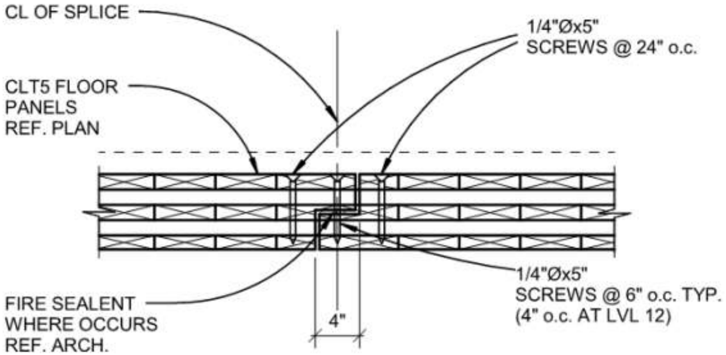
Single Surface Spline



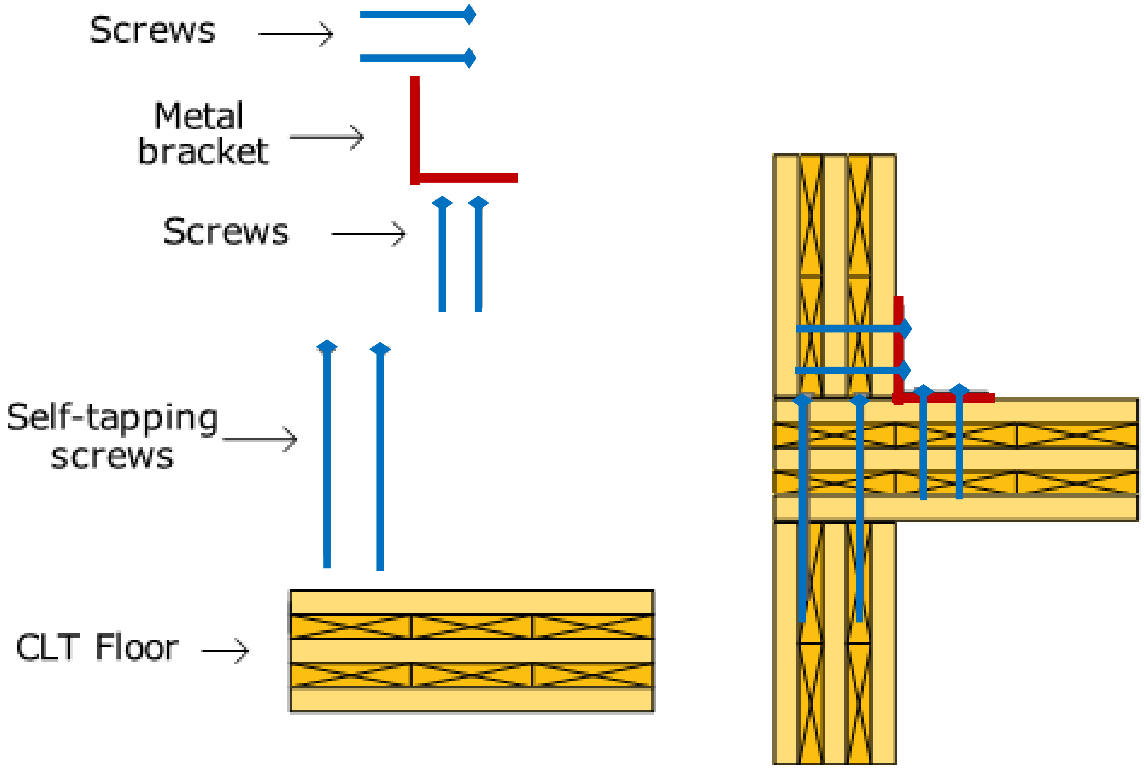
Half Lap







Connection Styles



Simple connections with:

- Metal angles
- Self taping Screws and Nails

Source: US CLT Handbook

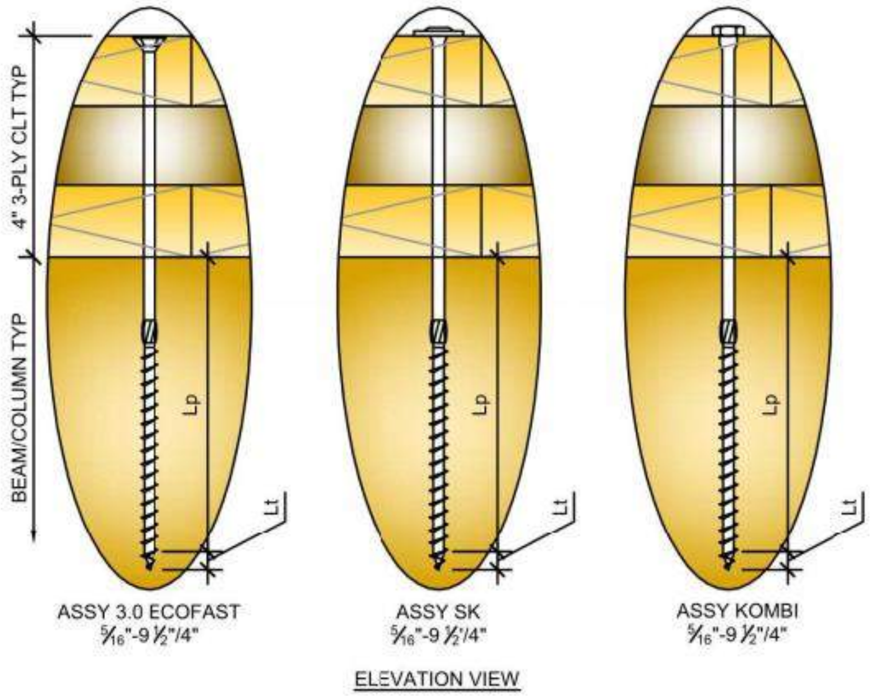
Mass Timber Design

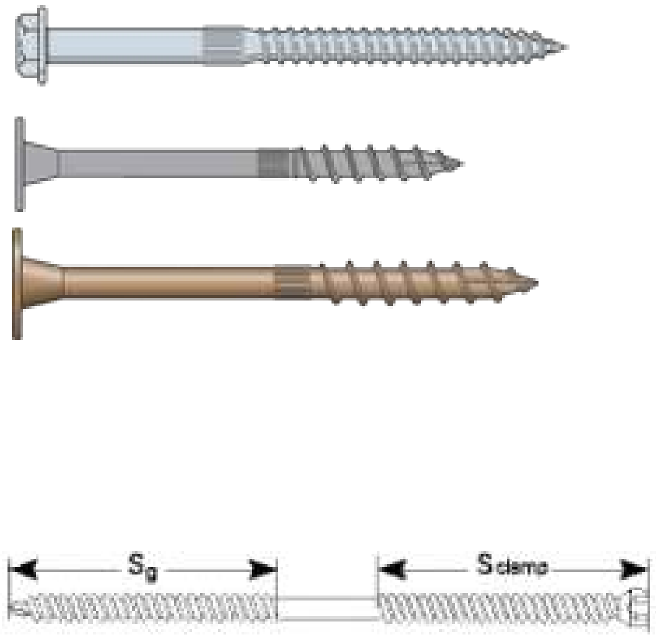
Connections


Photo Credit: Alex Schreyer

Long self tapping screws used extensively throughout mass timber construction

Proprietary Products





Variety of Self Tapping Screws

Proprietary Products

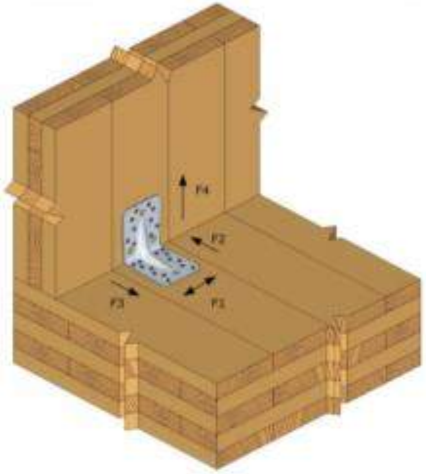


Figure 1: ABR105 – CLT Panel Connection

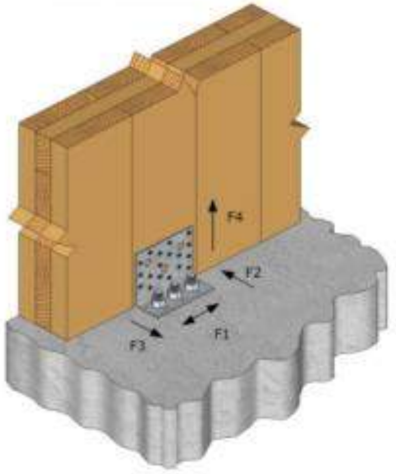


Figure 2: AE116 – CLT to Concrete

Source: Simpson Strong-Tie

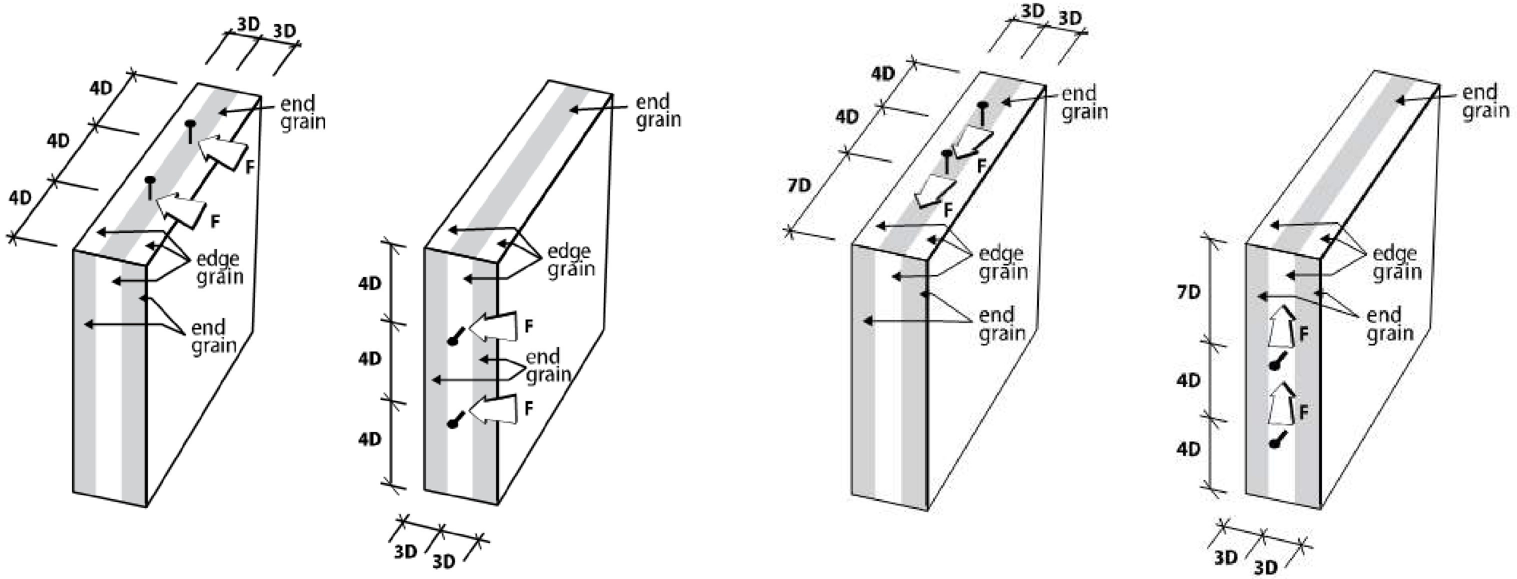
Source: rothoblaas

CLT in NDS 2015 - Connectors

Connectors for CLT in NDS 2015:

Dowel Type Fasteners, e.g. Lag Screws, Bolts and Nails

Figure 12I **End Distance, Edge Distance and Fastener Spacing Requirements in Narrow Edge of Cross-Laminated Timber**



Direction of loading perpendicular to the plane of CLT

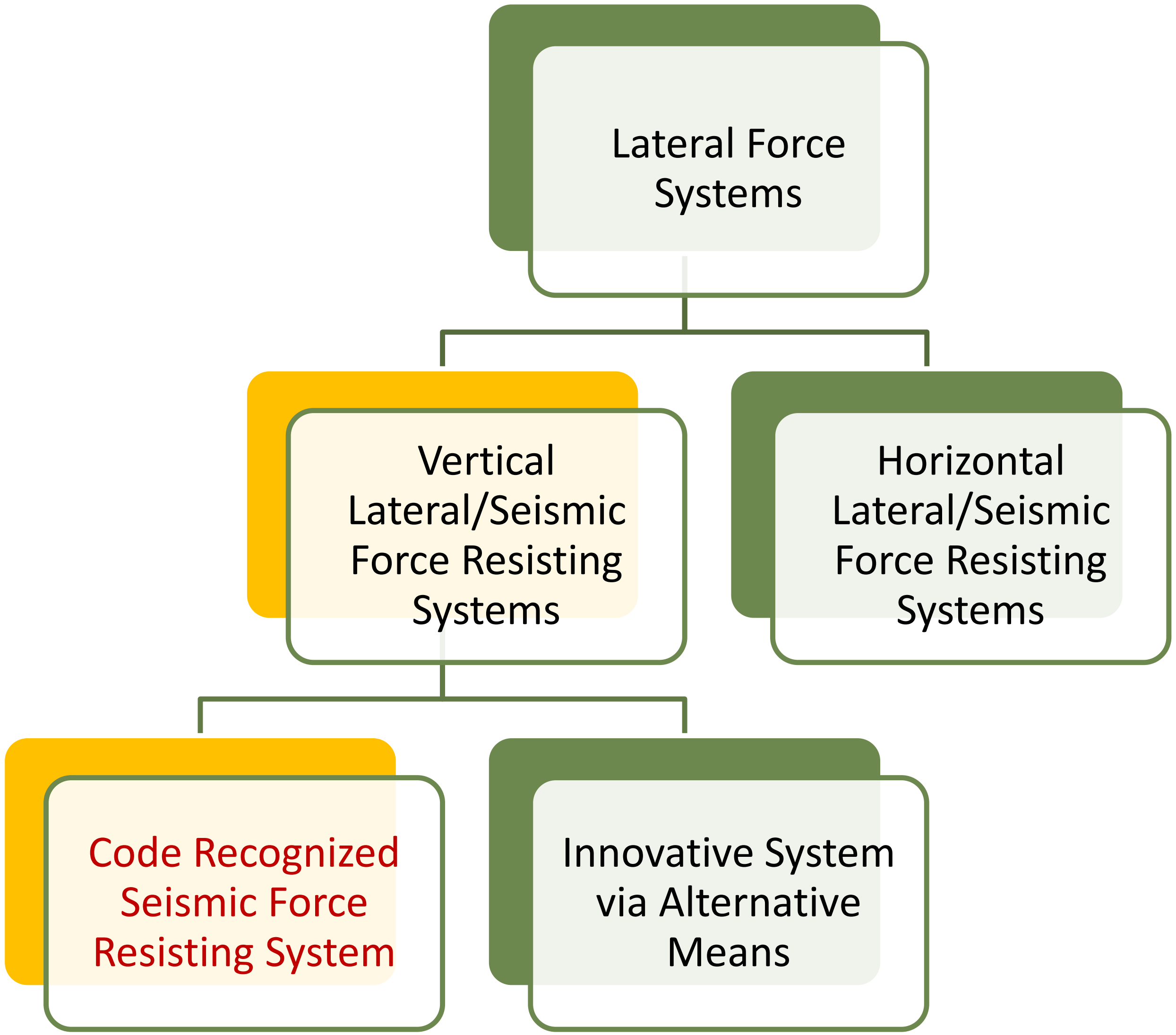
Direction of loading parallel to the plane of CLT

Lateral Systems

Mass Timber Lateral Systems

- Lateral Force Systems
  - Vertical Lateral/Seismic Force Resisting Systems
  - Horizontal Lateral/Seismic Force Resisting Systems

Mass Timber Lateral Systems



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

Mass Timber Design

Lateral framing systems

Exterior steel moment frame

Photo Credit: woodworks

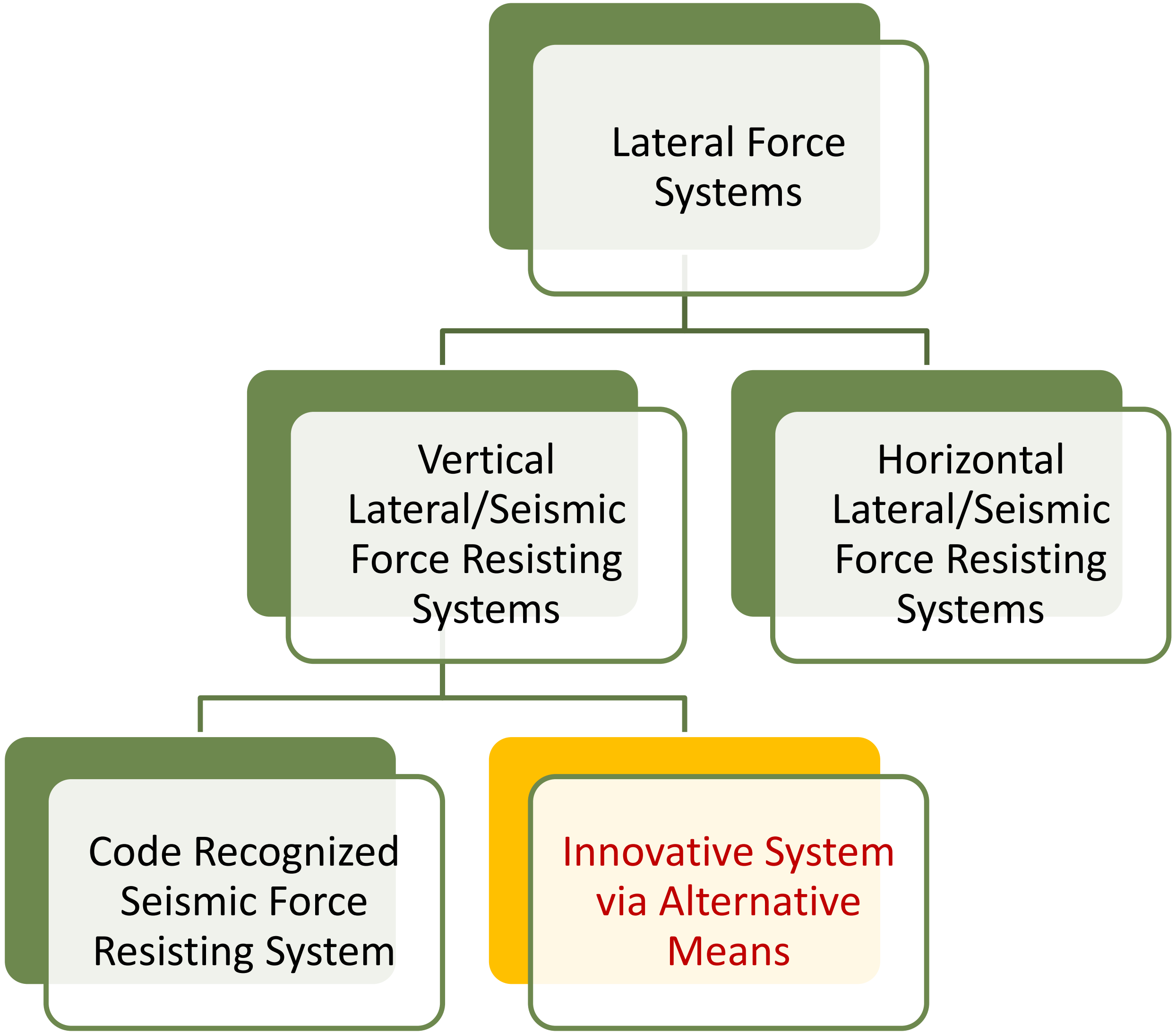
Mass Timber Design

Lateral framing systems

Steel Braced Frame

Photo Credit: john stamets

Tall Wood Structural Systems



Mass Timber Design

Lateral framing systems

Mass Timber Shearwalls

Photo Credit: alex schreyer

CLT Shear Wall Seismic Design Values

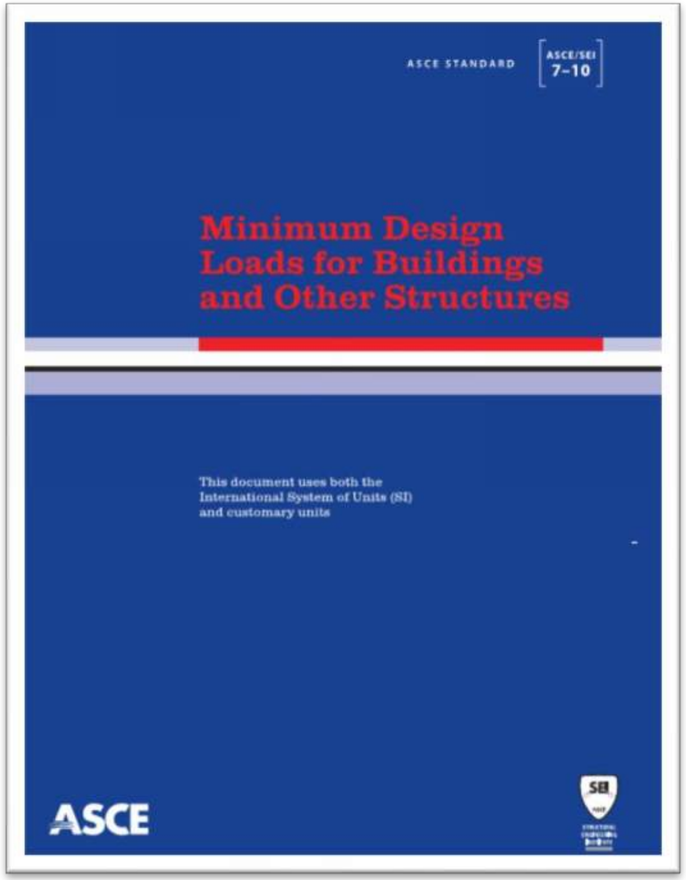
What R value can I use?

Photo: KLH

Photo: FPI

CLT Seismic Design

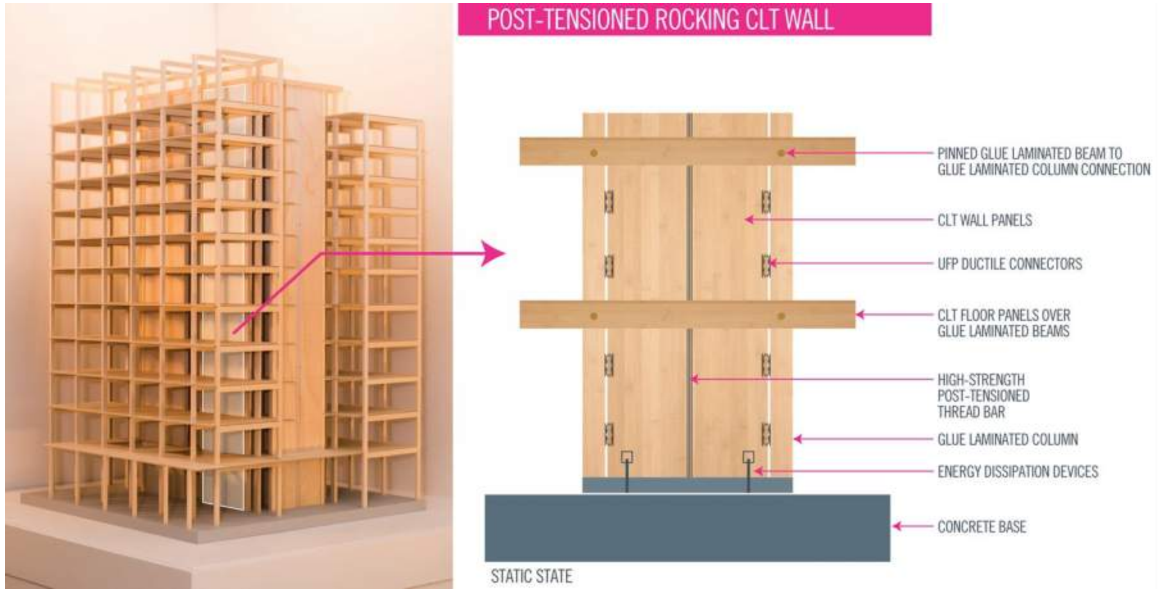
CLT Seismic Force Resisting Systems **Not** addressed In



ASCE/SEI 7-10 or 7/16

SDPWS 2015

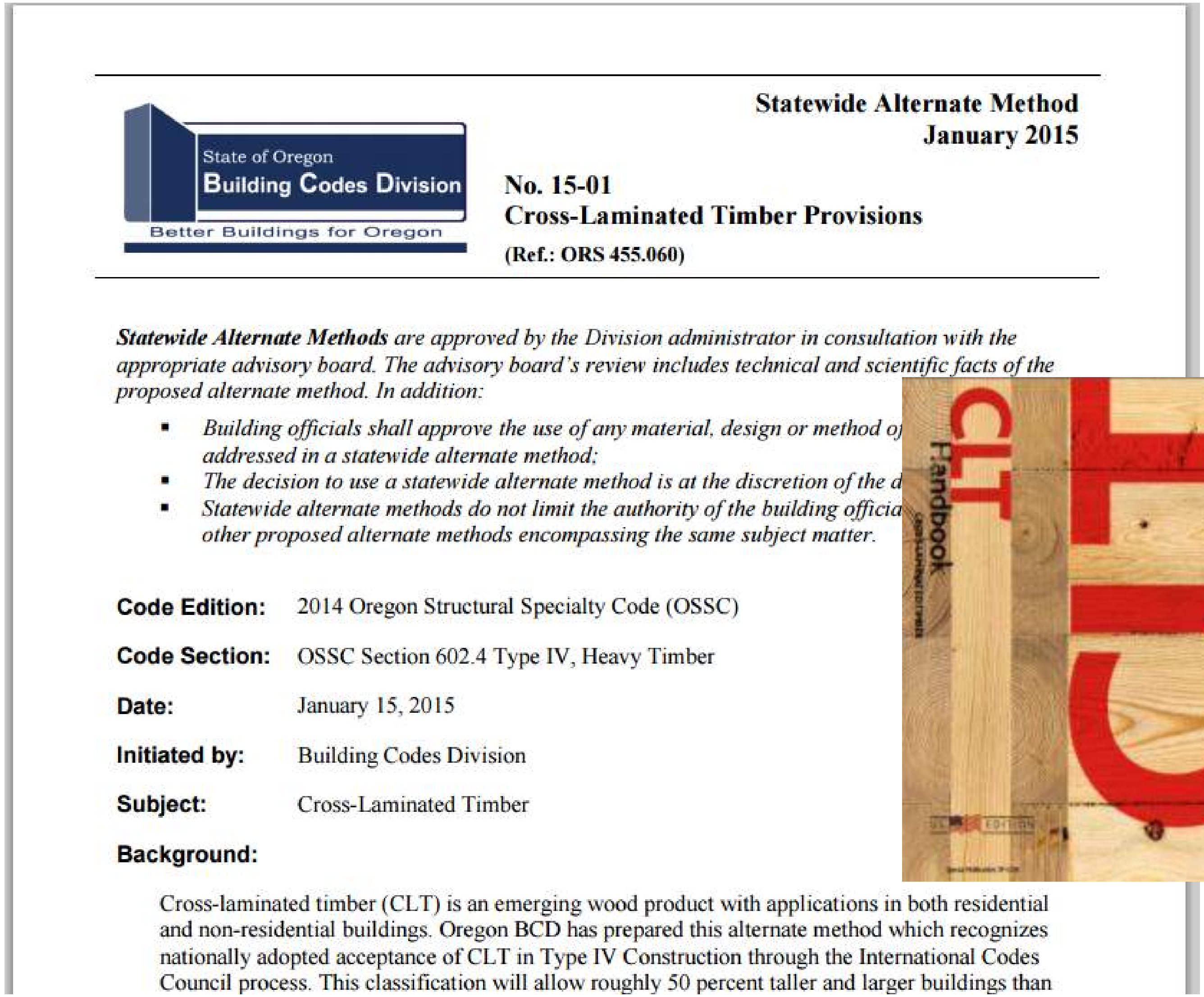
Range of Possible Shear Wall Systems



Rocking Wall Systems (R = ~6?)

Ordinary Shear Walls (R = ~1.5?)

State of Oregon Statewide Alternative



State of Oregon
Building Codes Division
Better Buildings for Oregon

Statewide Alternate Method
January 2015

No. 15-01
Cross-Laminated Timber Provisions
(Ref.: ORS 455.060)

Statewide Alternate Methods *are approved by the Division administrator in consultation with the appropriate advisory board. The advisory board's review includes technical and scientific facts of the proposed alternate method. In addition:*

- *Building officials shall approve the use of any material, design or method o*
  addressed in a statewide alternate method;
- *The decision to use a statewide alternate method is at the discretion of the d*
- *Statewide alternate methods do not limit the authority of the building officia*
  other proposed alternate methods encompassing the same subject matter.

Code Edition: 2014 Oregon Structural Specialty Code (OSSC)

Code Section: OSSC Section 602.4 Type IV, Heavy Timber

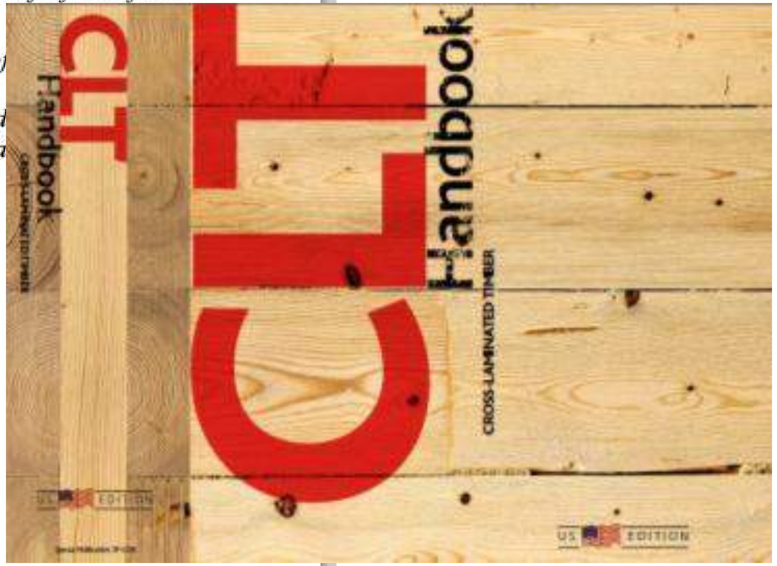
Date: January 15, 2015

Initiated by: Building Codes Division

Subject: Cross-Laminated Timber

Background:

Cross-laminated timber (CLT) is an emerging wood product with applications in both residential and non-residential buildings. Oregon BCD has prepared this alternate method which recognizes nationally adopted acceptance of CLT in Type IV Construction through the International Codes Council process. This classification will allow roughly 50 percent taller and larger buildings than



State of Oregon Statewide Alternative

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

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

Seismic Force-Resisting System	ASCE 7 Section Where Detailing Requirements Are Specified	Response Modification Coefficient, R^a	Overstrength Factor, Ω_0^g	Deflection Amplification Factor, C_d^b	Structural System Limitations Including Structural Height, h_n (ft) Limits[c]				
					Seismic Design Category				
					B	C	D[d]	E[d]	F[e]
A. BEARING WALL SYSTEMS									
15. Light-frame (wood) walls sheathed with wood structural panels rated for shear resistance	14.5	6 ½	3	4	NL	NL	65	65	65
19. Cross-laminated timber shear walls[f]	14.1 and 14.5	2	2 ½	2	NL	NL	NL	NL	NL

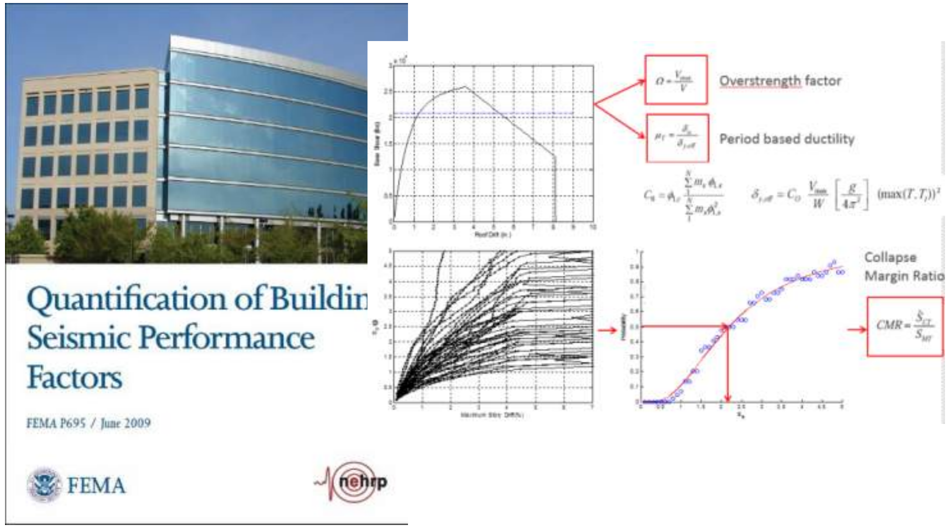
Platform Framed CLT Shear Walls

2021 SDPWS Update ***In Process****

- Platform Frame CLT Shear Walls
- Prescribed nailed metal plate connectors
- *Panel* aspect ratio, $h{:}b_p$ from 2:1 to 4:1

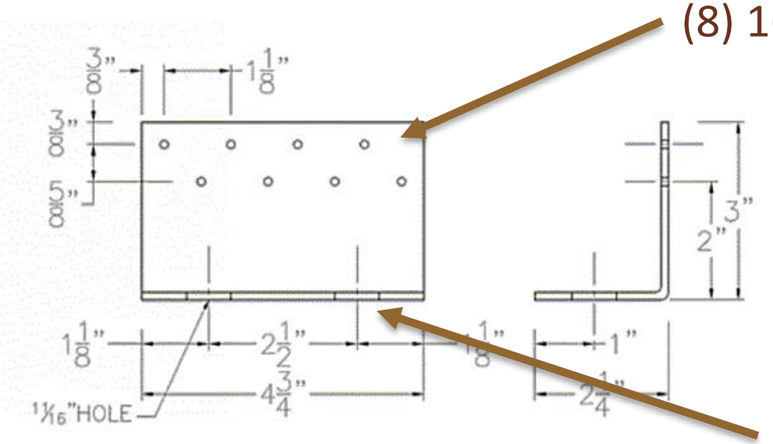
2022 ASCE 7 Update ***In Process****

- Include Platform Frame CLT Shear Walls
- R = 3
- 65 ft height limit – all Seismic Design Categories



*Final contents subject to ongoing balloting

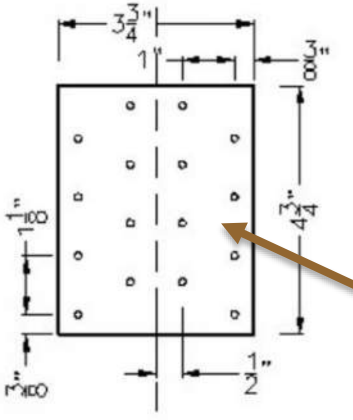
Platform Framed CLT Shear Walls



(8) 16d Box nails

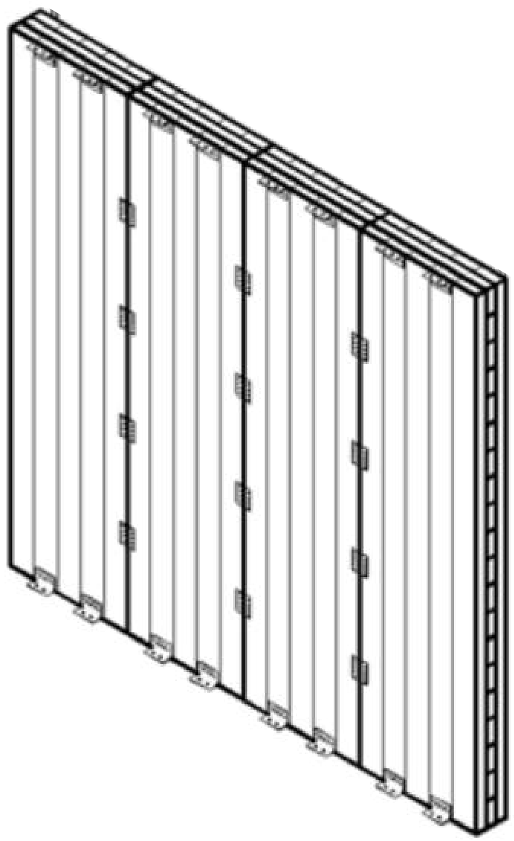
(2) 5/8” bolts
or lag screws

Top and Bottom of Wall Connector
.105” A653 Grade 33 Steel



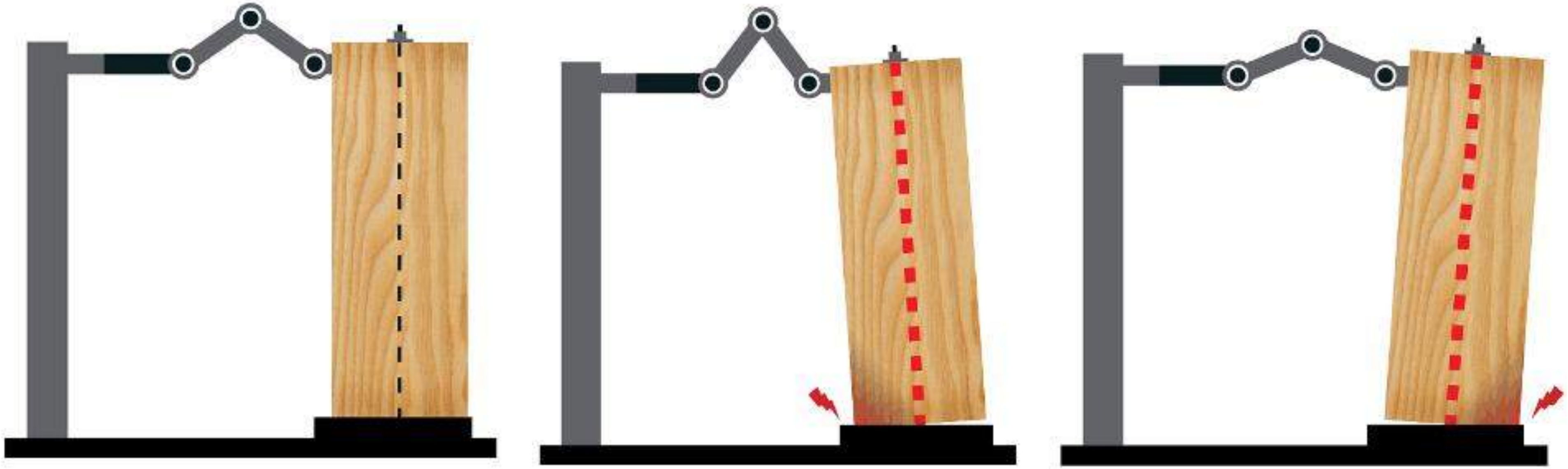
(8) 16d Box nails
each side

Panel to Panel Connector
.105” A653 Grade 33 Steel



Shear Wall System

Innovative Systems



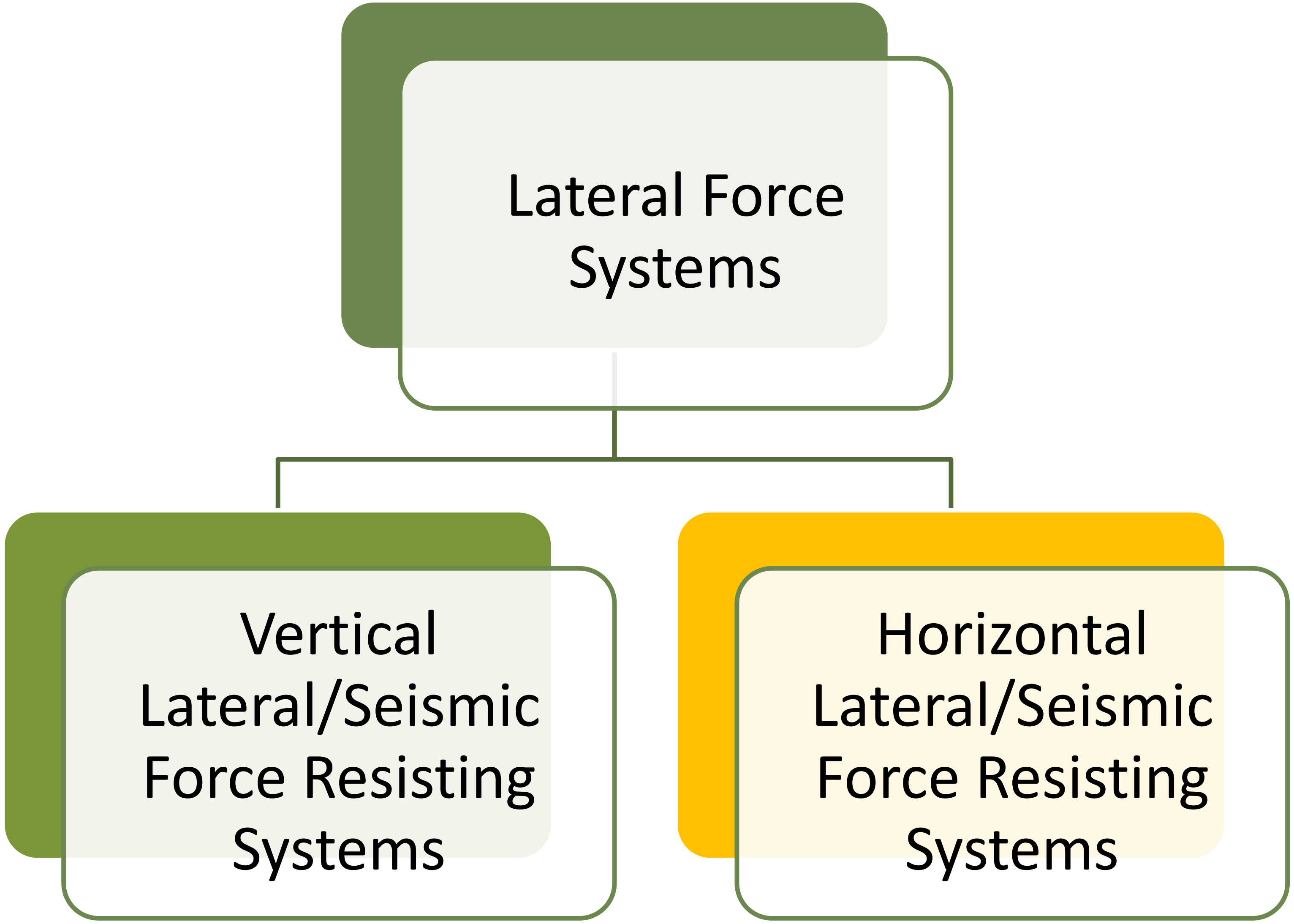
Cross-Laminated Timber Post-Tensioned Rocking Shear Walls

Mass timber design

Lateral framing systems

Photo Credit: alex schreyer

Mass Timber Lateral Systems



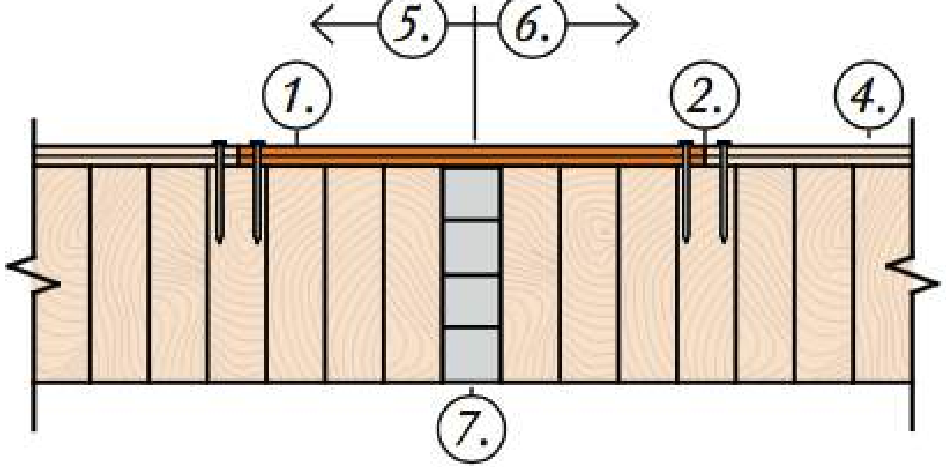
NLT Diaphragm Design


Photo Credit: structurecraft

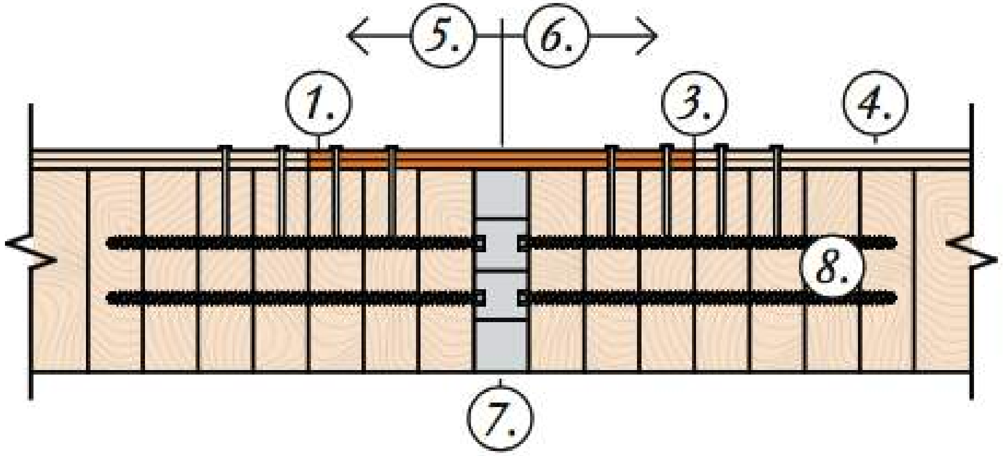
Pre-fabricated panels often pre-sheathed

Once installed, add splice strips, tape joint if applicable

NLT Diaphragm Design



Typical Diaphragm



High Load Diaphragm

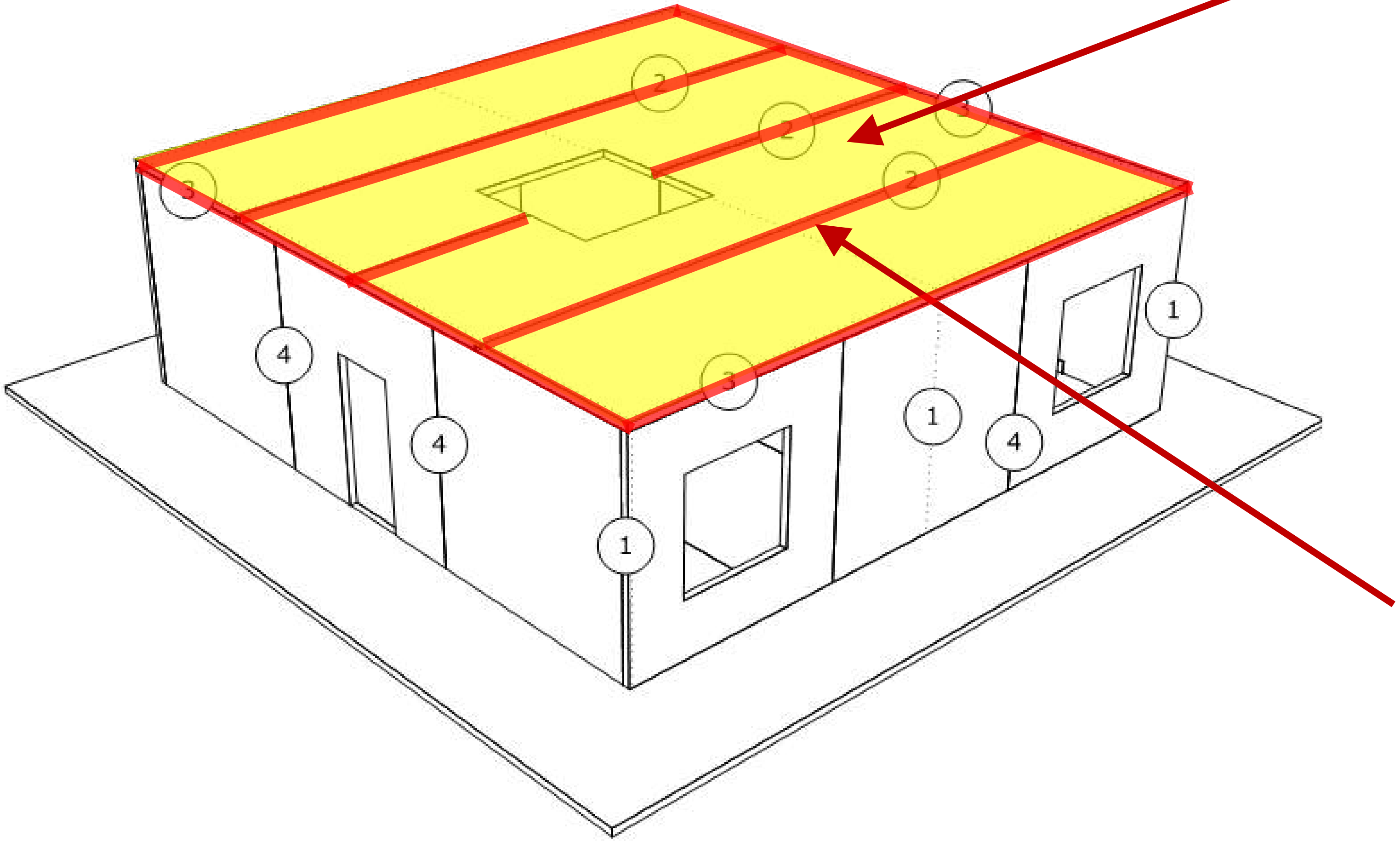
Figure 4.7: *Prefabricated Pre-sheathed Panels*

Key

1. *Field-intalled Plywood/OSB*
2. *Plywood/OSB splice location with typical diaphragm nailing*
3. *Plywood/OSB splice location for high load daiphragm 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

CLT Diaphragms



Strength of CLT rarely governs.

Strength of Connections covered by NDS and Proprietary Fastener Evaluation Reports

CLT in Lateral Force Resisting Systems

CLT Panels have a significant in-plane shear strength.

TABLE 3—REFERENCE DESIGN VALUES FOR IN-PLANE SHEAR OF THE STRUCTURLAM CROSSLAM® CLT PANELS[1]

CLT LAYUP[9]	CLT PANEL THICKNESS DESIGNATION	FACE LAMINATION ORIENTATION[2] (psi)		FACE LAMINATION ORIENTATION[3] (lbf/ft of width)	
		∥[4]	⊥[4]	∥[4]	⊥[4]
V2M1	99 V	175[8]	235[8]	8,200[8]	11,000[8]
	169 V	175[8]	235[8]	14,000[8]	18,800[8]
	239 V	175[8]	235[8]	19,800[8]	26,600[8]
	309 V	175[8]	235[8]	25,600[8]	34,300[8]
V2M1.1	105V	195	290	9,700	14,400
	175V	270	290[6]	22,400	24,000[6]
	245V	270[5]	290[6]	31,300[5]	33,600[6]
	315V	270[5]	290[6]	40,200[5]	43,200[6]

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

ane Shear Stress for Nordic X-Lam[a] (For Use in the U.S.)

	ID	Thickness, t_p (in.)	Allowable In-Plane Shear Stress	
			$F_{v,e,0}$ (psi)	$F_{v,e,90}$ (psi)
	…s	3 1/8	155[b]	190[b]
	…s	3 1/2	155	190[b]
	…s	4 1/8	155	190
	…5s	5 1/8	185[c]	215[c]
E1	140-4s	5 1/2	145	190[b]
	143-5s	5 5/8	185[c]	215[c]
	175-5s	6 7/8	185	215
	197-7s	7 3/4	155[b]	215[c]
	213-7l	8 3/8	185[c]	215[c]
	220-7s	8 5/8	185[c]	215[c]
	244-7s	9 5/8	185[c]	215[c]
	244-7l	9 5/8	185[c]	215[c]
	267-9l	10 1/2	155[b]	215[c]
	314-9l	12 3/8	185[c]	215[c]

Source: *APA Product Report PR-L306*

145 to 290 PSI Allowable Edgewise Shear
= 1.7 to 3.5 kips/ft/in
Cd = 1.6 for short term loading

= 2.8 to 5.6 kips/ft length (ASD)
per Inch of Thickness.

CLT in Lateral Force Resisting Systems

CLT Panels have a significant in-plane shear strength.

TABLE 3—REFERENCE DESIGN VALUES FOR IN-PLANE SHEAR OF THE STRUCTURLAM CROSSLAM® CLT PANELS[1]

GRADE	LAYUP DESIGNATION	FACE LAMINATION ORIENTATION (psi)	
		=[2]	⊥[2]
V2M1.1	105V	130	195
	175V	180	195[4]
	245V	180[3]	195[4]
	315V	180[3]	195[4]

Source: ICC-ES *ESR 3631*

Table 3. Allowable In-Plane Shear (psi) for Nordic X-Lam[(a)] (for use in the U.S.)

CLT Grade	Layup #	Thickness (in.)	Allowable In-Plane Shear Stress (psi), $F_{v,\ in\text{-}plane}$, with Face Lamination Orientation of	
			=	⊥
E1	78-3s	3 1/8	105[(b)]	130[(b)]
	89-3s	3 1/2	75	130[(b)]
	105-3s	4 1/8	105	130
	131-5s	5 1/8	125[(c)]	150[(c)]
	140-4s	5 1/2	105[(b)]	130[(b)]
	143-5s	5 5/8	105[(b)]	150[(c)]
	175-5s	6 7/8	125	150
	197-7s	7 3/4	105[(b)]	150[(c)]
	213-7l	8 3/8	125[(c)]	150[(c)]
	220-7s	8 5/8	125[(c)]	150[(c)]
	244-7s	9 5/8	125[(c)]	150[(c)]
	244-7l	9 5/8	125[(c)]	150[(c)]
	267-9l	10 1/2	105[(b)]	150[(c)]
	314-9l	12 3/8	125[(c)]	150[(c)]

Source: *APA Product Report PR-L306*

~75 to 195+ PSI Allowable Edgewise Shear

~900 to 2300 PLF *per Inch of Thickness.*

Consult with the Manufacturers for Details

Standard test method defined using ASTM D198

Suggestions for CLT Diaphragm Design

Until CLT diaphragms are formally defined through a consensus standardization, following are suggestions when considering diaphragms with CLT through an alternative means and methods process

CLT Diaphragm Design

Basic Design Provisions

- CLT diaphragms shall be designed in accordance with the principles of mechanics using fastener and member strength in accordance with the provisions of the NDS.

  (or proprietary connectors using 3rd party verified equivalence)

Calculations per NDS, not capacity tables in SDPWS

CLT Diaphragm Design *Suggestions*

Basic Design Provisions

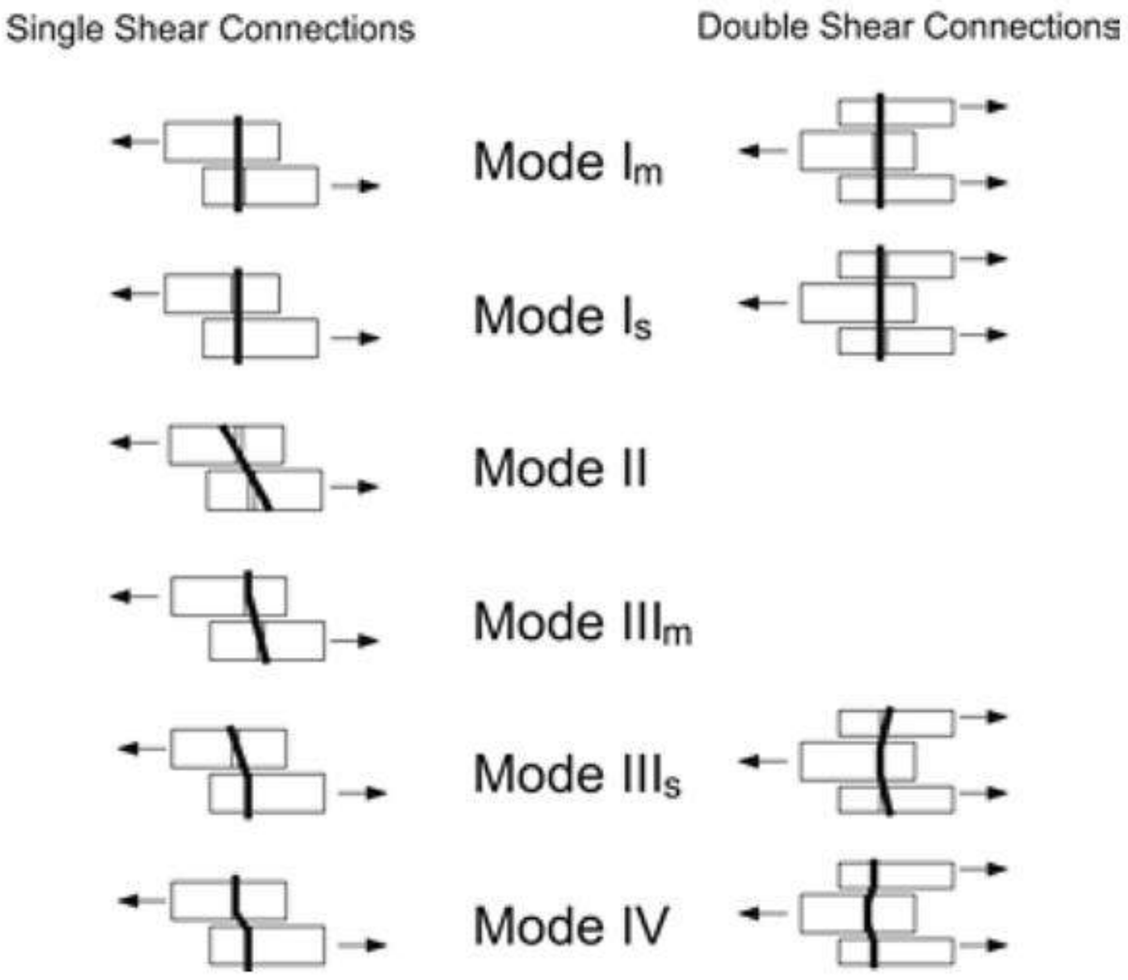
- Diaphragm **shear connections** at CLT panel edges and diaphragm boundary connections shall be designed to ensure that the connection capacity is limited by fastener yielding in accordance with **Mode IIIs or Mode IV** per NDS 12.3.1.

Design capacity of connection (ductile mode governing)

$$Z'_C \geq \mathrm{E}_h$$

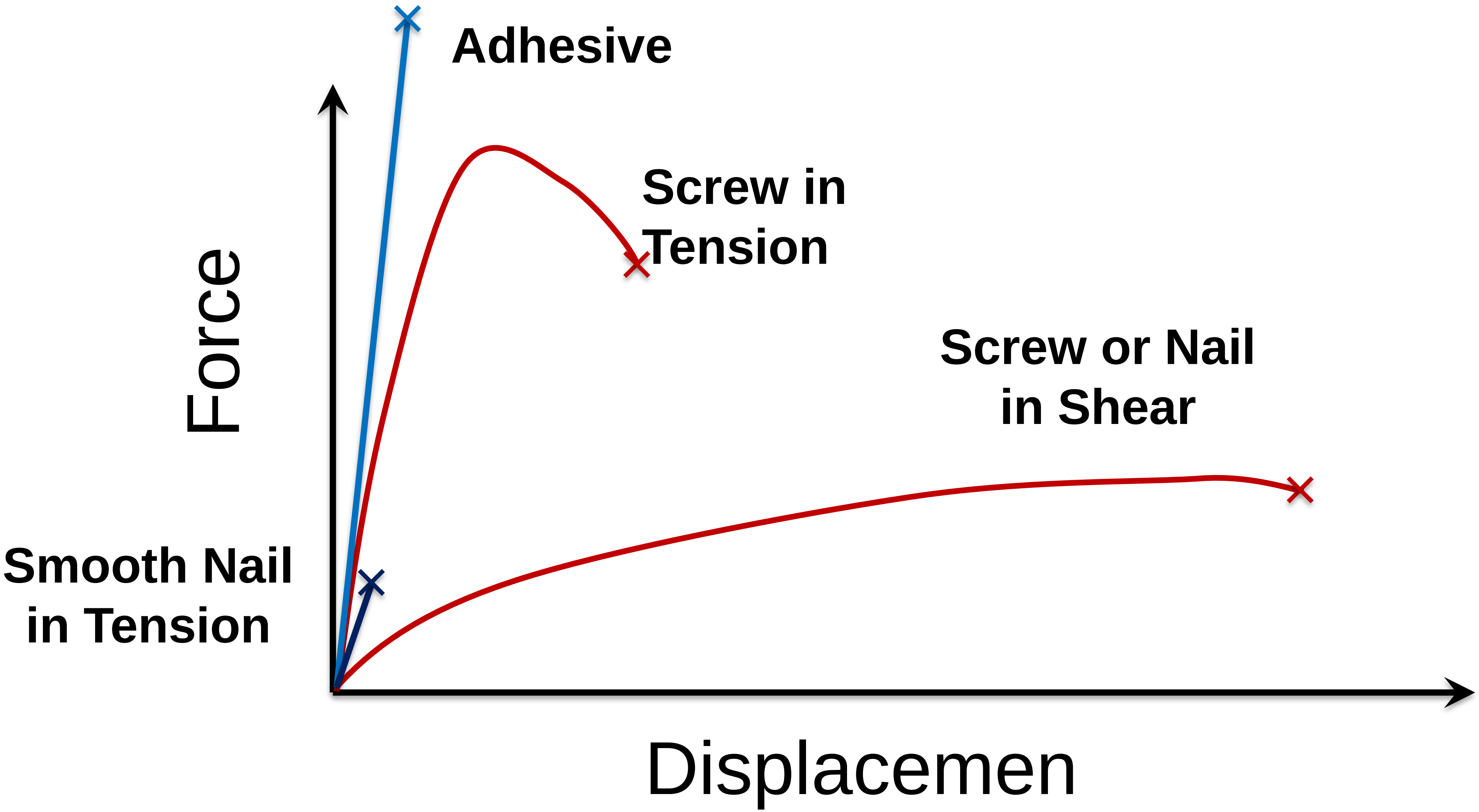
Applied Seismic Forces

Connection Yield Modes Per the NDS



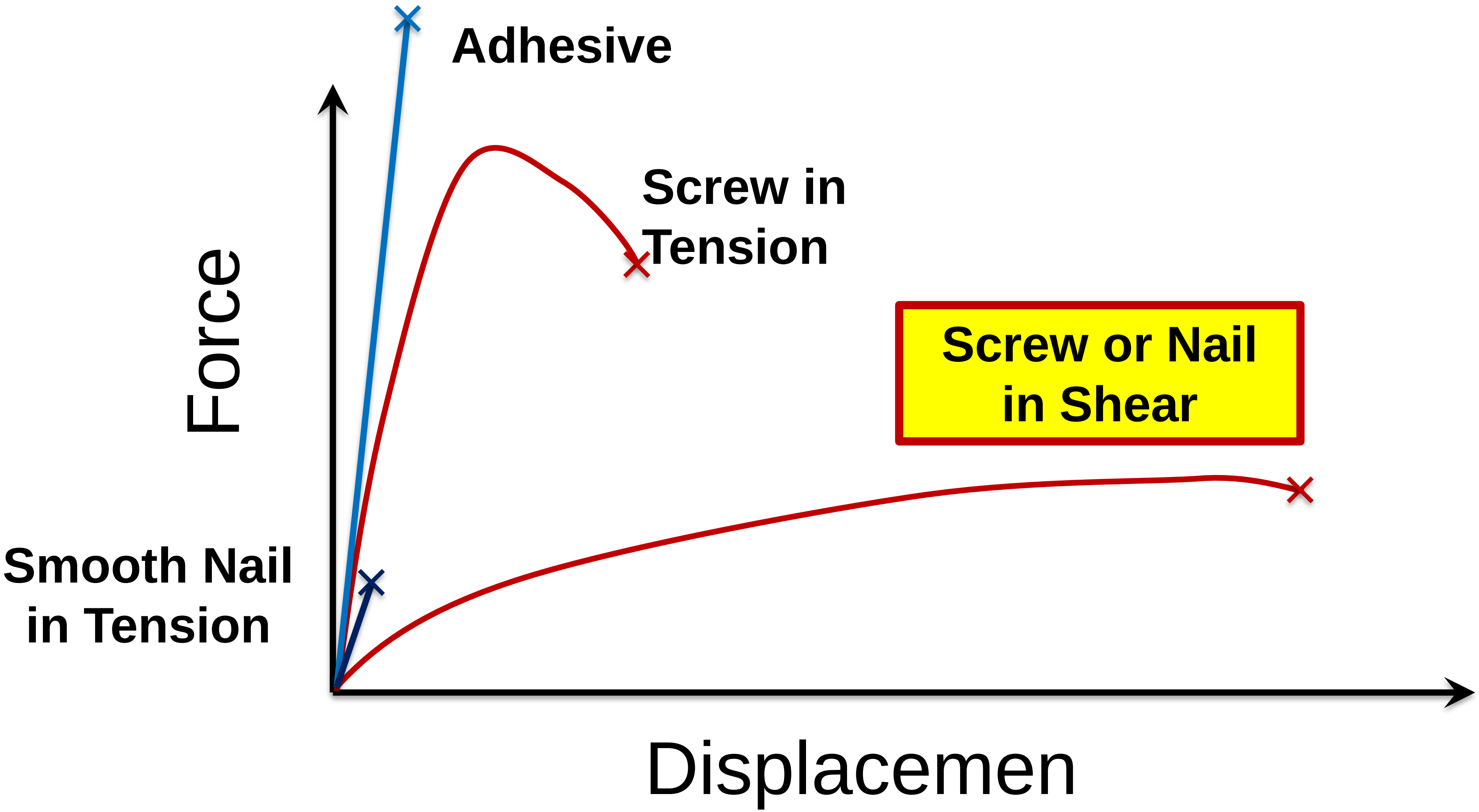
"m" denotes main member, "s" denotes side member

Conceptual Fastener Behavior



Conceptual Fastener Behavior

Well behaved seismic systems have ductile failure modes.

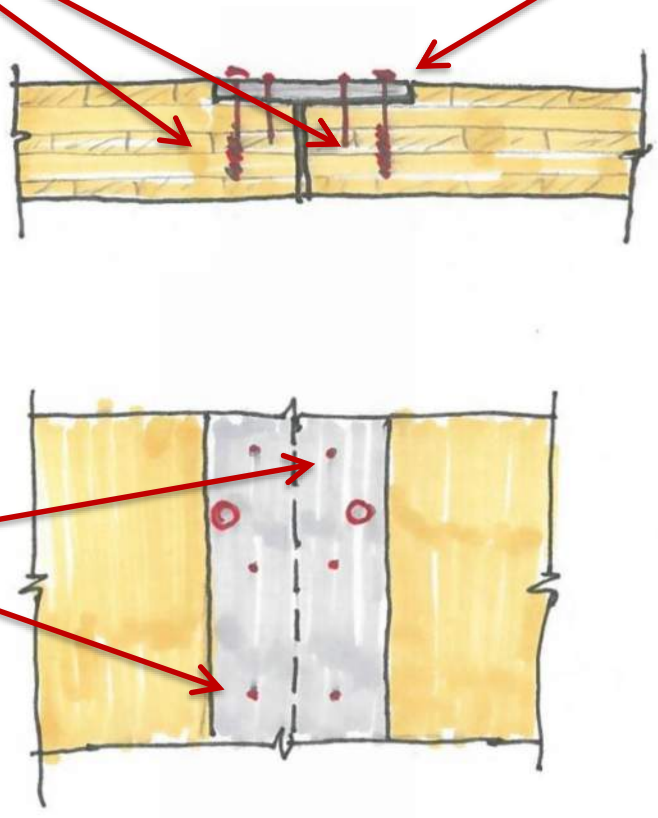


Connection Styles

An Efficient Panel to Panel Connection

Self-Tapping Screws as “erection bolts” @ 18” – 24” o.c

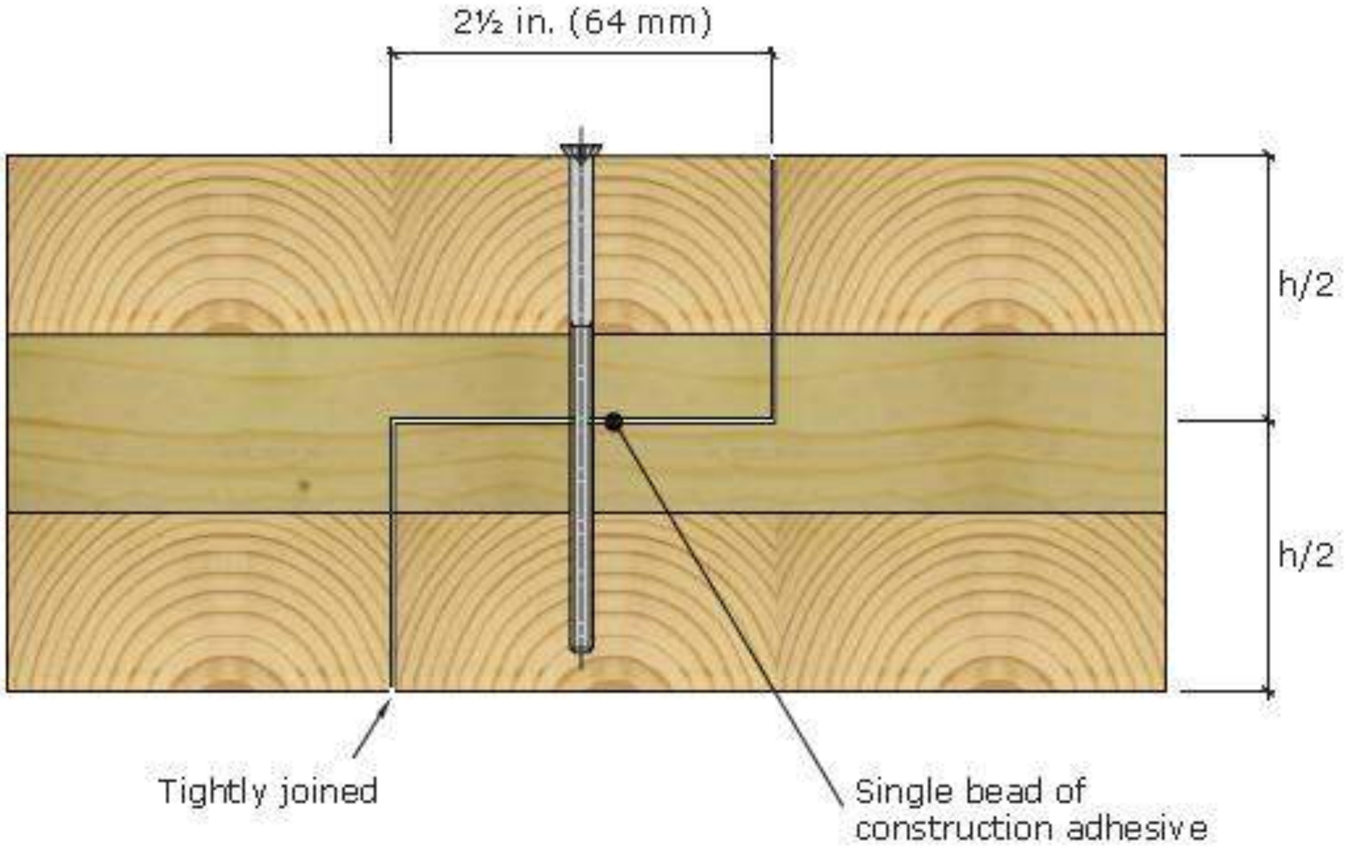
5 ½” to 6” plywood strip ¾” or 1” Thick



Nails at spacing required for shear transfer

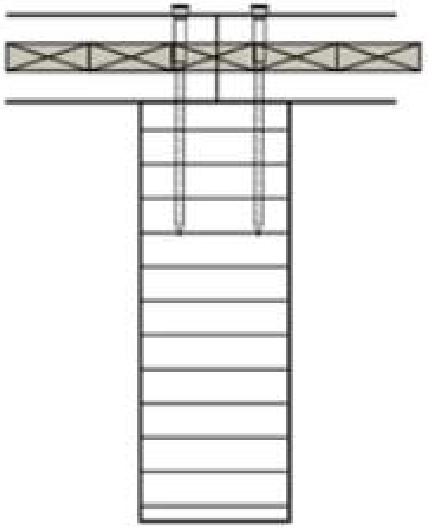
Graphics: ASPECT Structural Engineers

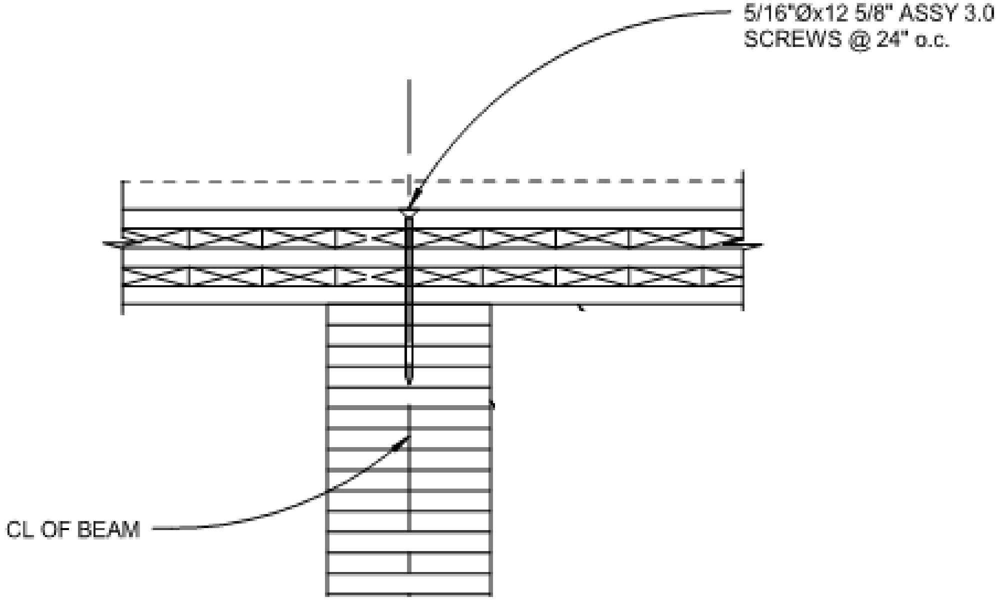
Connection Styles

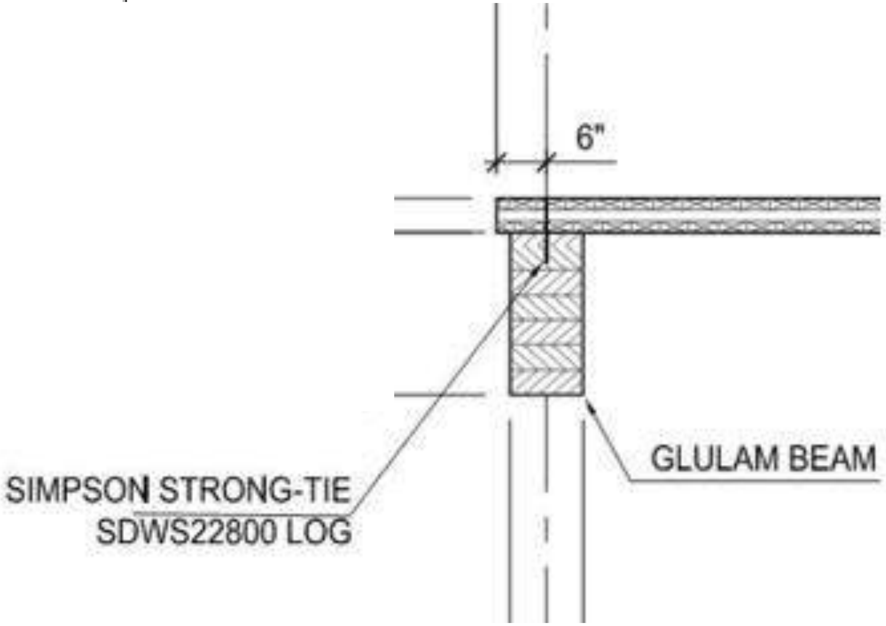


Graphics: US CLT Handbook

Panel to Beam Connection Styles







Fastener Vendor Design Support

MyTiCon Timber Connectors

Surface Splines

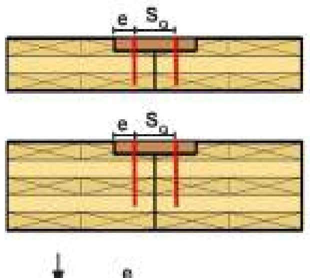
Table 1. Surface Spline Reference Design Values

CLT Details	Spline Thickness	Dimensions			Screws Details (For ASSY Ecofast or ASSY SK)	Reference Design Values		
		e	S_g	S_p		Z [lbs]	k [in/kip]	Z [lbs]
3-Ply S-P-F	3/4"	13/16"	1 - 9/16"	4 - 3/4"	5/16" x 3 - 1/8"	172	0.2	288
3-Ply D. Fir	1"	2 - 1/4"	4 - 1/2"	6"	5/16" x 4"	189	0.2	288
3-Ply D. Fir	1"	2 - 3/4"	5 - 1/2"	6"	3/8" x 4"	-	0.2	387
5-Ply S-P-F	11/16"	1 - 3/8"	2 - 3/4"	6"	1/4" x 6 - 1/4"	172	0.3	198
5-Ply S-P-F	1"	1 - 3/8"	2 - 3/4"	6"	5/16" x 6 - 1/4"	243	0.2	444

Notes:

1. Table 1 lists reference design values valid for allowable stress design in the USA for a single ASSY fastener conforming to the connection geometry and loading condition described on this page.
2. It is recommended to stagger the screws across the line of the joint, as illustrated to the left.
3. Listed reference lateral design values are only valid for ASSY Ecofast and ASSY SK.
4. Fastener must be installed in pair, one screw in each panel in order to transmit the load through the spline connection.
5. CLT panels ply thickness are assumed to be 1-3/8" [35 mm].
6. Listed reference lateral design values given correspond to load duration factor C_D = 1.0.

Connection Geometry Requirements



SIMPSON Strong-Tie

Table 1. Reference allowable load and slip modulus for SDWS Timber Screws (SDWS22400DB and SDWS22600DB) for CLT surface spline fastening with 1-1/8-in. APA rated Sturd-I-Floor wood structural panel, single-surface splines.		
CLT Wood Species Combination	Allowable load per Fastener (lb.)	Fastener slip modulus (in./K)
DFL	375	0.15
SPF SPF-S	335	0.15

1. Allowable loads are given at C_D=1.0 and maybe increased up to C_D=1.6 as permitted by the building code.
2. Applicable adjustments shall be applied following the ANSI/AWC NDS®-15 or NDS®-18.
3. Design values are applicable for all grain orientation combinations of major strength directions in the CLT and the wood structural panel spline and grades of CLT for the species combinations listed.
4. Designer is responsible to check shear capacity of spline (shear through the thickness and rolling shear).

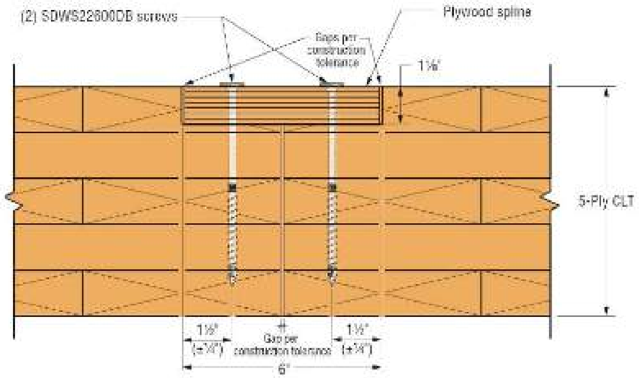


Figure 1: Typical end elevation -- Single-surface spline with 5-ply CLT panels, 1-1/8-in. spline (plywood

Additional Resources – WoodWorks.org

woodworks.org/publications-media/solution-papers/

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Wood Solution Papers

Mass Timber Cost and Design Optimization Checklists

Guides coordination between designers and builders (GCs, construction managers, estimators, fabricators, installers, etc.) as they are estimating and making cost-related decisions on mass timber projects

Fire Design of Mass Timber Members: Code Applications, Construction Types and Fire Ratings

Focuses on how to meet fire-resistance requirements in the IBC, including calculation and testing-based methods

Companion piece to WoodWorks' Inventory of Fire Resistance-Tested Mass Timber Assemblies

Tall Wood Buildings in the 2021 IBC – Up to 18 Stories of Mass Timber

Summarizes the changes as well as the background and technical research that supported their adoption.

Acoustics and Mass Timber: Room-to-Room Noise Control

Emphasizing room-to-room noise control, this paper covers key aspects of mass timber acoustical design. Companion piece to WoodWorks' Inventory of Mass Timber Acoustic Assemblies.

Additional Resources – WoodWorks.org

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Fire Design of Mass Timber Members

Code Applications, Construction Types and Fire Ratings

Richard McLain, PE, SE • Senior Technical Director • WoodWorks
Scott Breneman, PhD, PE, SE • Senior Technical Director • WoodWorks

For many years, exposed heavy timber framing elements

Inventory of Fire-Resistance Tested Mass Timber Assemblies

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Resistance Tests of Mass Timber Floor / Roof Assemblies

LT Grade r x Minor Grade	Ceiling Protection	Panel Connection	Floor Topping	Load Rating	Fire Resistance Achieved (Hours)	Source	Testing Lab
50 Fb 1.5E MSR x SPF #3	2 layers 1/2" Type X gypsum	Half-Lap	None	Reduced 36% Moment Capacity	1	1 (Test 1)	NRC Fire Laboratory
1/#2 x SPF #1/#2	1 layer 5/8" Type X gypsum	Half-Lap	None	Reduced 75% Moment Capacity	1	1 (Test 5)	NRC Fire Laboratory
E1	None	Topside Spline	2 staggered layers of 1/2" cement boards	Loaded, See Manufacturer	2	2	NRC Fire Laboratory March 2016
E1	1 layer of 5/8" Type X gypsum under Z-channels and furring strips with 3 5/8" fiberglass batts	Topside Spline	2 staggered layers of 1/2" cement boards	Loaded, See Manufacturer	2	5	NRC Fire Laboratory Nov 2014
E1	None	Topside Spline	3/4 in. proprietary gypcrete over Maxxon acoustical mat	Reduced 50% Moment Capactiy	1.5	3	UL
E1	1 layer 5/8" normal gypsum	Topside Spline	3/4 in. proprietary gypcrete over Maxxon acoustical mat or proprietary sound board	Reduced 50% Moment Capactiy	2	4	UL
E1	1 layer 5/8" Type X gyp under Resilient Channel under 7 7/8" I-Joists with 3 1/2" Mineral Wool beween Joists	Half-Lap	None	Loaded, See Manufacturer	2	21	Intertek 8/24/2012
E1M5 2100 x SPF #2	None	Topside Spline	1-1/2" Maxxon Cyp-Grete 2000 over Maxxon Reinforcing Mesh	Loaded, See Manufacturer	2.5	6	Intertek, 2/22/2016
V1	None	Half-Lap & Topside Spline	2" gypsum topping	Loaded, See Manufacturer	2	7	SwRI (May 2016)
1950 Fb MSR x SPF #3	None	Half-Lap	None	Reduced 59% Moment Capacity	1.5	1 (Test 3)	NRC Fire Laboratory
1/#2 x SPF #1/#2	1 layer 5/8" Type X gypsum	Half-Lap	None	Unreduced 101% Moment Capacity	2	1 (Test 6)	NRC Fire Laboratory
1/#2 x SPF #1/#2	None	Half-Lap	None	Unreduced 101% Moment Capacity	2.5	1 (Test 7)	NRC Fire Laboratory

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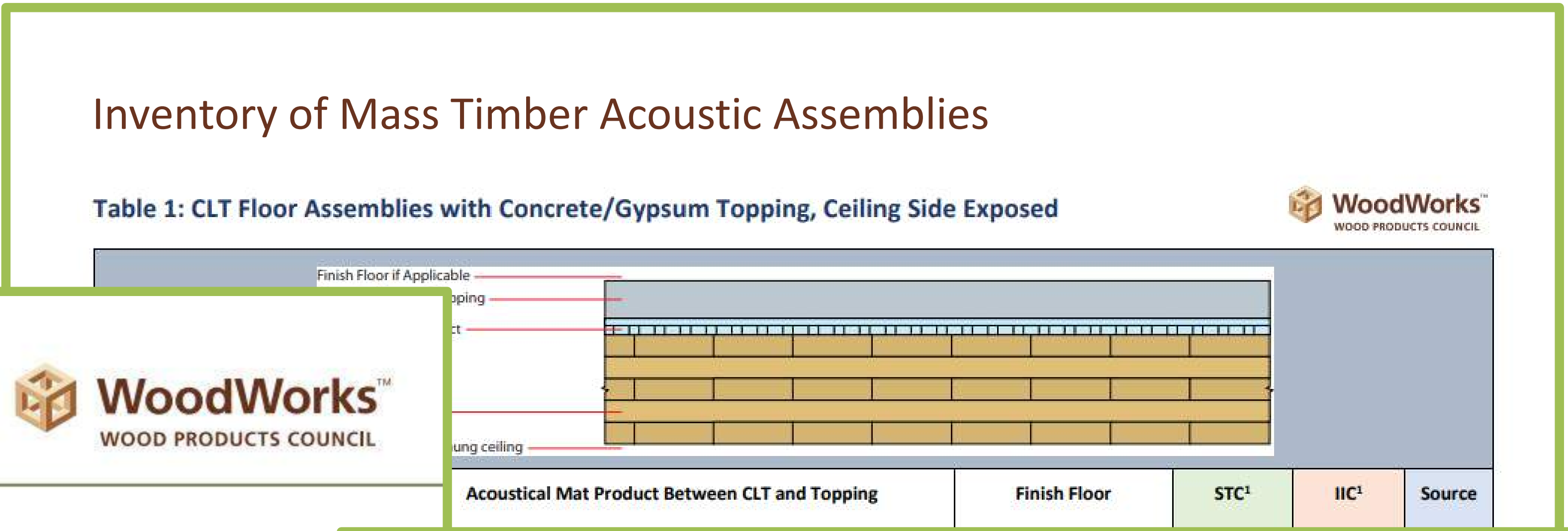
Mass Timber Cost and Design Optimization Checklists

WoodWorks has developed the following checklists to assist in the design and cost optimization of mass timber projects. The *design optimization* checklists are intended for building designers (architects and engineers), but many of the topics should also be discussed with the fabricators and builders. The

First Tech Federal

Additional Resources – WoodWorks.org



Inventory of Mass Timber Acoustic Assemblies

Table 1: CLT Floor Assemblies with Concrete/Gypsum Topping, Ceiling Side Exposed

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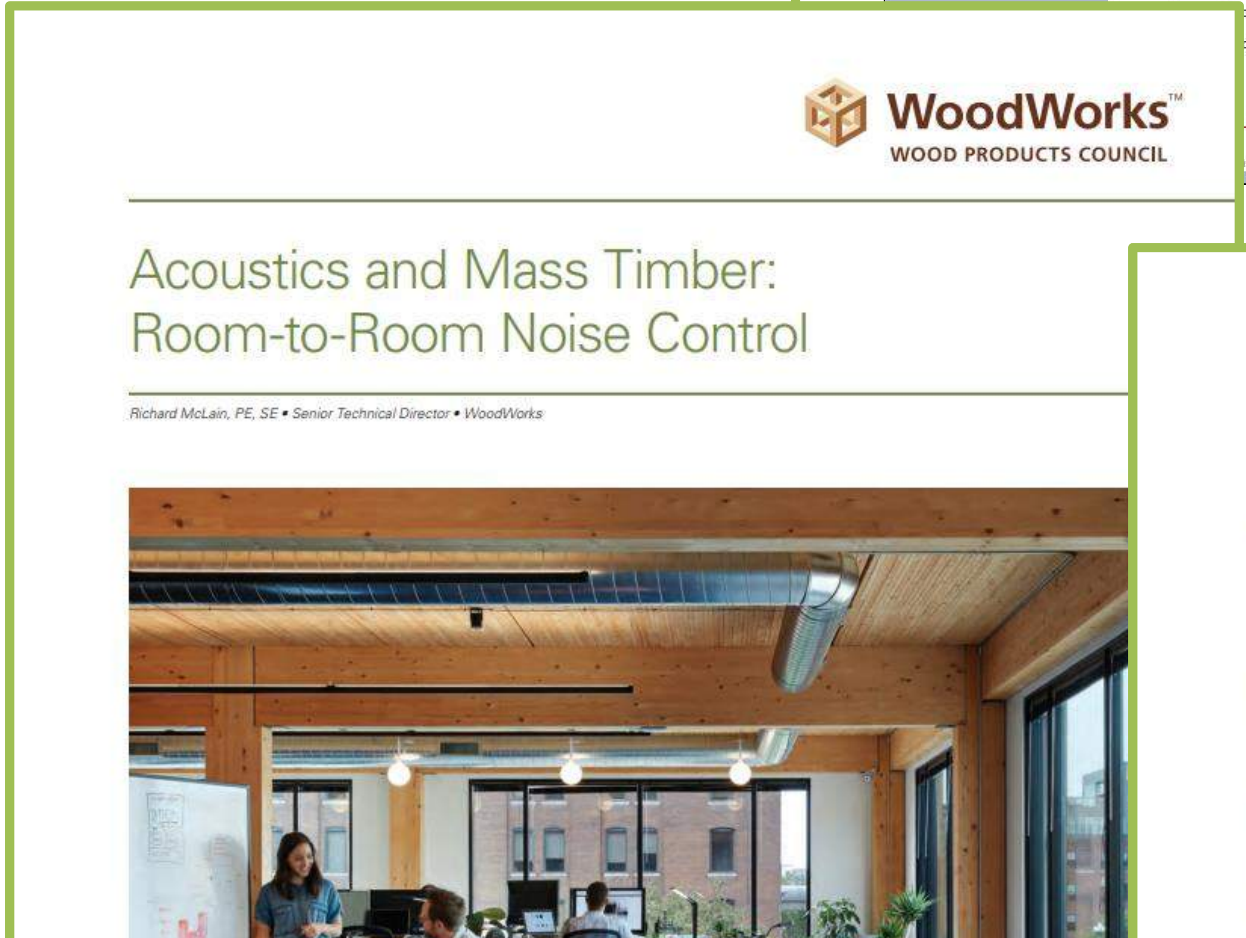
Acoustical Mat Product Between CLT and Topping	Finish Floor	STC[1]	IIC[1]	Source



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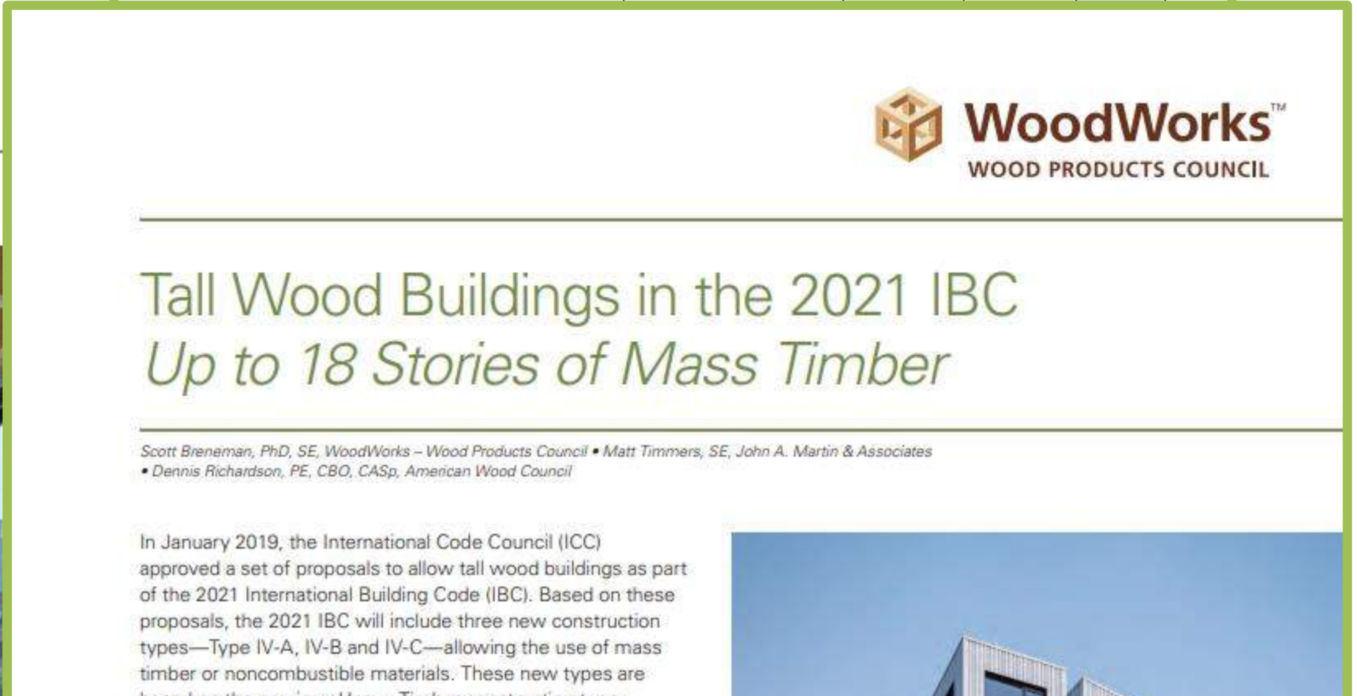
Acoustics and Mass Timber:
Room-to-Room Noise Control

Richard McLain, PE, SE • Senior Technical Director • WoodWorks



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Tall Wood Buildings in the 2021 IBC
Up to 18 Stories of Mass Timber

Scott Breneman, PhD, SE, WoodWorks – Wood Products Council • Matt Timmers, SE, John A. Martin & Associates • Dennis Richardson, PE, CBO, CASp, American Wood Council

In January 2019, the International Code Council (ICC) approved a set of proposals to allow tall wood buildings as part of the 2021 International Building Code (IBC). Based on these proposals, the 2021 IBC will include three new construction types—Type IV-A, IV-B and IV-C—allowing the use of mass timber or noncombustible materials. These new types are

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Questions?

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Scott.Breneman@woodworks.org

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at www.woodworks.org: