Gravity and Lateral Design of Mass Timber Structures

Presented By:

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Mass Timber Structural Design: Engineering Modern Timber Structures

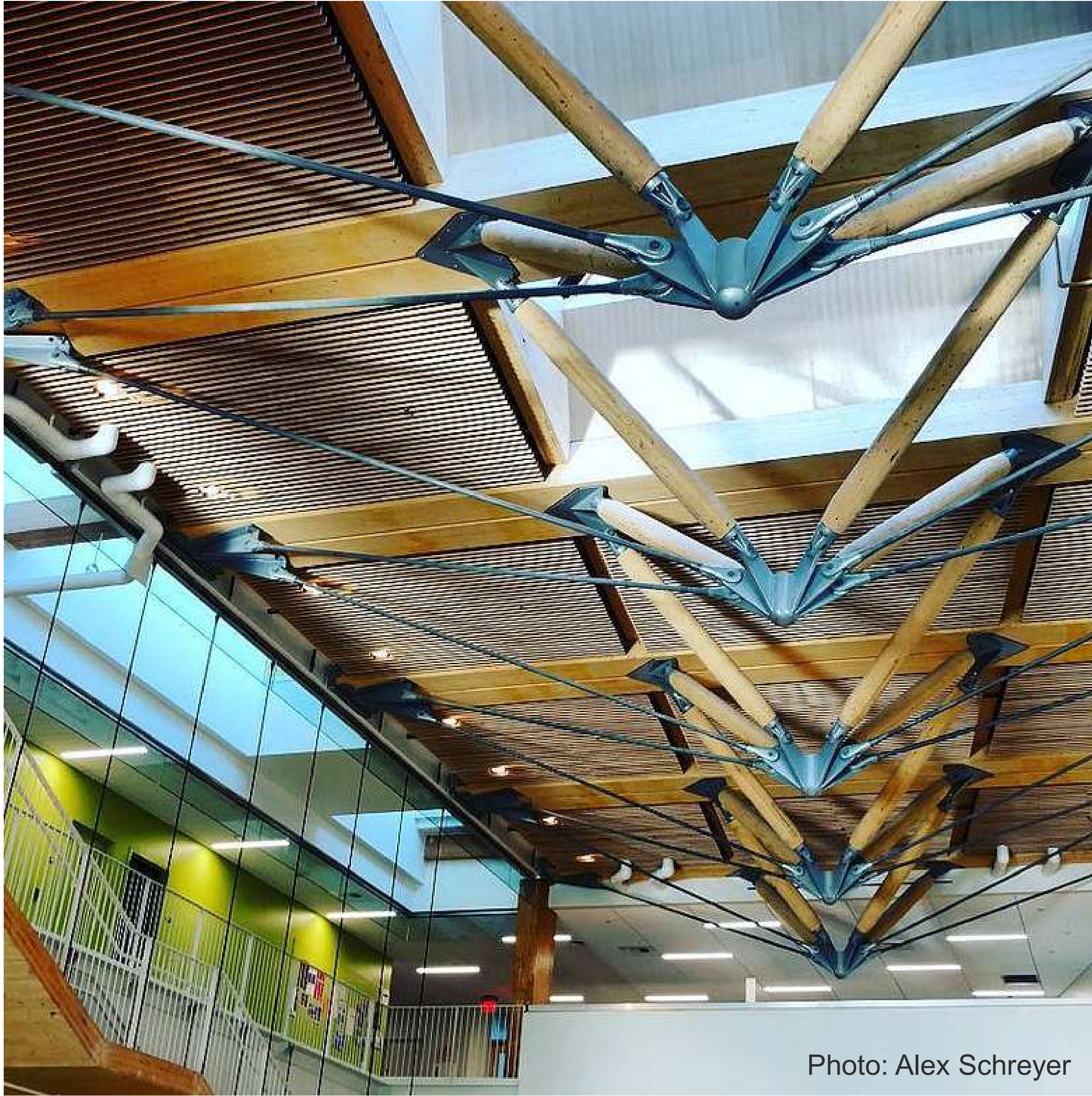


Photo: Alex Schreyer

Course Description

This presentation will provide a detailed look at the structural design processes associated with a variety of mass timber (MT) products, including glued-laminated timber (glulam), cross-laminated timber (CLT), and nail-laminated timber (NLT). Applications for the use of these products in gravity force-resisting systems under the 2021 IBC/2022 CBC will be discussed. Other technical topics will include MT floor vibration design and connection details. Also, MT framing components are often left exposed to act as a finish while taking advantage of their aesthetics. As such, they are often required to provide a fire-resistance rating demonstrating their ability to maintain structural integrity in the event of a fire. This presentation will also discuss the structural design of mass timber elements under fire conditions.

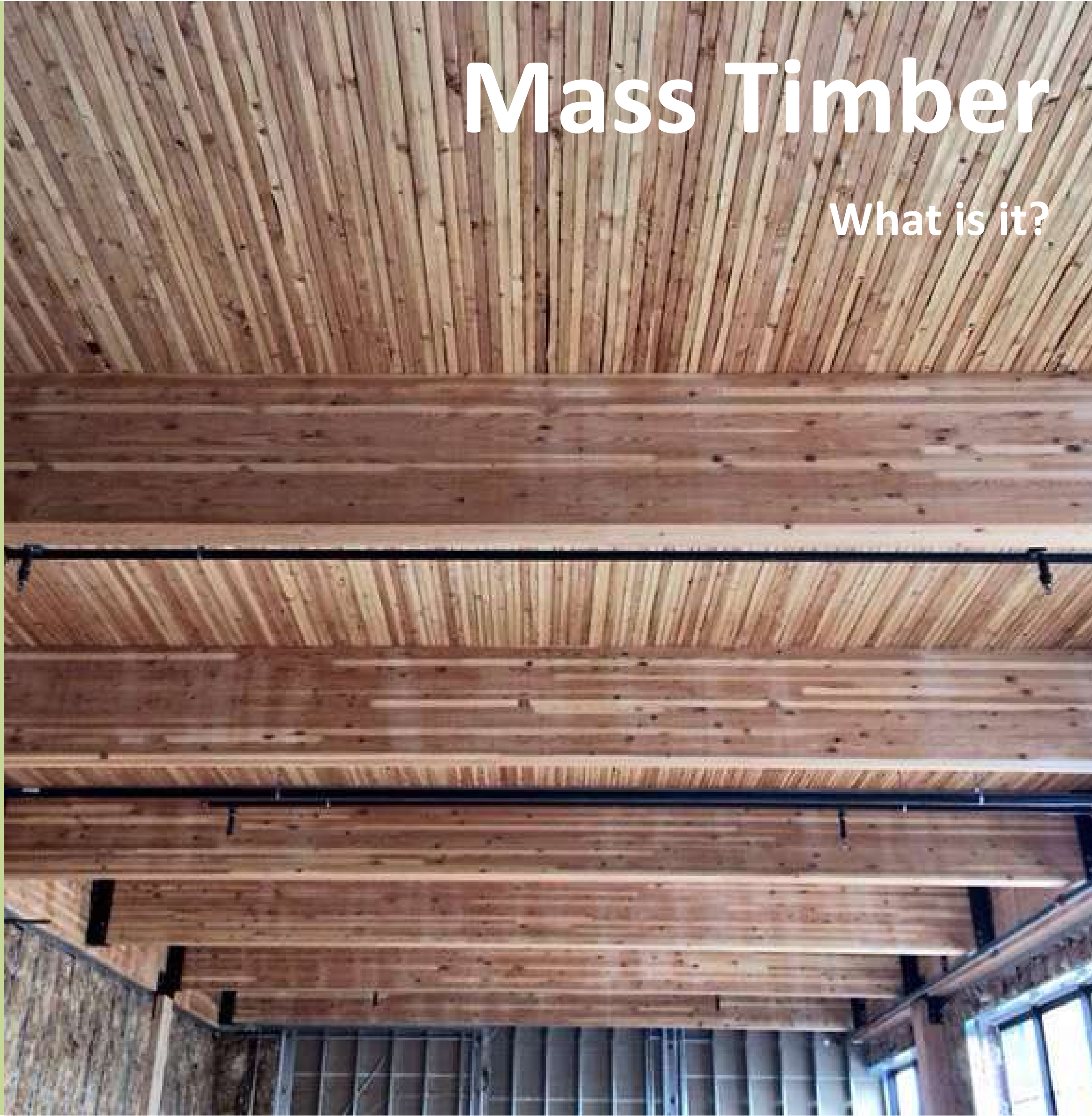
Learning Objectives

1. Compare different mass timber framing systems and review their unique design considerations.
2. Highlight common connection details in modern timber structures.
3. Review structural design steps for components in common mass timber framing systems.
4. Demonstrate design steps for calculating fire resistance of exposed timber structural elements.

Mass Timber

What is it?

Mass timber (MT) is a category of framing products often using small wood members formed into large (massive) panelized solid wood elements including CLT, NLT or glulam panels for floor, roof and wall framing



Mass Timber Products

Horizontal Framing

Nail-Laminated Timber (NLT)

Cross-Laminated Timber (CLT)

Glue-Laminated Timber (GLT)

Tongue & Groove Decking (T&G)

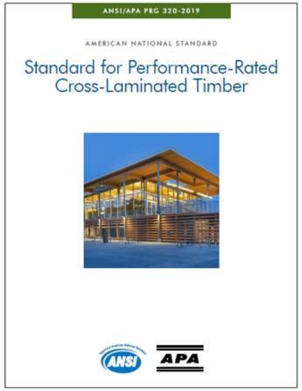
Timber/Concrete Composite

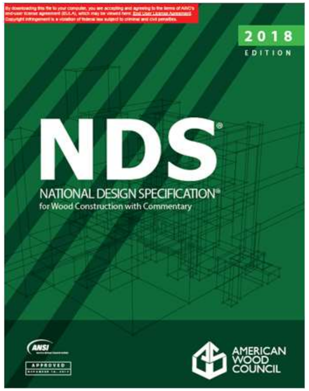
Structural Composite Lumber (SCL)

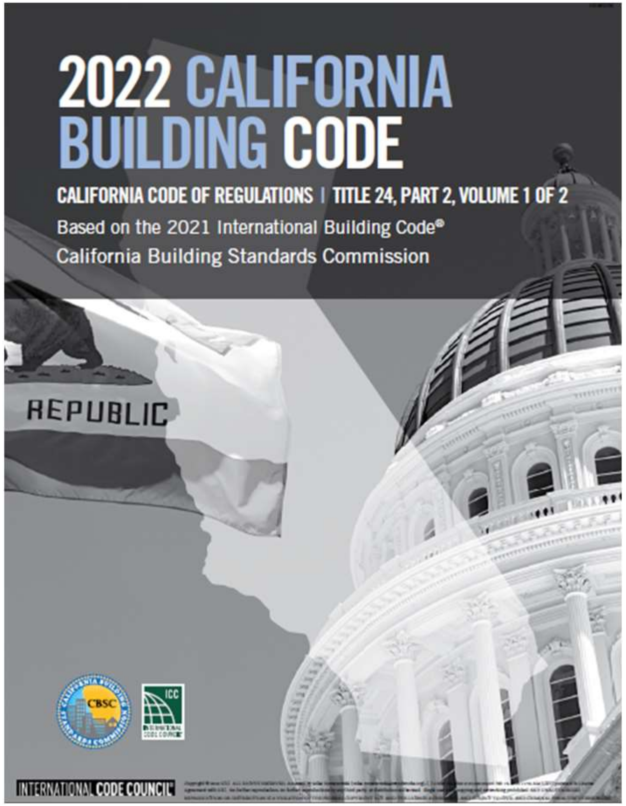
Image source: StructureCraft

Mass Timber Gravity Framing Systems

Building Code Acceptance of CLT (Gravity)







2022 CBC
(2021 IBC similar)

Mass Timber Gravity Framing Systems

- **Gravity Framing Systems**
  - **Post & Beam**
  - Mass Timber Walls (Honeycomb)
  - Hybrid Light-Frame & Mass Timber
  - Two-Way Deck

T3 Minneapolis

Minneapolis, MN

Image Credit: Blaine Brownell

Mass Timber Gravity Framing Systems

- **Gravity Framing Systems**
  - Post & Beam
  - **Mass Timber Walls (Honeycomb)**
  - Hybrid Light-Frame & Mass Timber
  - Two-Way Deck

Candlewood Suites

Huntsville, AL

Image Credit: Lend Lease

Mass Timber Gravity Framing Systems

- **Gravity Framing Systems**
  - Post & Beam
  - Mass Timber Walls (Honeycomb)
  - **Hybrid Light-Frame & Mass Timber**
  - Two-Way Deck

Virtuoso

Vancouver, BC

Image: Adera

Image: Seagate Structures

Mass Timber Gravity Framing Systems

- **Gravity Framing Systems**
  - Post & Beam
  - Mass Timber Walls (Honeycomb)
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  - **Two-Way Deck**

BROCK COMMONS

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Images: acton ostry architects

Connection Details

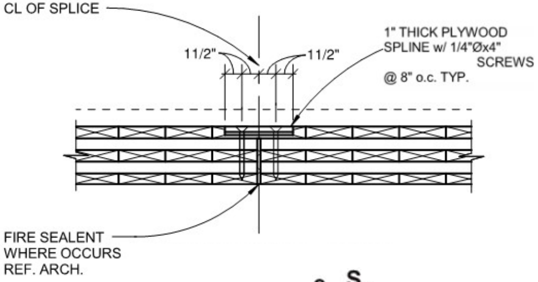
Connection Details

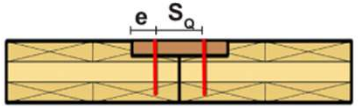

Photo Credit: Alex Schreyer

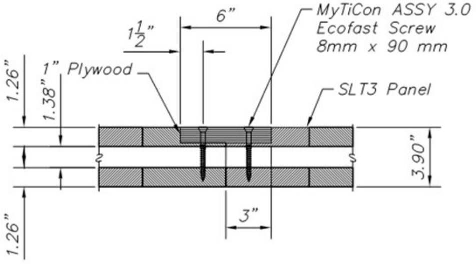
Long self tapping screws used extensively throughout mass timber construction

Connection Details – Panel to Panel

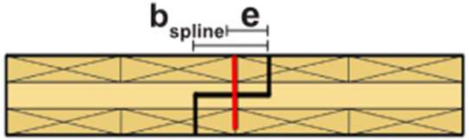
Single Surface Spline

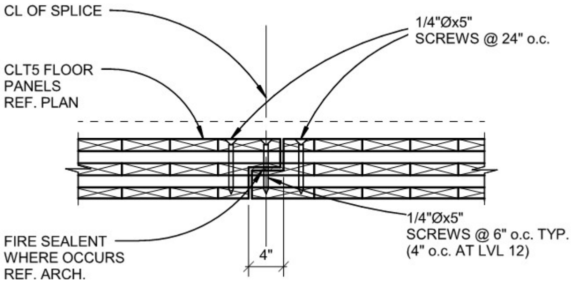




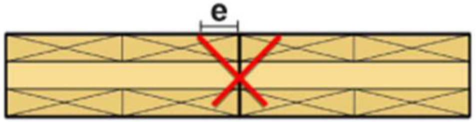


Half Lap

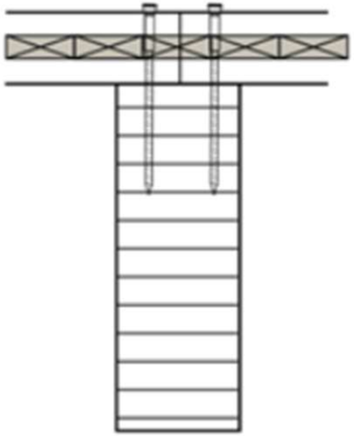


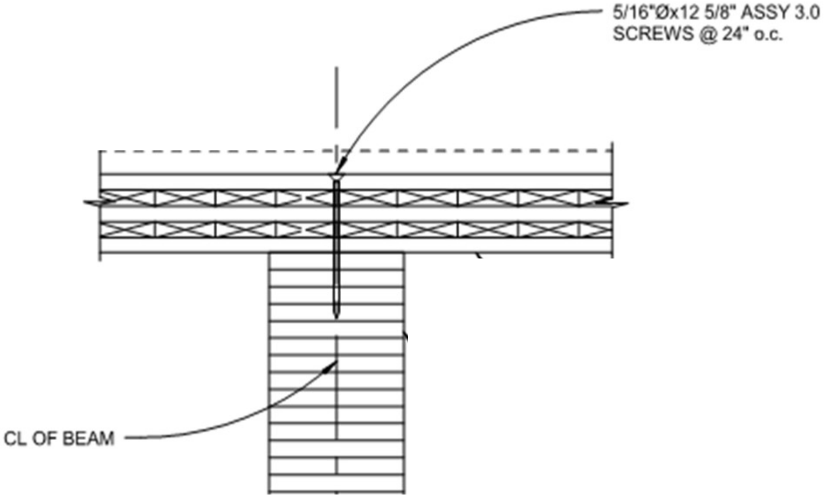


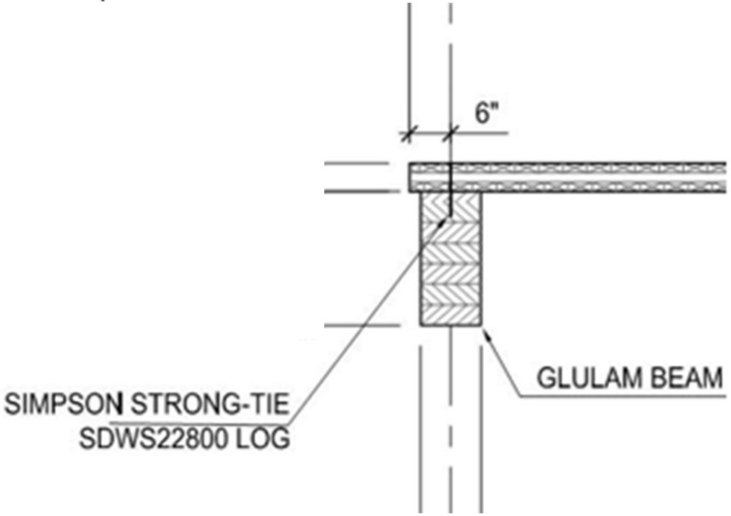
Butt Joint



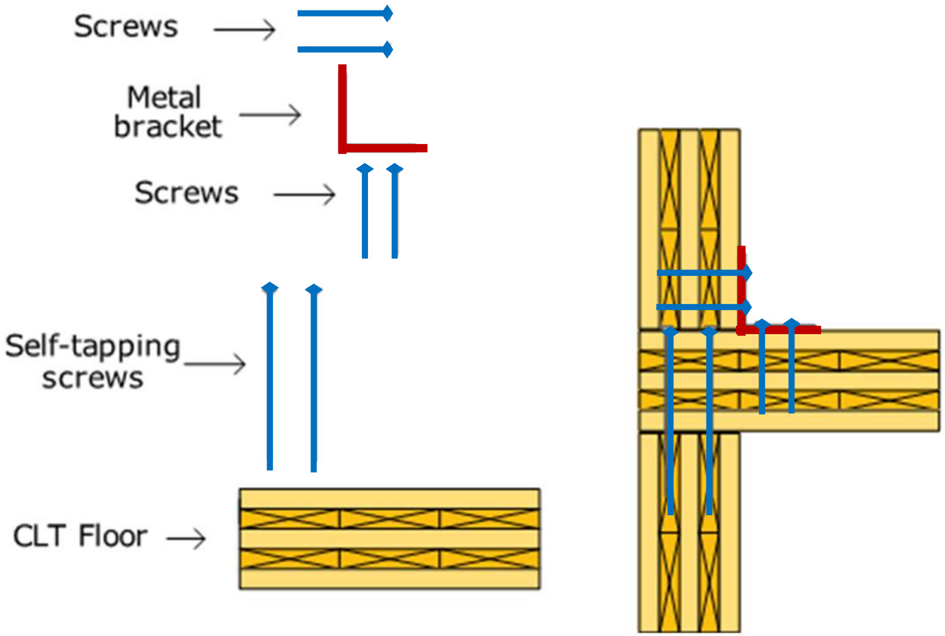
Connection Details – Panel to Beam







Connection Details – Platform Framing

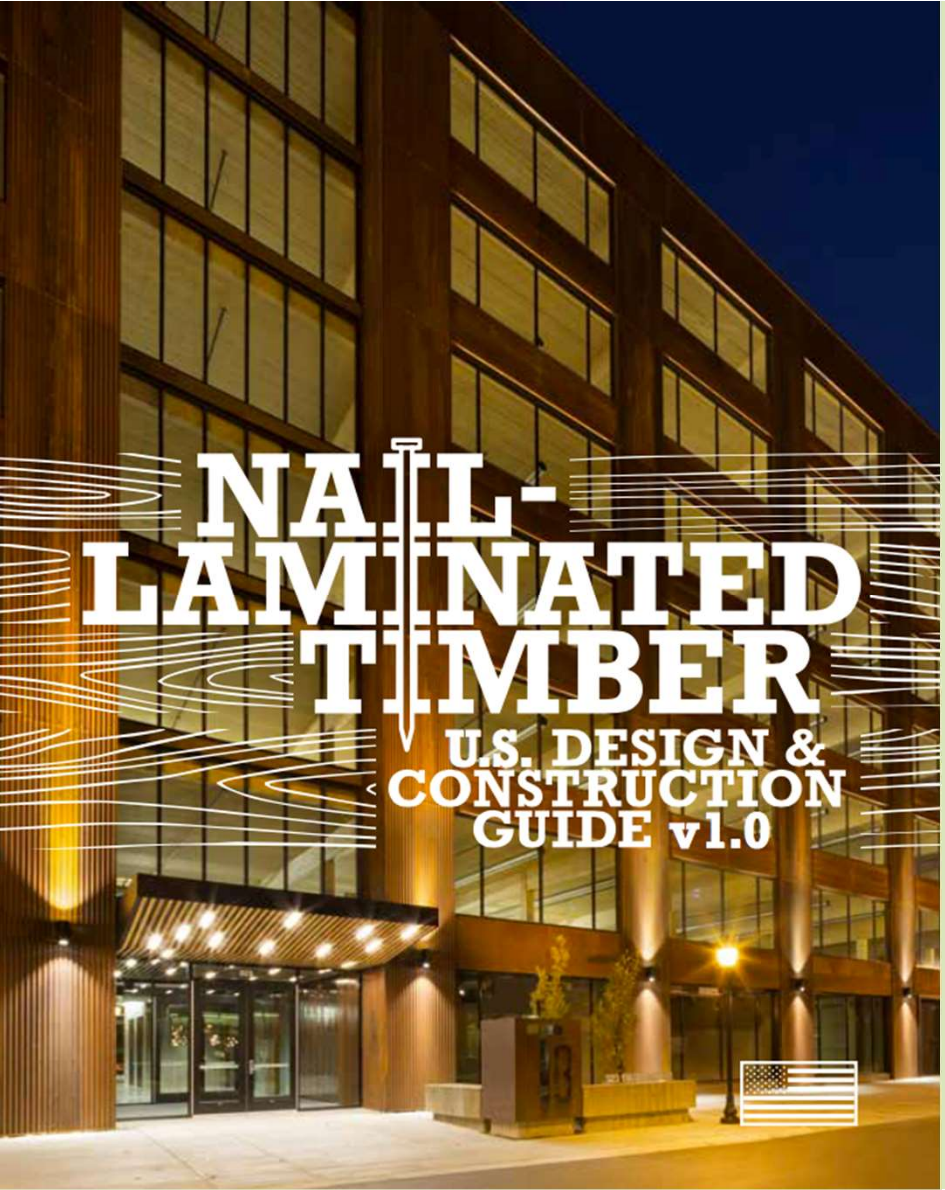


Source: US CLT Handbook

Simple connections with:

- Metal angles
- Self tapping screws

Component Design (Gravity)



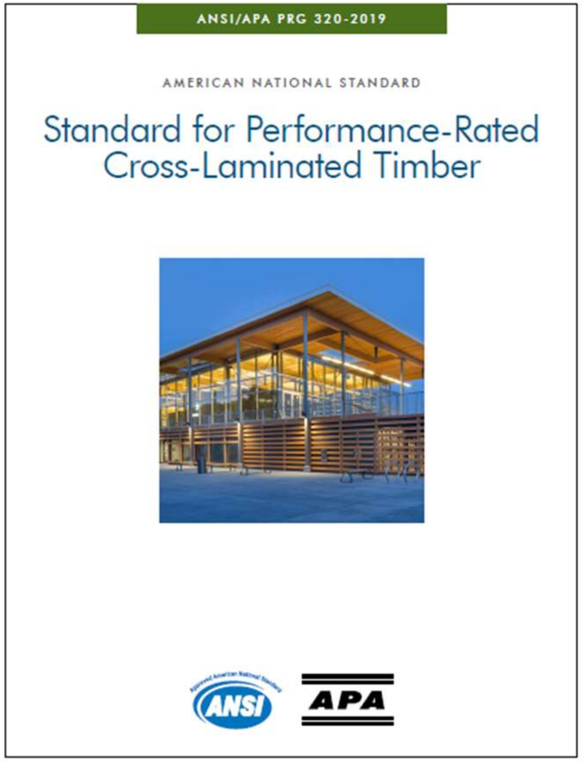
NLT Design

NLT Design Guide includes:

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

Free download from www.thinkwood.com

CLT Design



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

The Standard Covers:

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

CLT Design – Scope of PRG 320

CLT Panels shall be used in dry service conditions, such as in most covered structures, where the average equilibrium content of solid wood is less than 16 percent… CLT panels qualified in accordance with the provisions of this standard are intended to resist the effects of moisture on structural performance as may occur due to construction delays or other conditions of similar severity.

CLT Design – PRG 320 Basic Layups

CLT Grade (basic)

Layup

Panel Properties

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)
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

CLT Design – Product Report Custom Layups

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

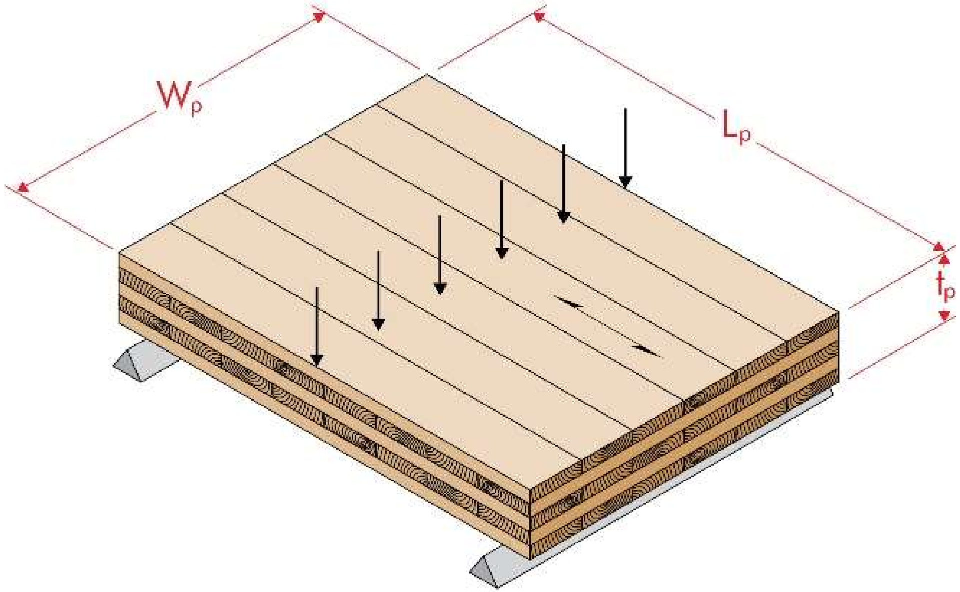
For SI: 1 psi = 0.006895 MPa

[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).

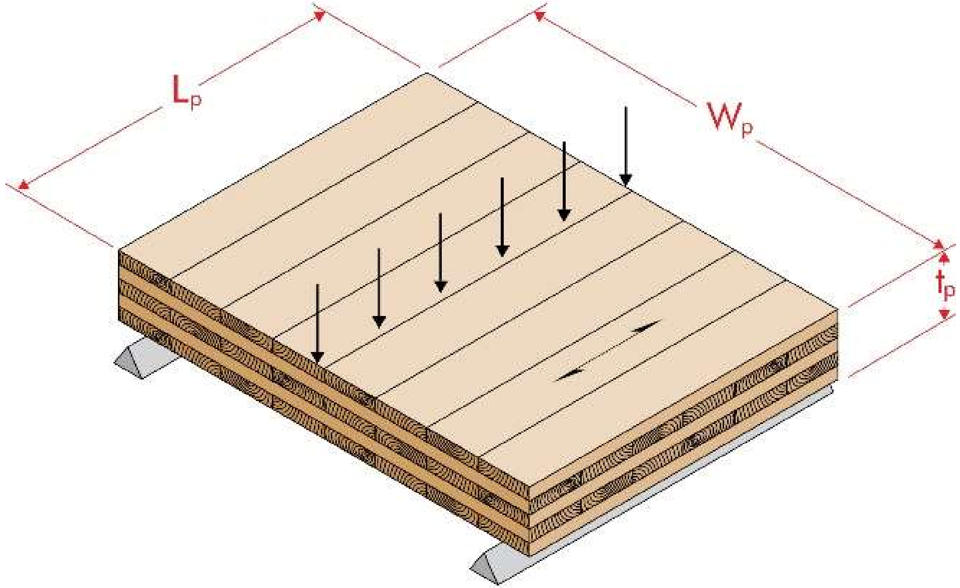
Table 2. Allowable Design Capacities[a] for SmartLam Balanced CLT (for Use in the U.S.)

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

CLT Design – FLATWISE Panel Loading



Span in MAJOR Strength Direction
"Parallel" Direction



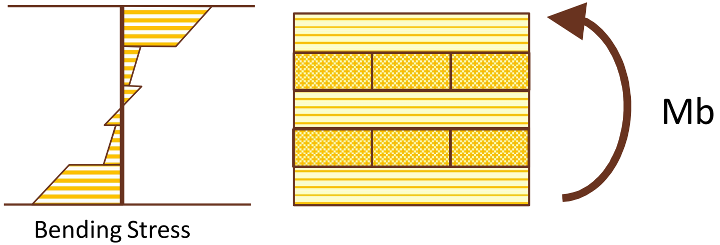
Span in MINOR Strength Direction
"Perpendicular" Direction

Reference: ANSI/APA PRG 320

CLT Design – Flatwise Flexural Strength

Design properties based on an Extreme Fiber Stress Model:

Flexural Capacity Check:



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

M_b = applied bending moment

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

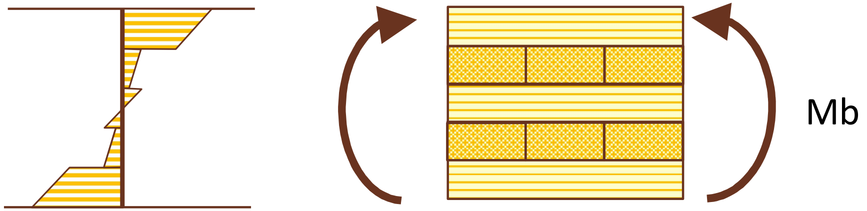
S_{eff} = effective section modulus

F_b = reference bending design stress of outer lamination

Reference: NDS

CLT Design – Flatwise Flexural Strength

Flexural Capacity Check (ASD):



Bending Stress

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

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

Reference: NDS

CLT Design – Flatwise Shear Strength

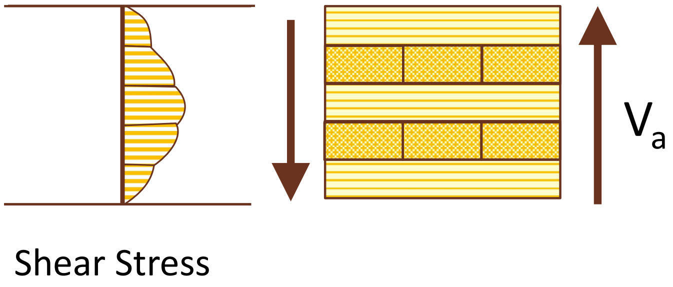
Design properties based on Extreme Fiber Stress Model:

Shear Capacity Check:

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

V_a = applied shear

$F_s(Ib/Q)_{eff}'$ = adjusted shear strength

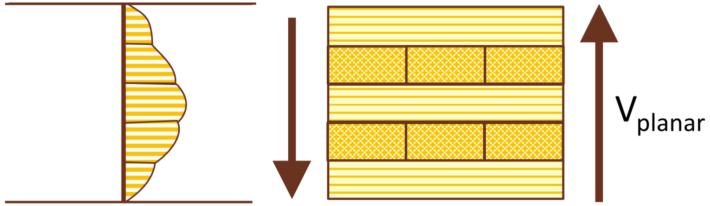


Reference: NDS

CLT Design – Flatwise Shear Strength

Design properties based on Extreme Fiber Stress Model:

Shear Capacity Check (ASD):



$$F_s(Ib/Q)_{eff}' = \underbrace{C_M\, C_t}_{\text{Commonly 1.0}}\ \underbrace{(F_s(Ib/Q)_{eff})}_{\text{Provided as combined value by manufacturer}} = C_M\, C_t\, V_s$$

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

Reference: NDS & CLT Product Reports

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

CLT Design – Flatwise Deflection Calculations

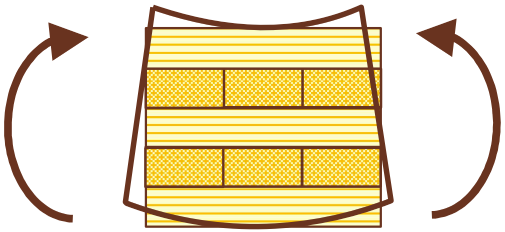
General Purpose: One-Way, Beam Action

Needed Stiffness: EI_{eff} GA_{eff}

Analyze as beam representing a 1 ft wide strip of CLT

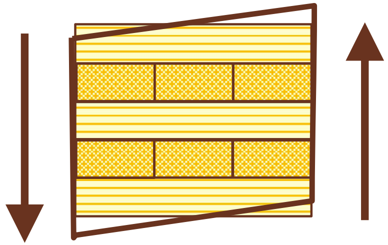
Can model multiple spans, cantilevers, etc.

CLT Design – Flatwise Flexural and Shear 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$_{eff}$

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

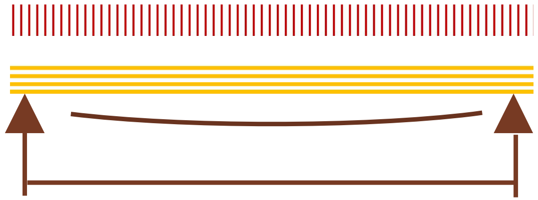
Reference: ANSI/APA PRG 320 Appendix X3

CLT Design – Flatwise 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

CLT Design – Floor Vibration Concepts

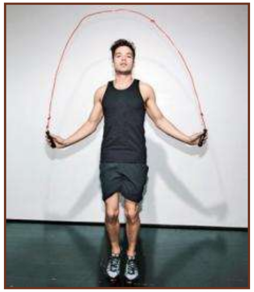
- The natural frequency of a floor, and harmonics of the fundamental frequency, are the most important parameters in vibration design and evaluation
- Most practical floors have fundamental frequencies in the range of 5 to 15 Hz, although values outside this range are possible
- Generally, the higher the frequency the better

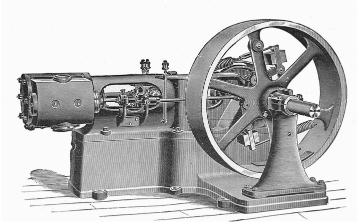
CLT Design – Common Vibration Sources for Buildings

Vibration <u>sources</u> 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







CLT Design – Floor Vibration

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

Limit CLT floor span such that:

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

Where:

L = floor span (ft)

EI_{app} = apparent stiffness for pinned supported, uniformly loaded, simple span beam, 1 ft wide (lb-in^2)

ρ = specific gravity of the CLT

A = the cross-sectional area (thickness x 12) (in^2)

Reference: US CLT Handbook, Chapter 7

CLT Design – Floor Vibration

FPI Method recommends limiting CLT Floor Span such that:

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

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

Using iterative approach:

1) Estimate L
2) Calculate EI_{app}
3) Calculate L
4) Repeat until L converges

OR use values provided by manufacturer

Reference: US CLT Handbook, Chapter 7

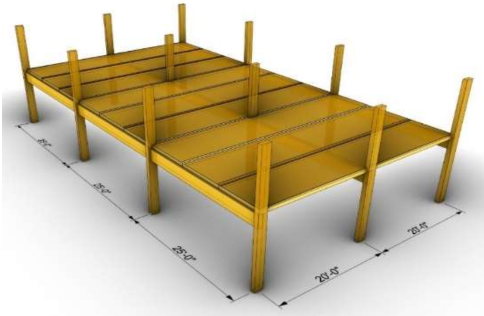
CLT Design – Floor Vibration

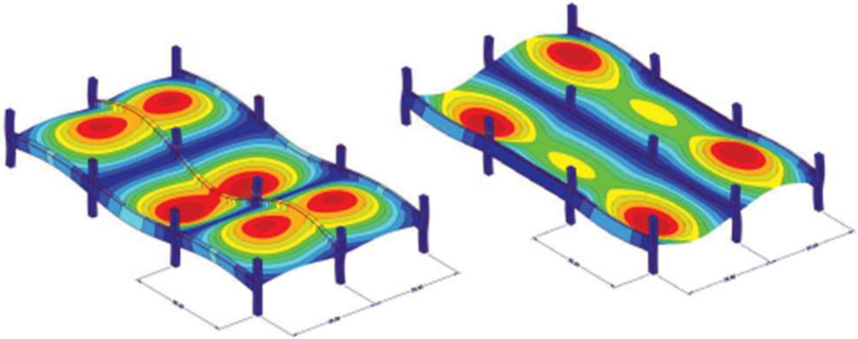
- Experience has shown that the FPI Method consistently produces well performing floors

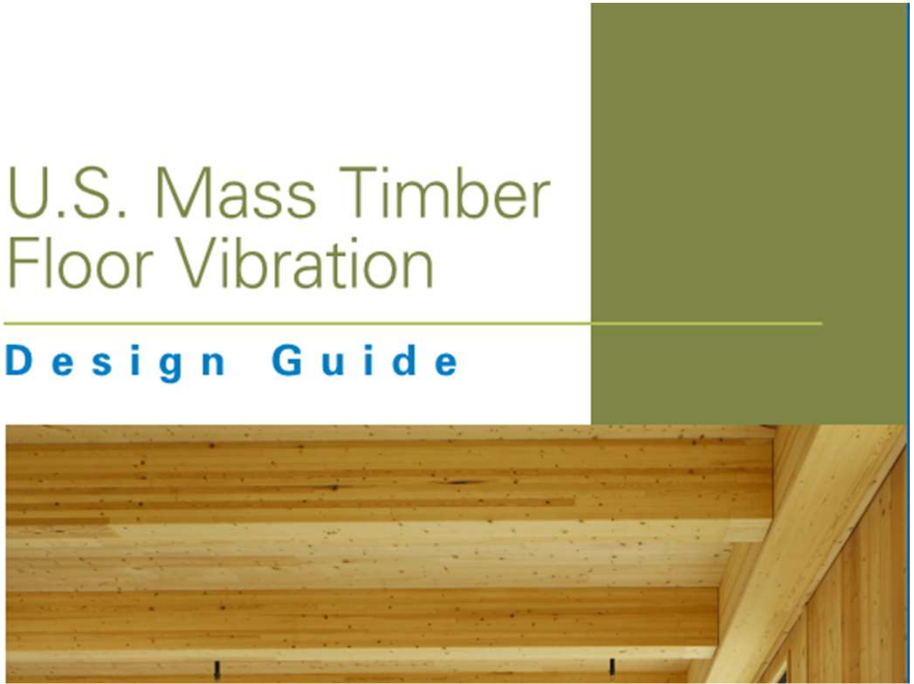
- Does not consider
  - Multi-span panels (improves performance)
  - Flexibility of supports, e.g. beams (lowers performance)
  - Impact of topping slabs (may improve or lower performance)

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

NEW MASS TIMBER FLOOR VIBRATION DESIGN GUIDE







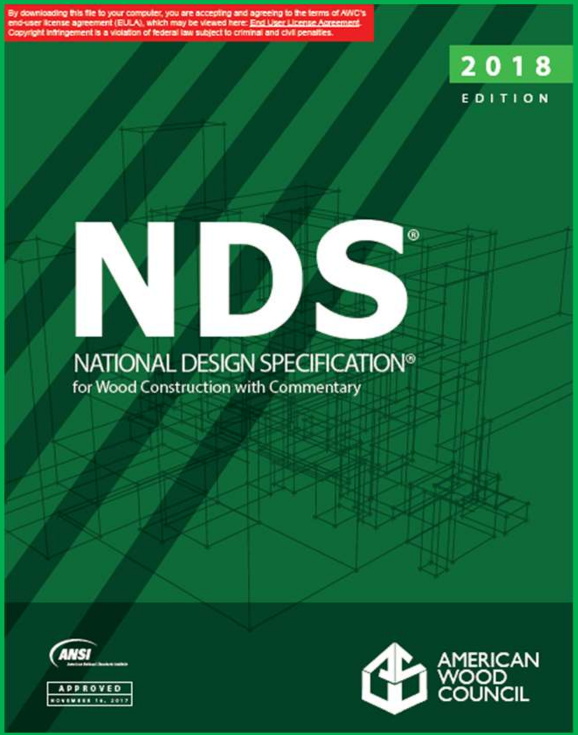
Worked office, lab and residential examples

Covers simple and complex methods for bearing wall and frame supported floor systems

Fire Resistance

Fire Resistance – Charring

For exposed wood members, CBC Section 722.1 references AWC's NDS Chapter 16 (AWC's TR 10 is a design aid to NDS Chapter 16)




NATIONAL DESIGN SPECIFICATION FOR WOOD CONSTRUCTION 149

FIRE DESIGN OF WOOD MEMBERS

16.1	General	150
16.2	Design Procedures for Exposed Wood Members	150
16.3	Wood Connections	151
Table 16.2.1	Effective Char Rates and Char Layer Thicknesses (for β_n = 1.5 in./hr.)	150
Table 16.2.2	Adjustment Factors for Fire Design	151

16

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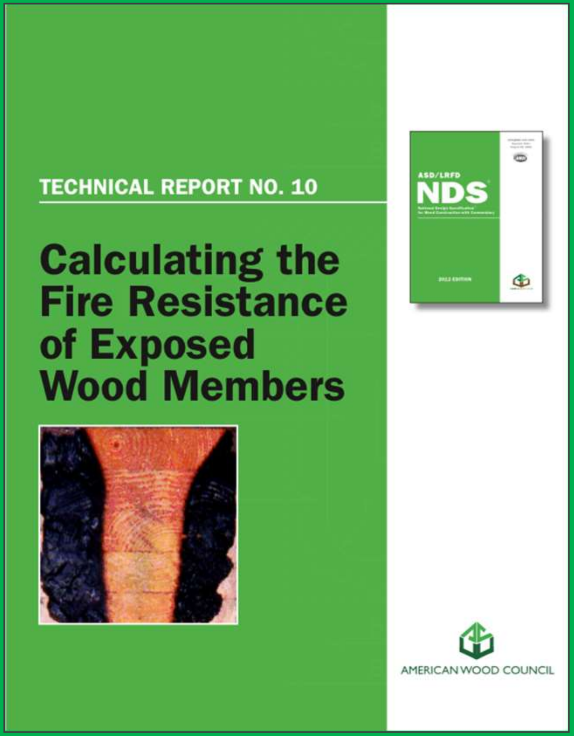
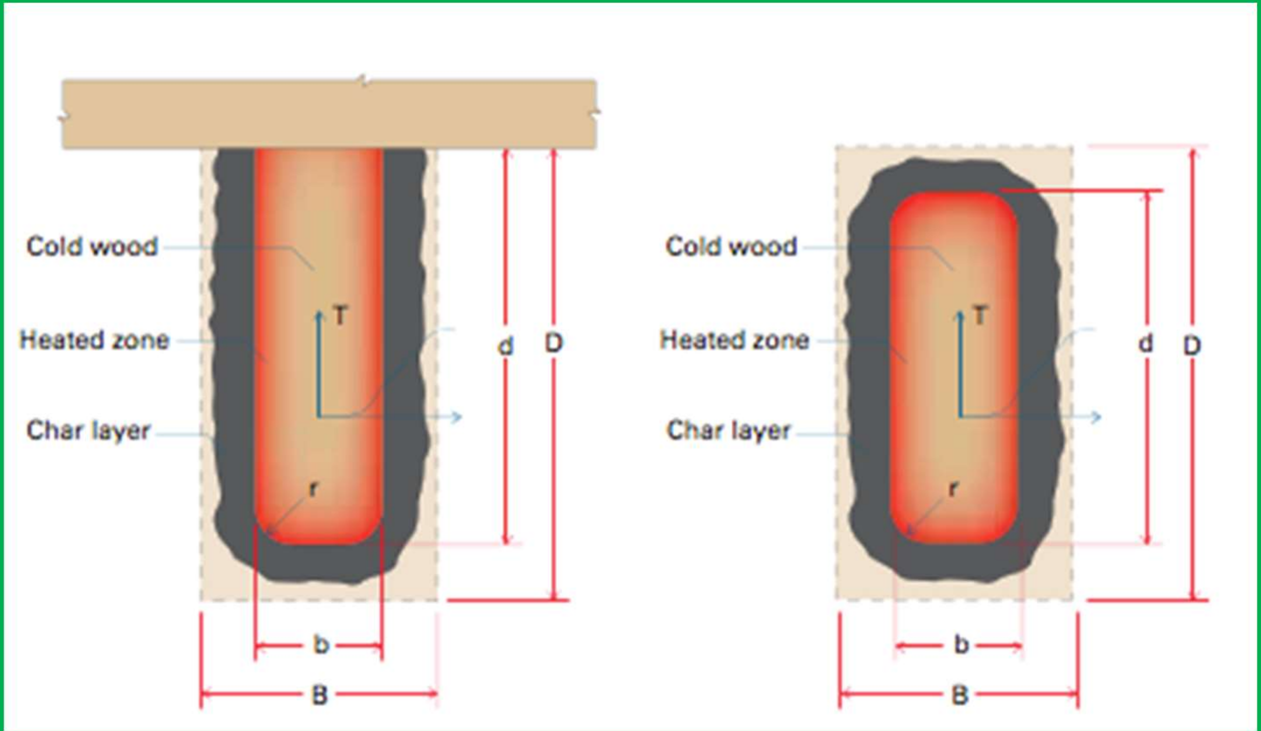
AMERICAN WOOD COUNCIL



Fire Resistance – Charring

Similar to heavy timber, mass timber products have inherent fire resistance properties



Source: AWC's TR 10

Fire Resistance - Glulams

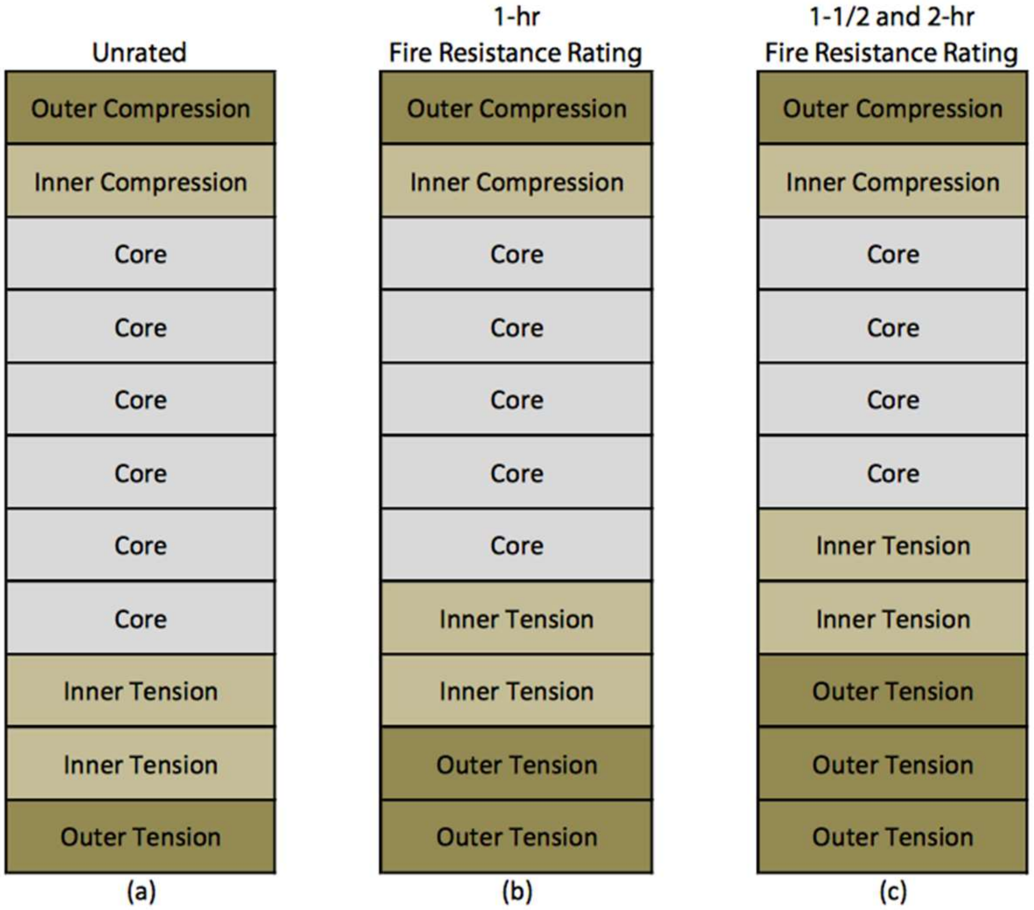
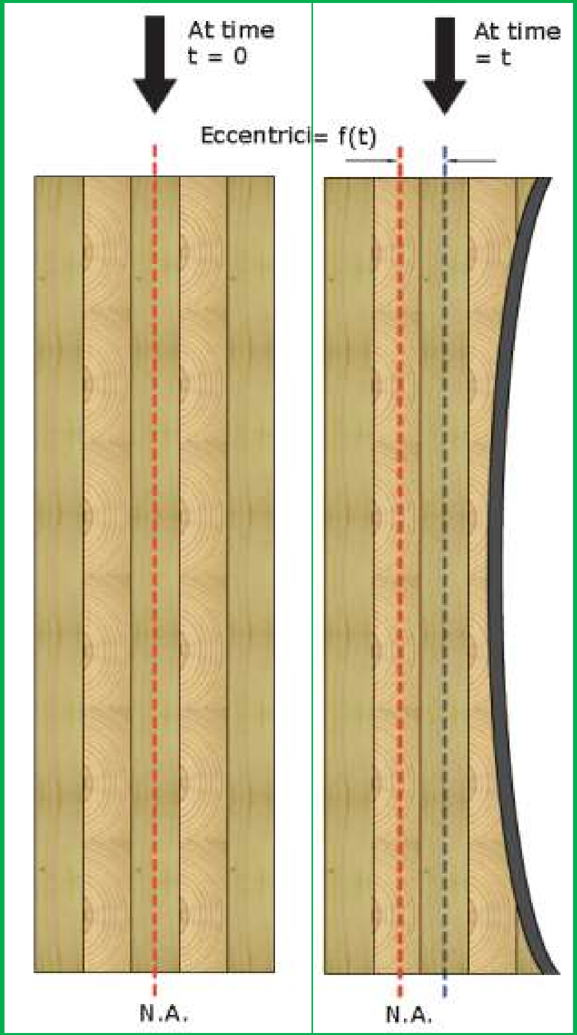


Figure 3-1 Typical glulam unbalanced beam layups

<u>Glulam beam fire design:</u>

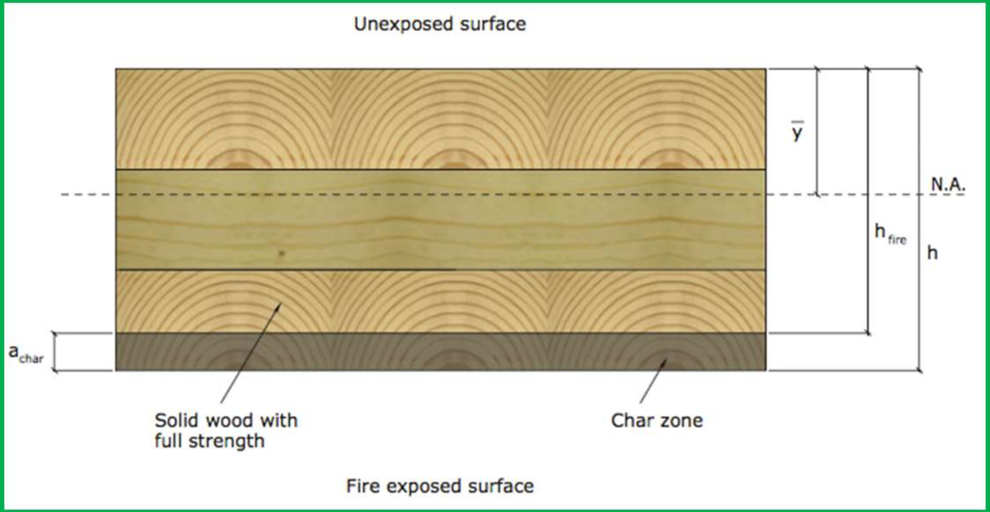
- Add 1 additional outer tension lam at bottom for each hour of resistance required
- Widen as required

Fire Resistance – CLT



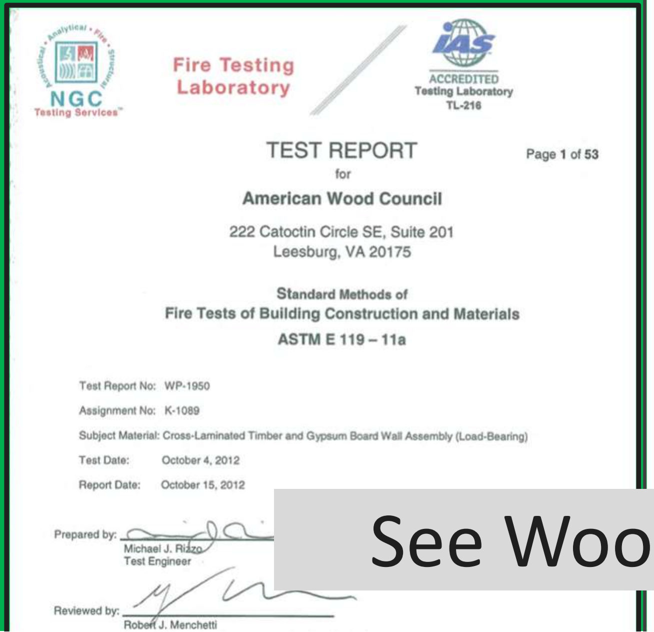
CLT fire design:

- Neutral axis shifts as charring occurs at exposed layers



Fire Resistance – CLT

Many successful CLT fire tests have been conducted, both with and without gypsum board protection


Fire Testing Laboratory

NGC Testing Services

IAS ACCREDITED Testing Laboratory TL-216

TEST REPORT

Page 1 of 53

for

American Wood Council

222 Catoctin Circle SE, Suite 201
Leesburg, VA 20175

Standard Methods of
Fire Tests of Building Construction and Materials
ASTM E 119 – 11a

Test Report No: WP-1950

Assignment No: K-1089

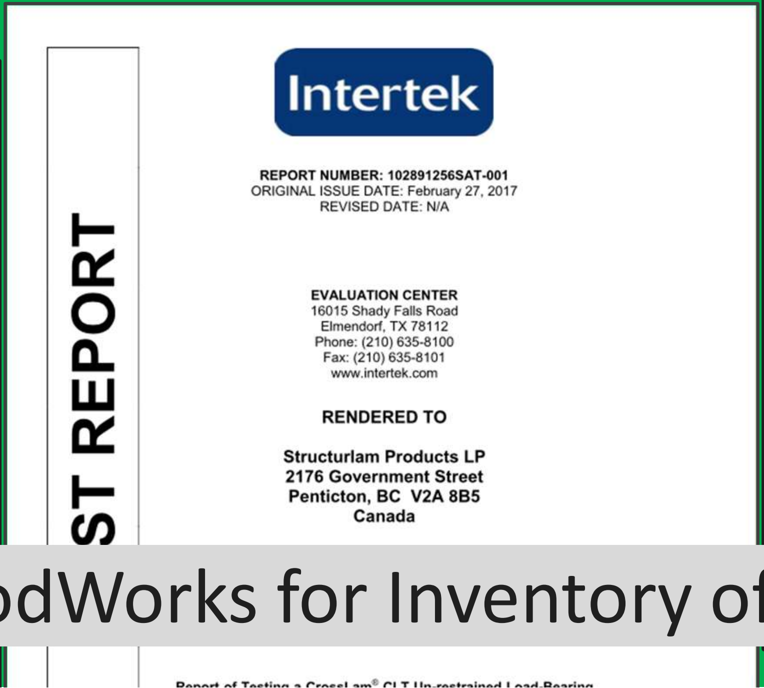
Subject Material: Cross-Laminated Timber and Gypsum Board Wall Assembly (Load-Bearing)

Test Date: October 4, 2012

Report Date: October 15, 2012

Prepared by: Michael J. Rizzo, Test Engineer

Reviewed by: Robert J. Menchetti


ST REPORT

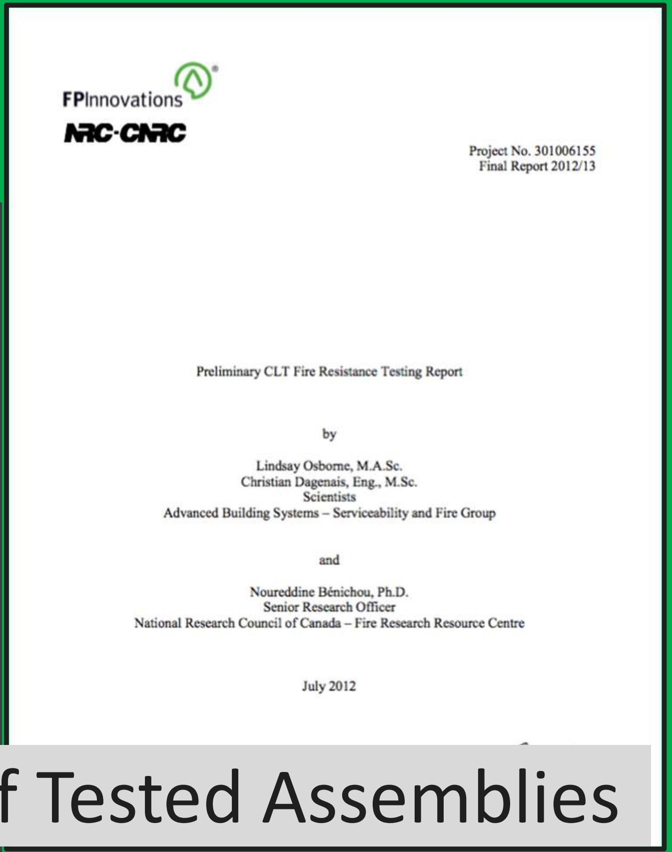
Intertek

REPORT NUMBER: 102891256SAT-001
ORIGINAL ISSUE DATE: February 27, 2017
REVISED DATE: N/A

EVALUATION CENTER
16015 Shady Falls Road
Elmendorf, TX 78112
Phone: (210) 635-8100
Fax: (210) 635-8101
www.intertek.com

RENDERED TO

Structurlam Products LP
2176 Government Street
Penticton, BC V2A 8B5
Canada


FPInnovations

NRC-CNRC

Project No. 301006155
Final Report 2012/13

Preliminary CLT Fire Resistance Testing Report

by

Lindsay Osborne, M.A.Sc.
Christian Dagenais, Eng., M.Sc.
Scientists
Advanced Building Systems – Serviceability and Fire Group

and

Noureddine Bénichou, Ph.D.
Senior Research Officer
National Research Council of Canada – Fire Research Resource Centre

July 2012

See WoodWorks for Inventory of Tested Assemblies

Additional Resources

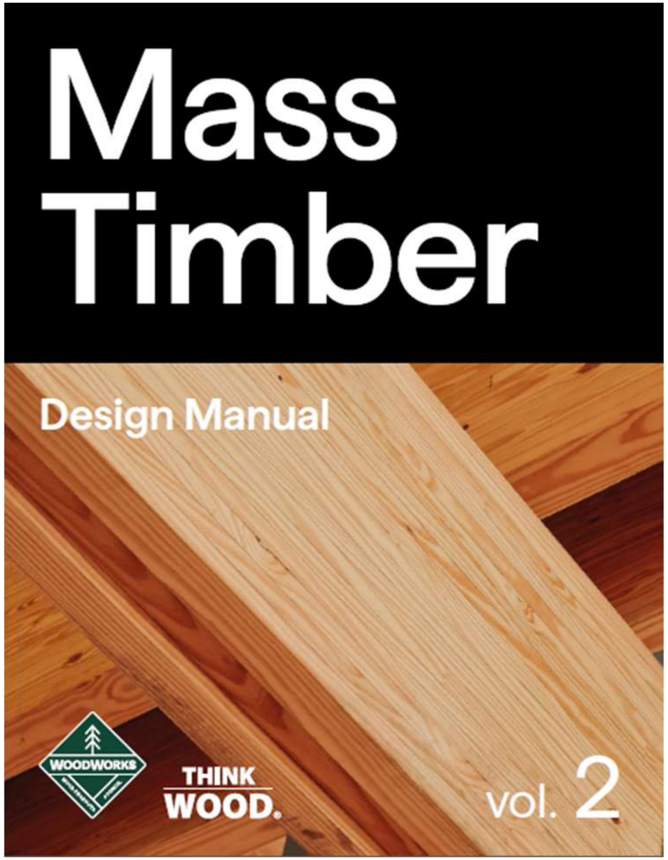
NEW MASS TIMBER DESIGN MANUAL

110+ pages of mass timber technical resources, case studies and more. Links directly to many additional resources.

Jointly Produced By:

WoodWorks™
WOOD PRODUCTS COUNCIL

THINK
WOOD®



https://info.thinkwood.com/masstimberdesignmanual

Additional Resources – woodworks.org

WoodWorks™
WOOD PRODUCTS COUNCIL

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
have been permitted in U.S. buildings due to their inheren
fire-resistance properties. The predictability of wood's ch
rate has been well-established for decades and has long
recognized in building codes and standards.

Today, one of the exciting trends in building design is the
growing use of mass timber—i.e., large solid wood panel
products such as cross-laminated timber (CLT) and nail-
laminated timber (NLT)—for floor, wall and roof construct
Like heavy timber, mass timber products have inherent
fire resistance that allows them to be left exposed and st
achieve a fire-resistance rating. Because of their strength
dimensional stability, these products also offer an alterna
steel, concrete, and masonry for many applications, but h
much lighter carbon footprint. It is this combination of ex
structure and strength that developers and designers acr

Inventory of Fire-Resistance Tested Mass Timber Assemblies

Table 1: North American Fire Resistance Tests of Mass Timber Floor / Roof Assemblies

WoodWorks™
WOOD PRODUCTS COUNCIL

CLT Panel	Manufacturer	CLT Grade or Major x Minor Grade	Ceiling Protection	Panel Connection	Floor Topping	Load Rating	Fire Resistance Achieved (Hours)	Source	Testing Lab
3-ply CLT (114mm 4.488 in)	Nordic	SPF 1650 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
3-ply CLT (105mm 4.133 in)	Structurlam	SPF #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
5-ply CLT (175mm 6.875")	Nordic	E1	None	Topside Spline	2 staggered layers of 1/2" cement boards	Loaded, See Manufacturer	2	2	NRC Fire Laboratory March 2016
5-ply CLT (175mm 6.875")	Nordic	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
5-ply CLT (175mm 6.875")	Nordic	E1	None	Topside Spline	3/4 in. proprietary gypcrete over Maxxon acoustical mat	Reduced 50% Moment Capactiy	1.5	3	UL
5-ply CLT (175mm 6.875")	Nordic	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
5-ply CLT (175mm 6.875")	Nordic	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
5-ply CLT (175mm 6.875")	Structurlam	E1M5 MSR 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
5-ply CLT (175mm 6.875")	DR Johnson	V1	None	Half-Lap & Topside Spline	2" gypsum topping	Loaded, See Manufacturer	2	7	SwRI (May 2016)
5-ply CLT (175mm 6.875")	Nordic	SPF 1950 Fb MSR x SPF #3	None	Half-Lap	None	Reduced 59% Moment Capacity	1.5	1 (Test 3)	NRC Fire Laboratory
5-ply CLT (175mm 6.875")	Structurlam	SPF #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
7-ply CLT (245mm 9.65")	Structurlam	SPF #1/#2 x SPF #1/#2	None	Half-Lap	None	Unreduced 101% Moment Capacity	2.5	1 (Test 7)	NRC Fire Laboratory

CLT Shear Wall and Diaphragm Design Under the 2021 SDPWS

Apex Plaza / Courtesy William McDonough + Partner

Course Description

The use of cross-laminated timber (CLT) panels for structural floor and roof assemblies has seen incredible growth in the U.S. over the past decade. However, CLT's use as part of a seismic or wind force-resisting system—either as a shear wall or a diaphragm—has only recently been codified. Up until now, this has required the use of the Alternate Materials and Methods Request (AMMR) process for CLT lateral force-resisting system design. This presentation will introduce the new provisions for CLT shear wall and diaphragm design contained in the American Wood Council's 2021 Special Design Provisions for Wind and Seismic (SDPWS), including detailing and design requirements, and the range of seismic response modification coefficients (e.g., "R" values) recognized for CLT shear wall design in ASCE 7-22.

Learning Objectives

1. Develop an understanding of the design challenges related to using CLT for wind and seismic resistance while meeting the intent of the 2021 IBC/2022 CBC.
2. Discuss the new provisions in the 2021 Special Design Provisions for Wind and Seismic (SDPWS) applicable to all lateral systems.
3. Understand the new detailing options and path to code acceptance of several CLT shear wall systems.
4. Review the engineering design requirements for using CLT floor and roof assemblies as horizontal diaphragms for wind and seismic resistance.

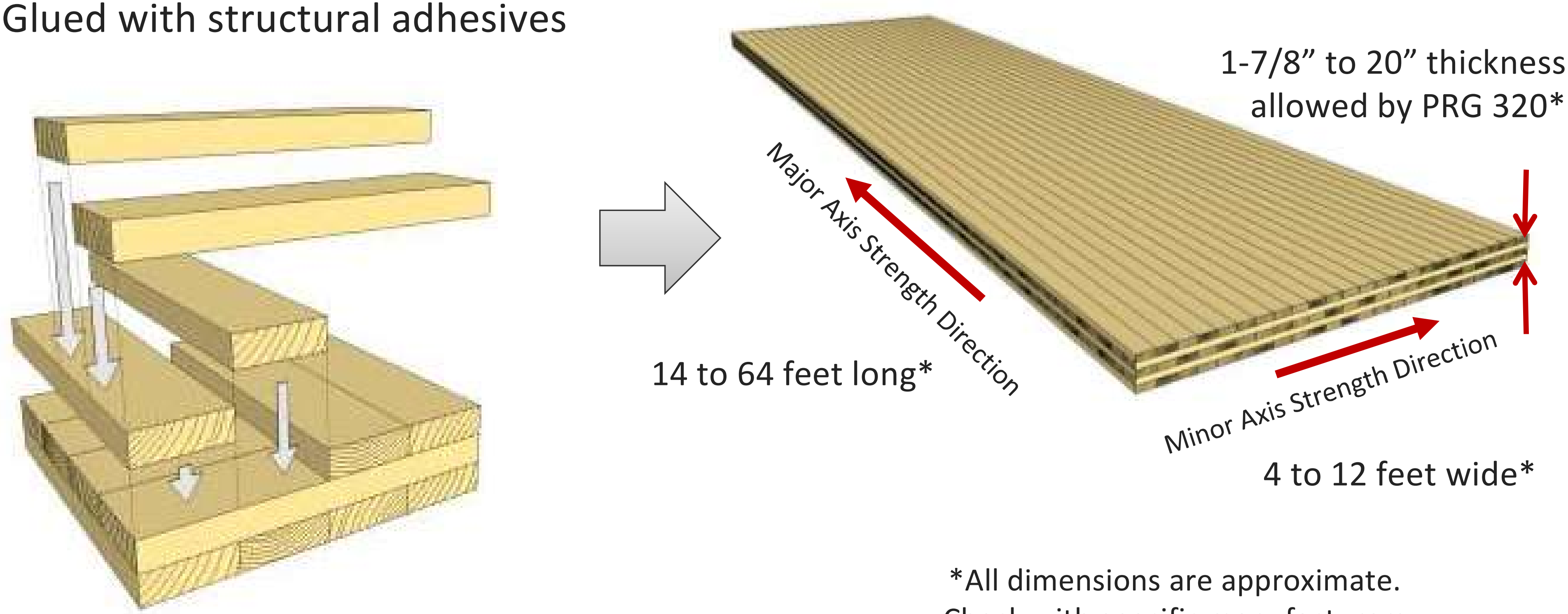
What is CLT?

Solid-sawn or Structural Composite Lumber (SCL) laminations

3 layers minimum

Each layer rotated 90° (sim. to plywood sheathing)

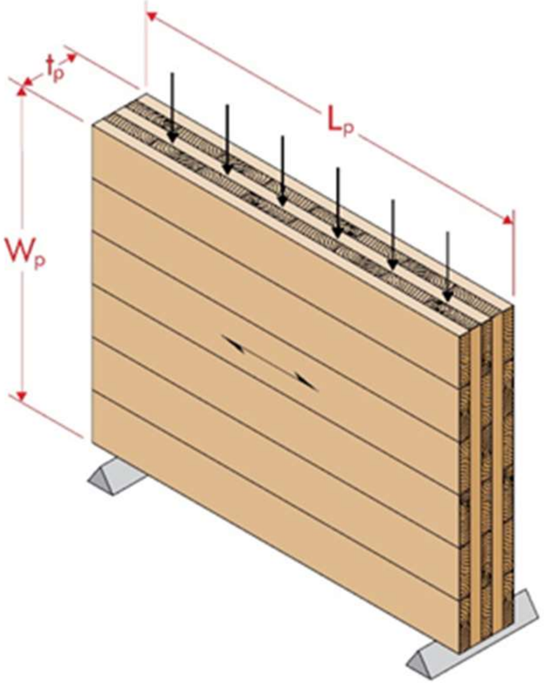
Glued with structural adhesives



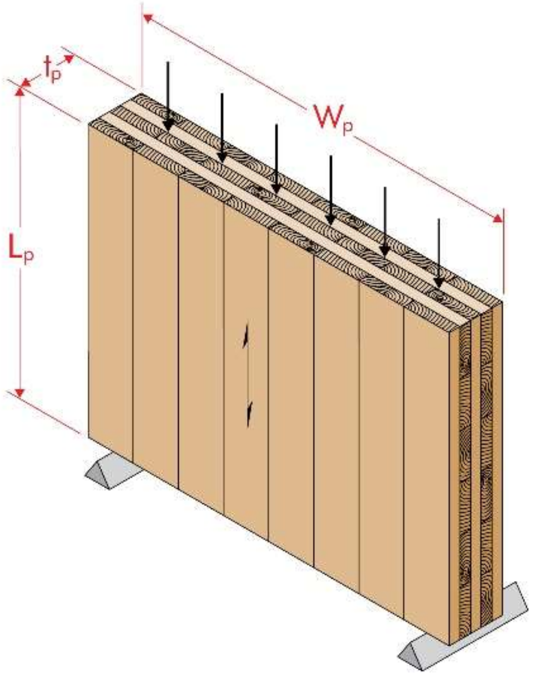
*All dimensions are approximate.
Check with specific manufacturers

CLT Lateral Systems

EDGEWISE Panel Loading



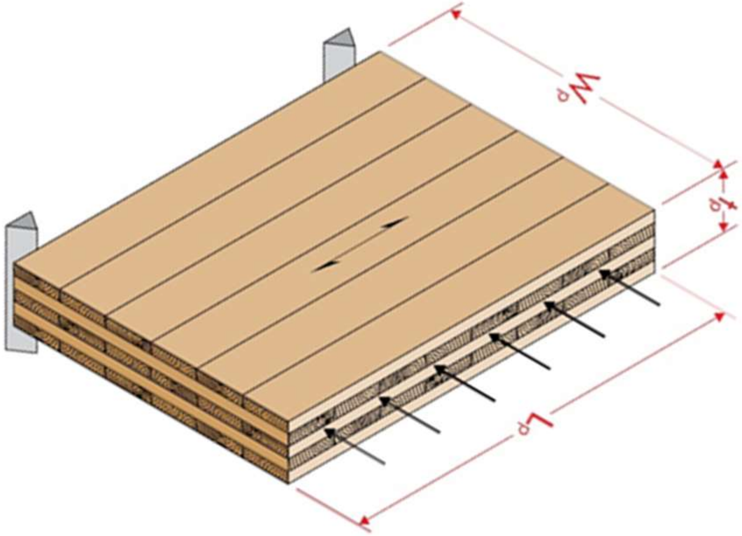
Span in MAJOR Strength Direction



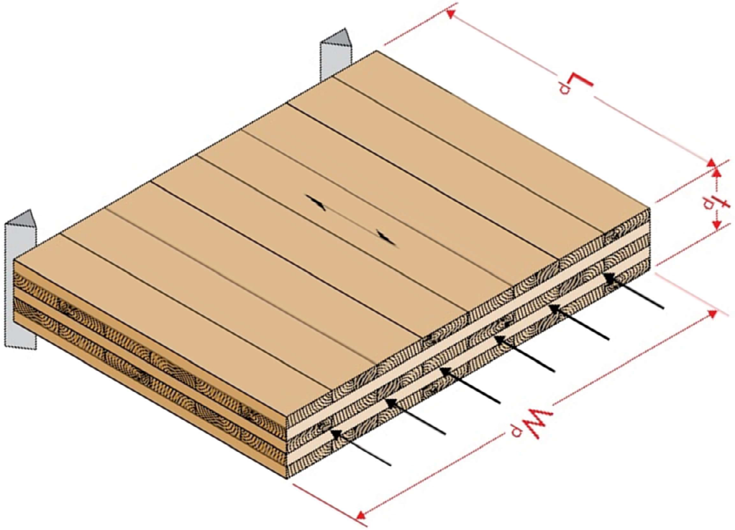
Span in MINOR Strength Direction

Source: PRG 320

EDGEWISE Panel Loading



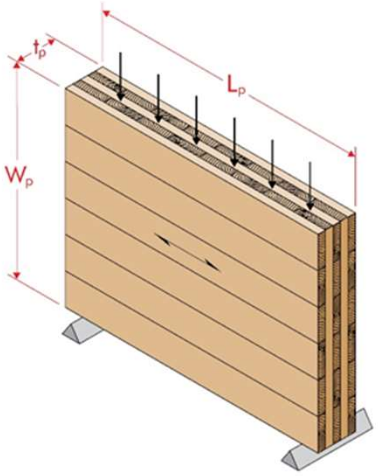
Span in MAJOR Strength Direction



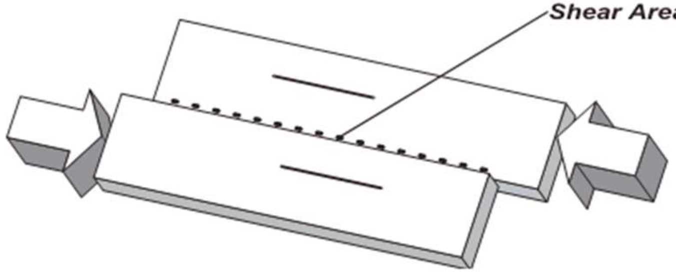
Span in MINOR Strength Direction

Source: PRG 320

Shear Force Terminology



Source: PRG 320



Source: 2018 NDS Commentary

Through-the-Thickness Shear
In-plane Shear Forces
EDGEWISE Shear in PRG 320-2018

2018 NDS: $F_v(t_v)$
PRG 320: $F_{v,e,0}\, t_p$ & $F_{v,e,90}\, t_p$

CLT In-Plane (Edgewise) 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*

145 to 290 PSI Edgewise Shear Capacity
= 1.7 to 3.5 kips/ft (ASD)
per inch of thickness!

Consult with manufacturers for values

Multiply by ***Cd = 1.6***
for short term ASD strength

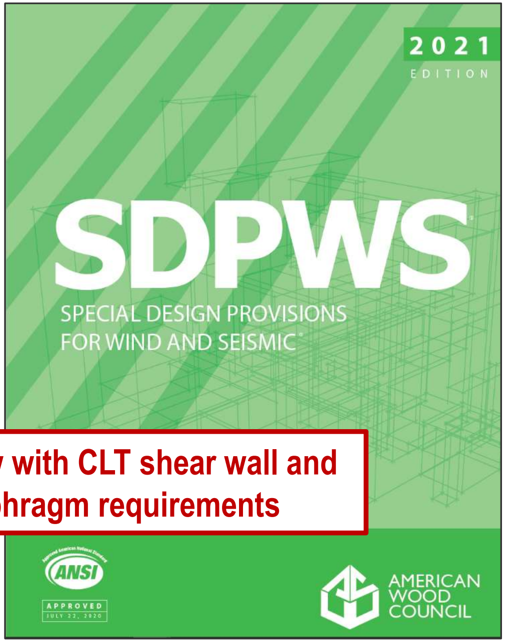
Reference Design Values for Nordic X-Lam Listed in Table 1 (For Use in

			Major Strength Direction		Minor Strength Direction	
			$F_{v,e,0}$[a] (psi)	$G_{e,0}\,t_p$[d] (10^6 lbf/ft)	$F_{v,e,90}$[a] (psi)	$G_{e,90}\,t_p$[d] (10^6 lbf/ft)
			155[b]	1.36	190[b]	1.36
			155	1.52	190[b]	1.52
			155	1.79	190	1.79
			185[c]	2.23	215[c]	2.23
	140-4s	5 1/2	145	2.39	190[b]	2.39
	143-5s	5 5/8	185[c]	2.44	215[c]	2.44
	175-5s	6 7/8	185	2.99	215	2.99
E1	197-7s	7 3/4	155[b]	3.37	215[c]	3.37
	213-7l	8 3/8	185[c]	3.64	215[c]	3.64
	220-7s	8 5/8	185[c]	3.75	215[c]	3.75
	244-7s	9 5/8	185[c]	4.18	215[c]	4.18
	244-7l	9 5/8	185[c]	4.18	215[c]	4.18
	267-9l	10 1/2	155[b]	4.56	215[c]	4.56
	314-9l	12 3/8	185[c]	5.38	215[c]	5.38

Source: *APA Product Report PR-L306*

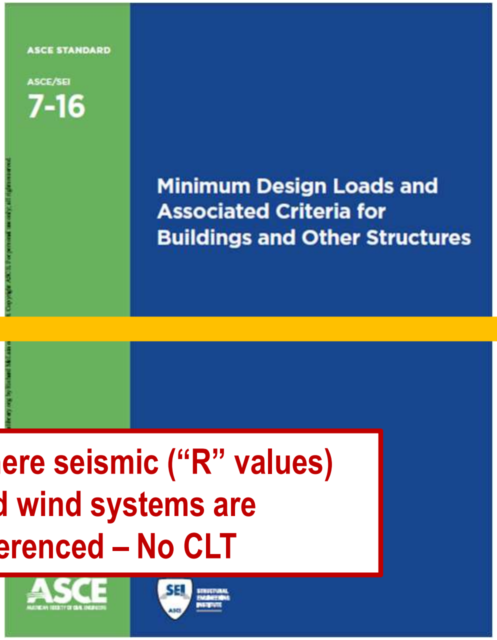
CLT Panels can have > 9 kips / ft in-plane shear capacity

CLT in the 2021 IBC/2022 CBC (Lateral)



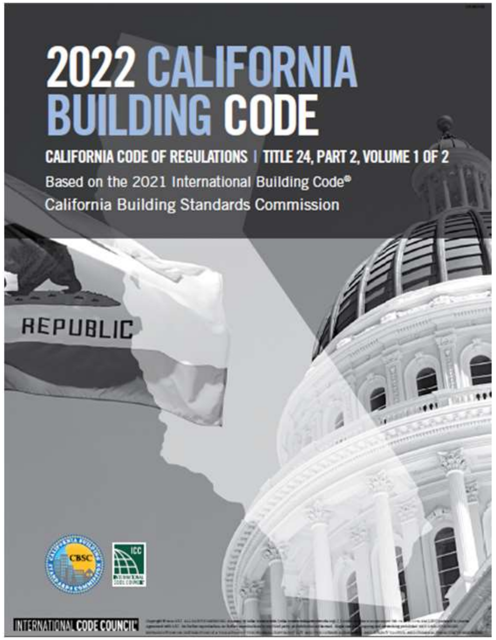
Now with CLT shear wall and diaphragm requirements

2021 SDPWS



Where seismic ("R" values) and wind systems are referenced – No CLT

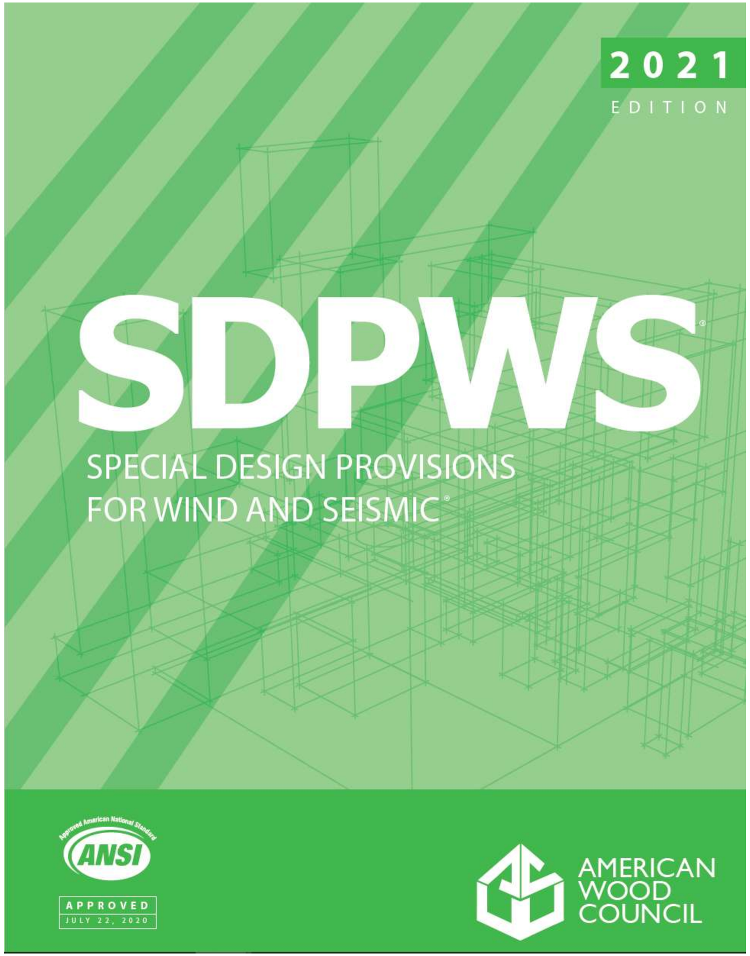
ASCE/SEI 7-16



2022 CBC (2021 IBC similar)

CLT lateral systems from the 2021 SDPWS (not "R" values for shear wall design) are referenced in the 2021 IBC/2022 CBC

2021 Special Design Provisions for Wind and Seismic

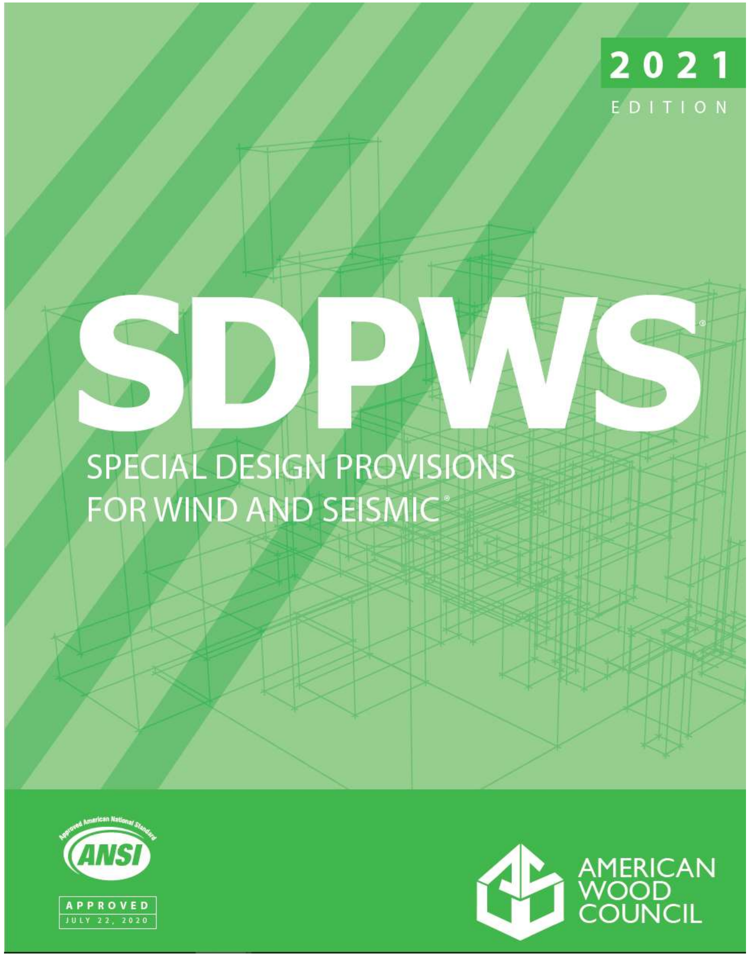


Top Changes Relevant to CLT Lateral Systems:

- New unified nominal shear capacity
- New CLT Shear Wall requirements
- New CLT Diaphragm requirements

Free (view only) version at awc.org

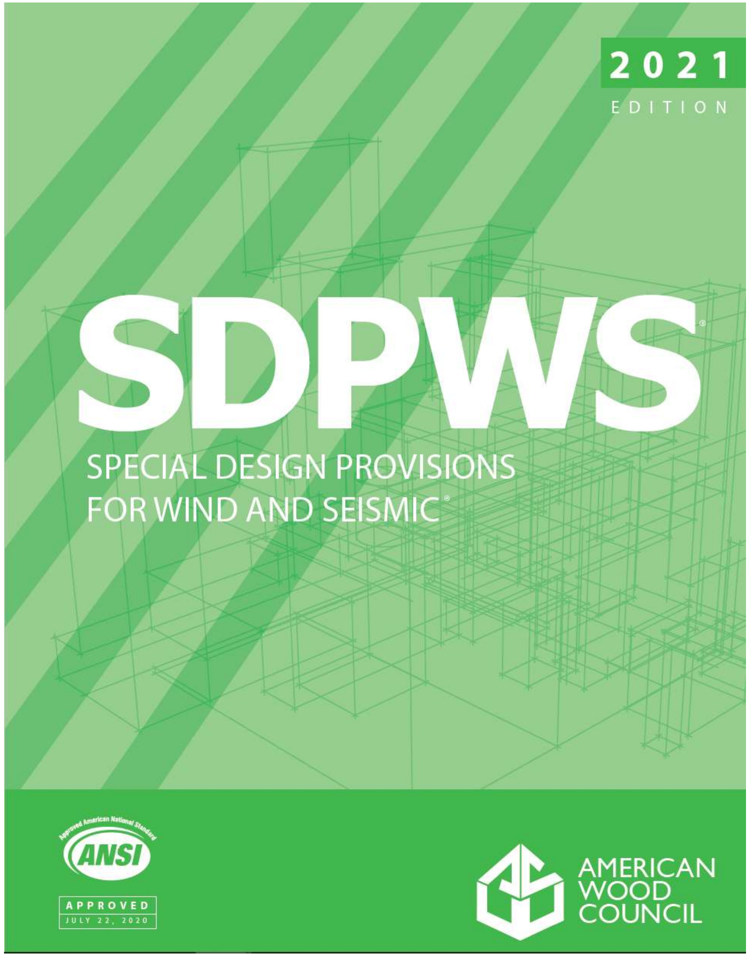
2021 Special Design Provisions for Wind and Seismic



Top Changes Relevant to CLT Lateral Systems:

- **New unified nominal shear capacity**
- New CLT Shear Wall requirements
- New CLT Diaphragm requirements

2021 SDPWS – Unified Nominal Shear Capacity



For Wood Structural Panel (WSP) shear walls and diaphragms, the 2015 SDPWS has two nominal shear capacities:

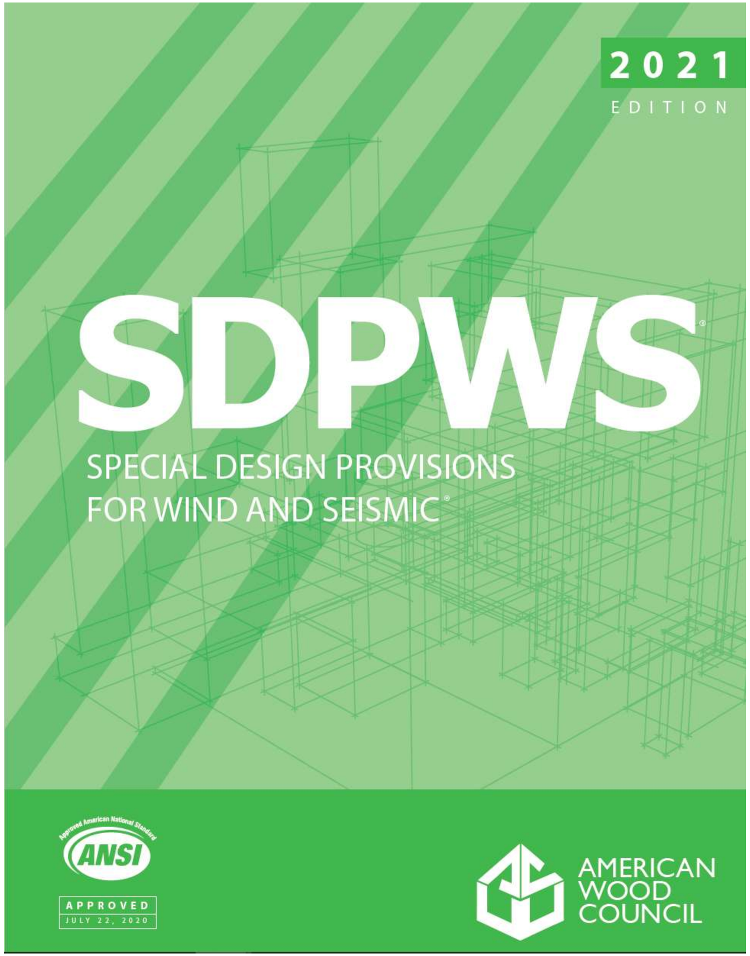
v_s Nominal shear capacity for seismic loads

v_w Nominal shear capacity for wind loads

The 2021 SDPWS has one nominal shear capacity for both wind and seismic loads (for all systems such as WSP and CLT):

v_n Nominal shear capacity

2021 SDPWS – Unified Nominal Shear Capacity



To calculate the ASD or LRFD shear capacity, the 2021 SDPWS has different reduction factors for wind and seismic

Loading	ASD Design Capacity v_n / Ω_D	LRFD Design Capacity $\phi_D v_n$
Seismic	$v_n/2.8$	$0.50\ v_n$
Wind	$v_n/2.0$	$0.80\ v_n$

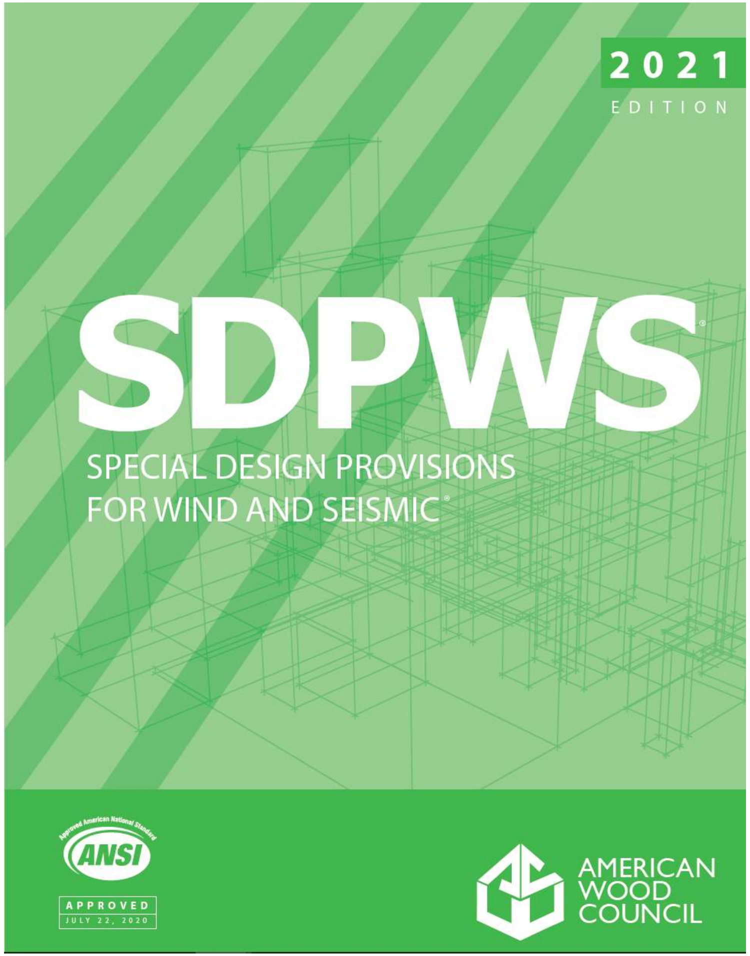
Source: 2021 SDPWS Section 4.1.4

CLT Shear Wall Design

CLT Shear Wall Design

Denver University Burwell Center for Career Achievement Photo Credit: WoodWorks

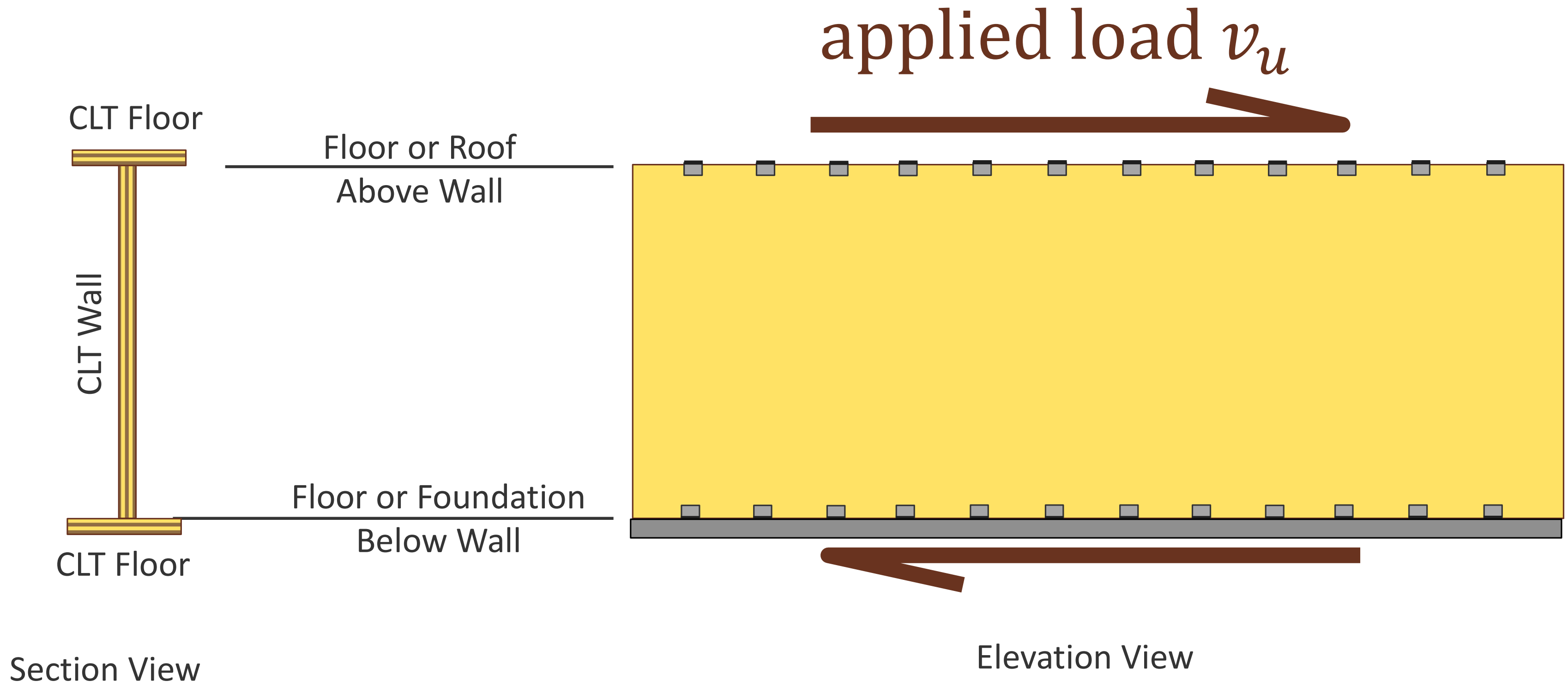
2021 Special Design Provisions for Wind and Seismic



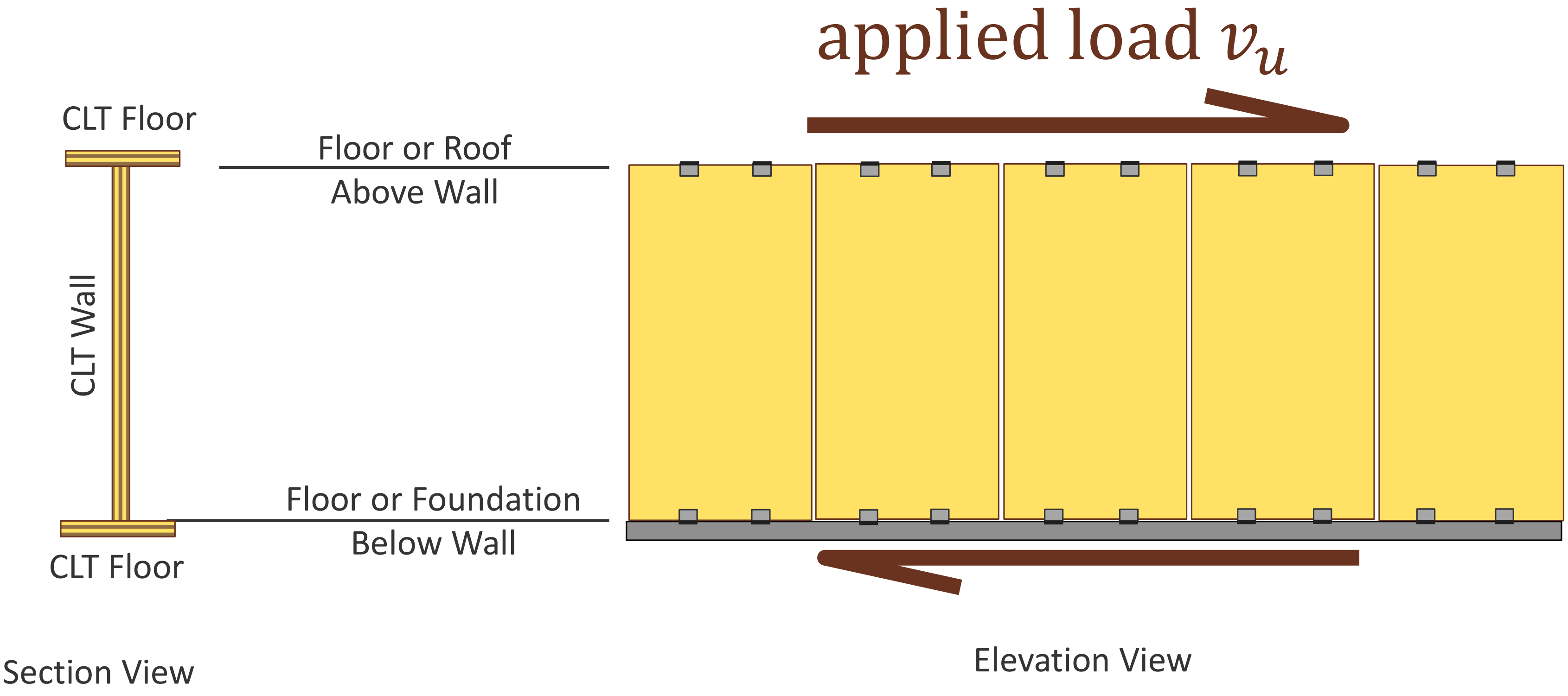
Top Changes Relevant to CLT Lateral Systems:

- New unified nominal shear capacity
- **New CLT Shear Wall requirements**
- New CLT Diaphragm requirements

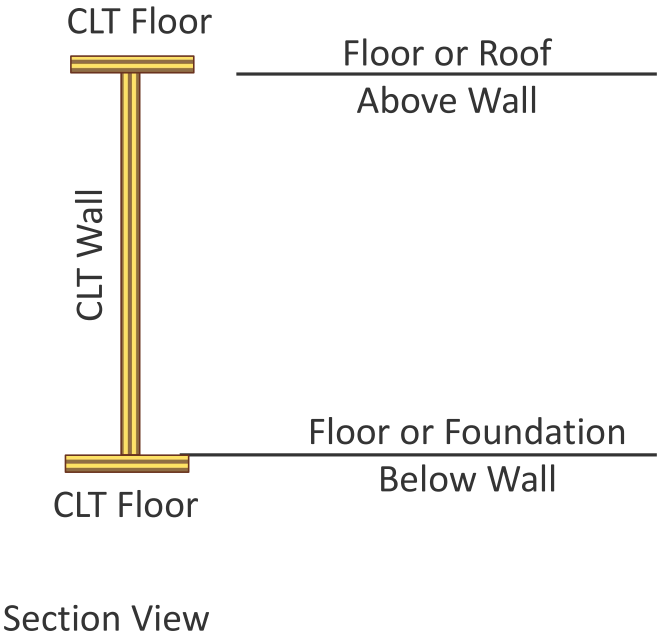
2021 SDPWS – CLT Shear Wall requirements

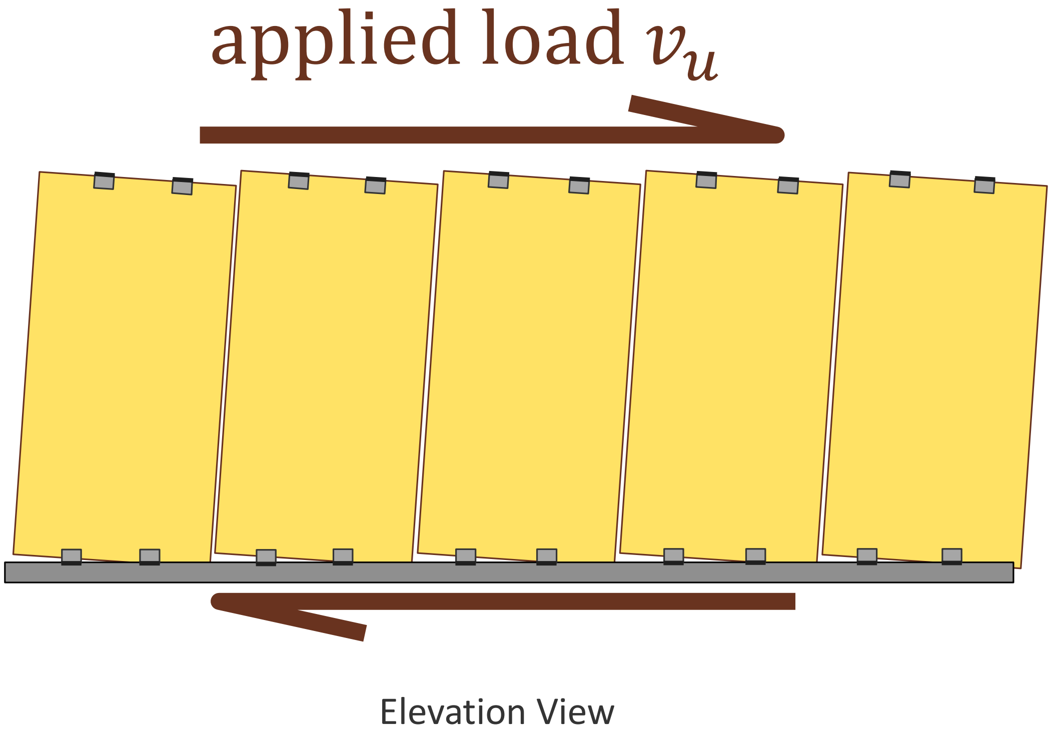


2021 SDPWS – CLT Shear Wall requirements

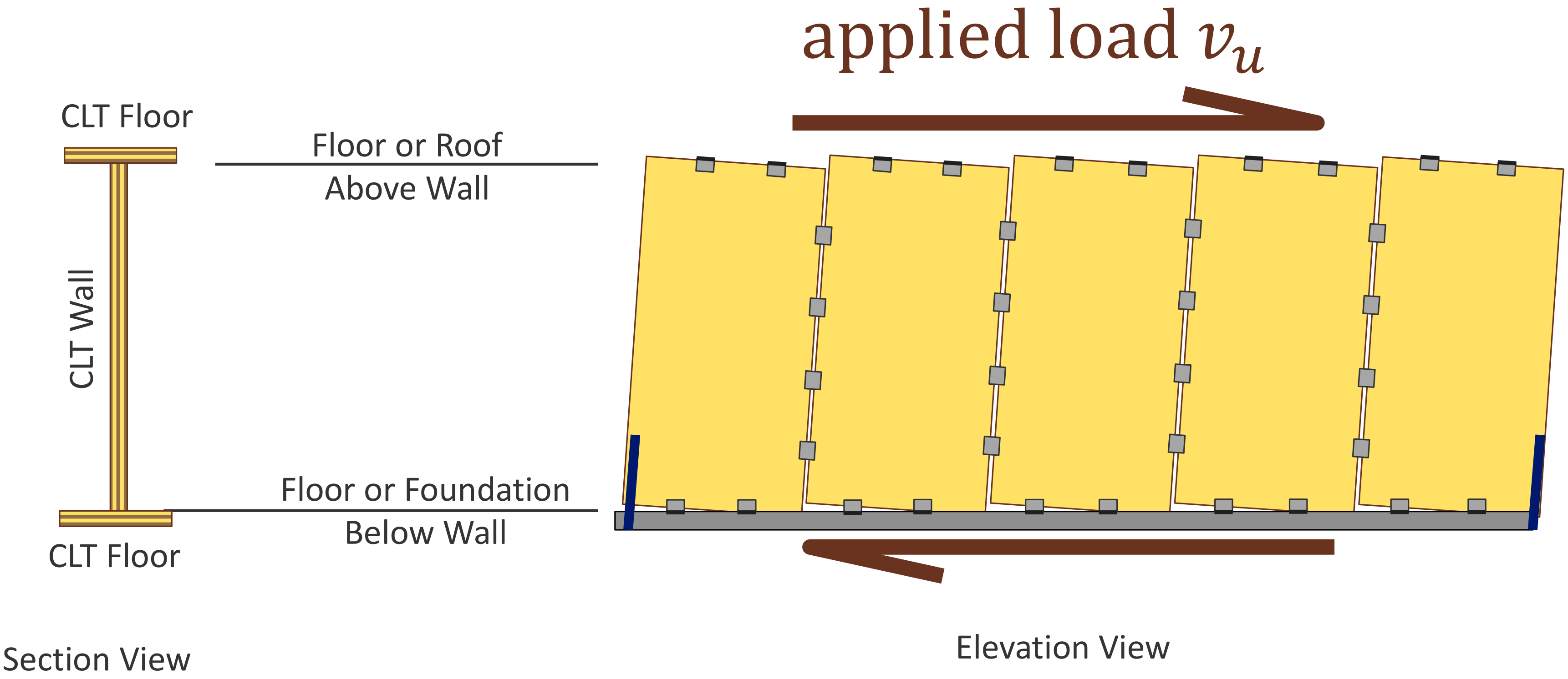


2021 SDPWS – CLT Shear Wall requirements



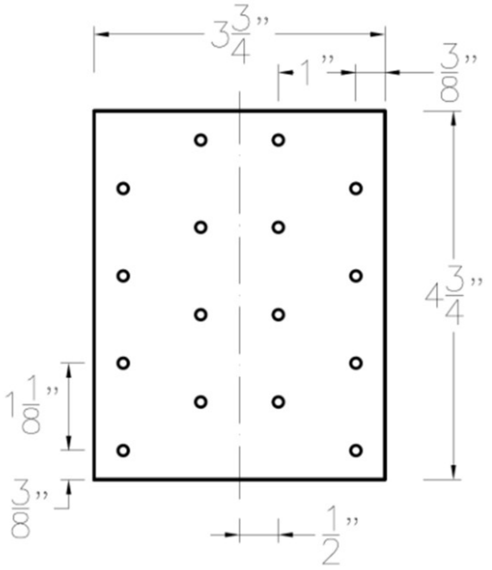


2021 SDPWS – CLT Shear Wall requirements



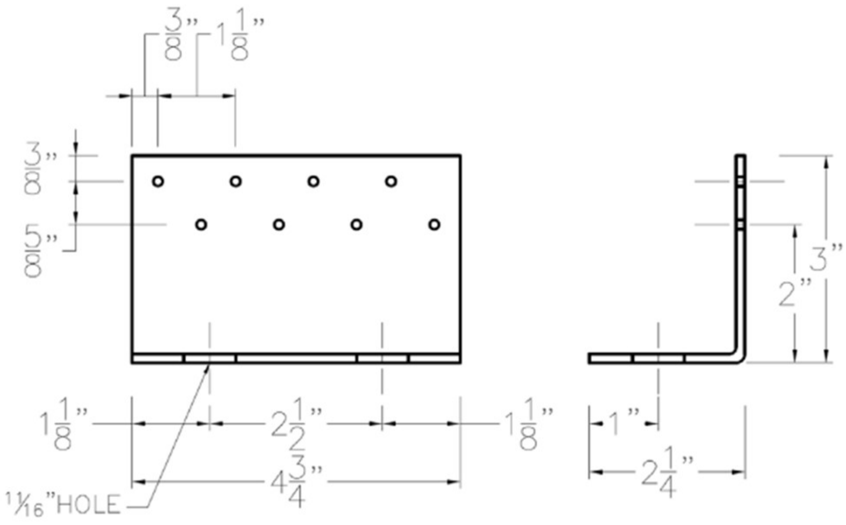
2021 SDPWS – CLT Shear Wall requirements

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

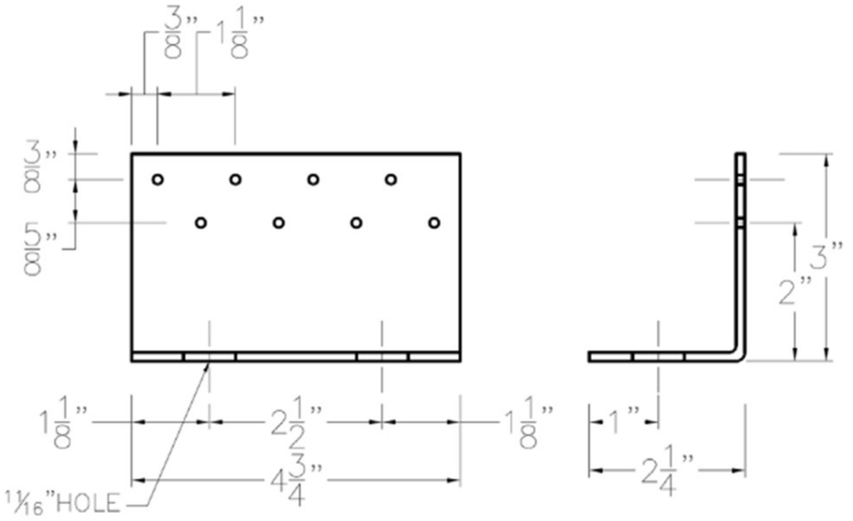
Panel to Platform Connection



Same steel plate material and nails plus
(2) 5/8” Ø bolts or lag screws to roof, floor or foundation

2021 SDPWS – CLT Shear Wall requirements

Panel to Platform Connection



Nominal shear capacity of connector

v_n = 2605 C_G [lbs] per angle connector

C_G adjusts for specific gravity, G of CLT

C_G = 1.0	for G ≥ 0.42
= 0.86	for G = 0.35
= 1.0 – 2 (0.42-G)	for 0.42 > G > 0.35

Nominal unit shear capacity:

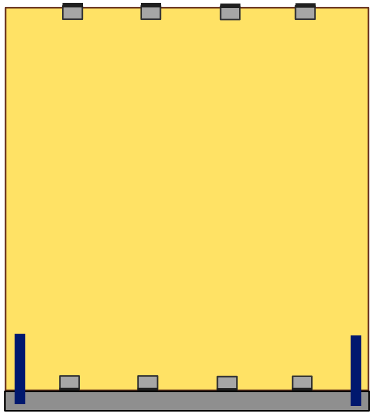
v_n = n (2605 / b_s) C_G [lbs/ft]

2021 SDPWS – CLT Shear Wall requirements

(platform or balloon-framed)

CLT Shear Walls

not meeting 2021 SDPWS Appendix B

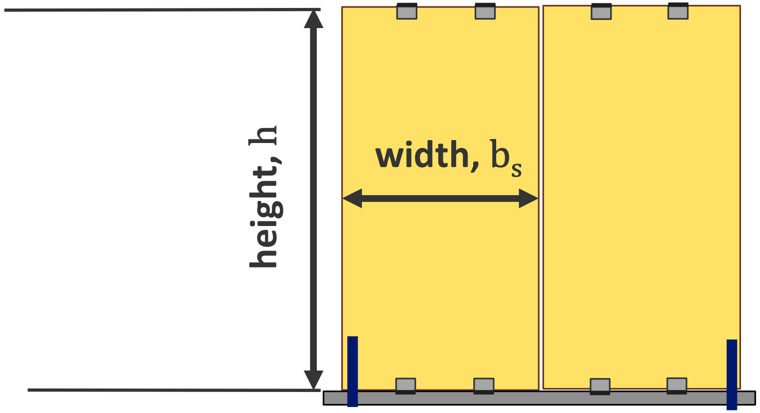


Seismic Design Category A or B only (2021 SDPWS 4.6.3)

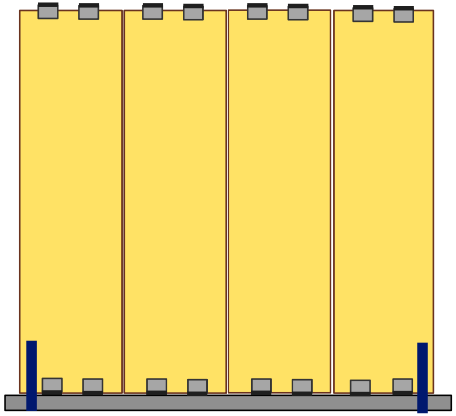
(platform-framed only)

CLT Shear Walls

meeting 2021 SDPWS Appendix B



Panel aspect ratios
$2 \leq \mathbf{h/b_s} \leq 4$



Shear resistance provided by high aspect ratio panels only (2021 SDPWS B.3.7)

Panel aspect ratios
$\mathbf{h/b_s} = 4$

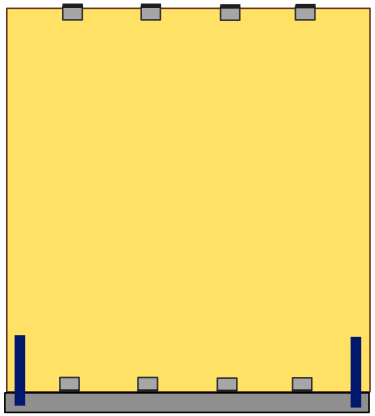
What "R" value can I use?

2021 SDPWS – "R" Values for CLT Shear Walls

(platform or balloon framed)

CLT Shear Walls

not meeting 2021 SDPWS Appendix B



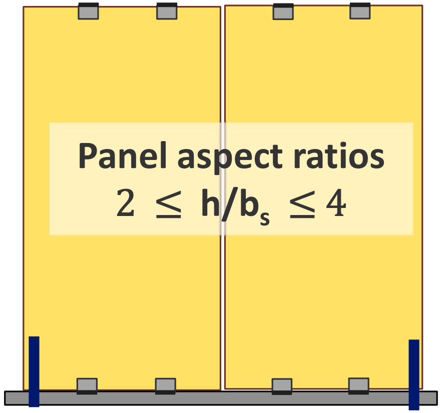
"R" = 1.5

C_d=1.5, Ω_o=2.5, max. ht.=65'
(2021 SDPWS 4.6.3)

(platform-framed only)

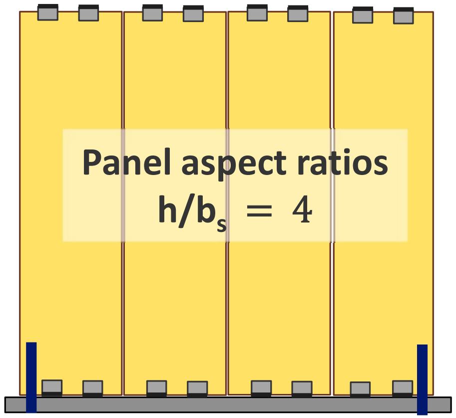
CLT Shear Walls

meeting 2021 SDPWS Appendix B



"R" = 3.0

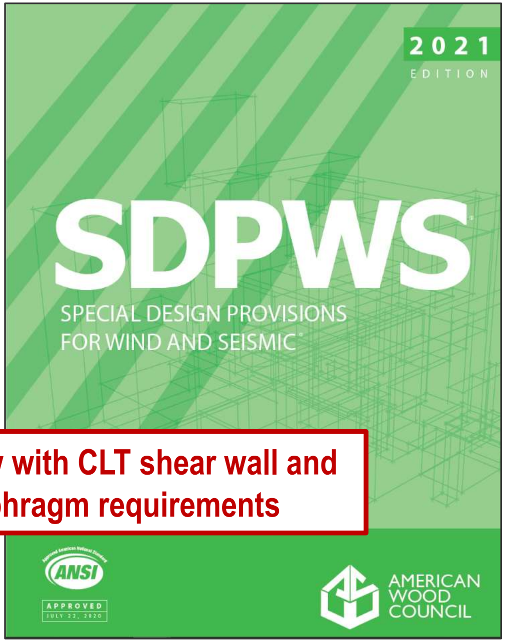
C_d=3.0, Ω_o=3.0, max. ht.=65'
(ASCE 7-22)



"R" = 4.0

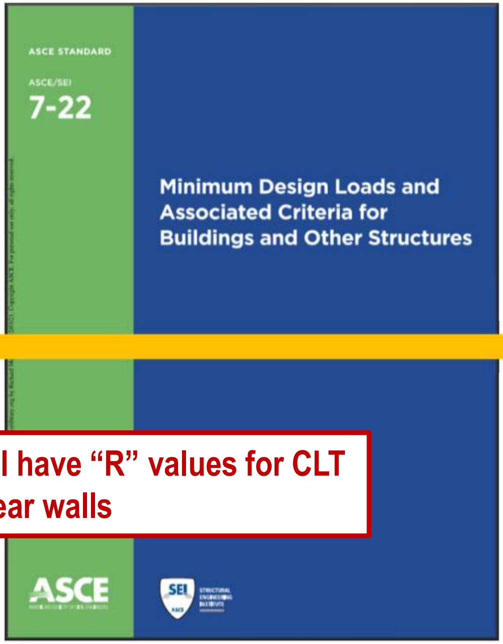
C_d=4.0, Ω_o=3.0, max. ht.=65'
(ASCE 7-22)

CLT in the 2024 IBC/2025 CBC (Lateral)



Now with CLT shear wall and diaphragm requirements

2021 SDPWS



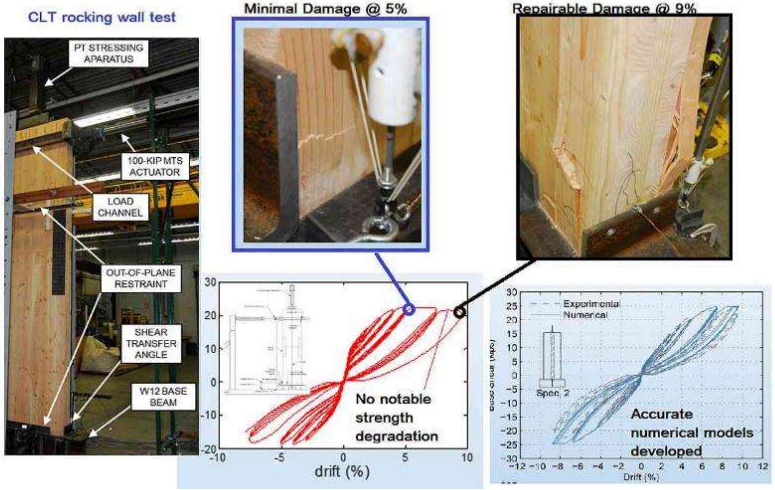
Will have "R" values for CLT shear walls

ASCE/SEI 7-22

2025 CBC (2024 IBC similar)

CLT lateral systems will be fully recognized in the 2024 IBC/2025 CBC

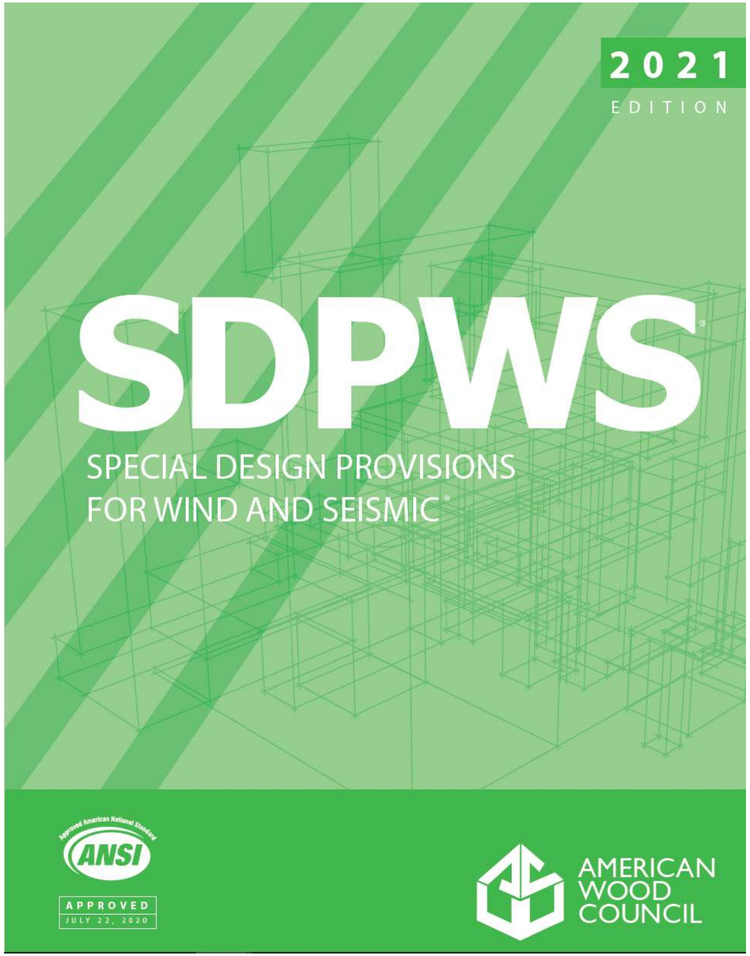
CLT Post-Tensioned Rocking Shear Wall System Tests



Source: S. PEI et al. http://nheritallwood.mines.edu/

CLT Diaphragm Design

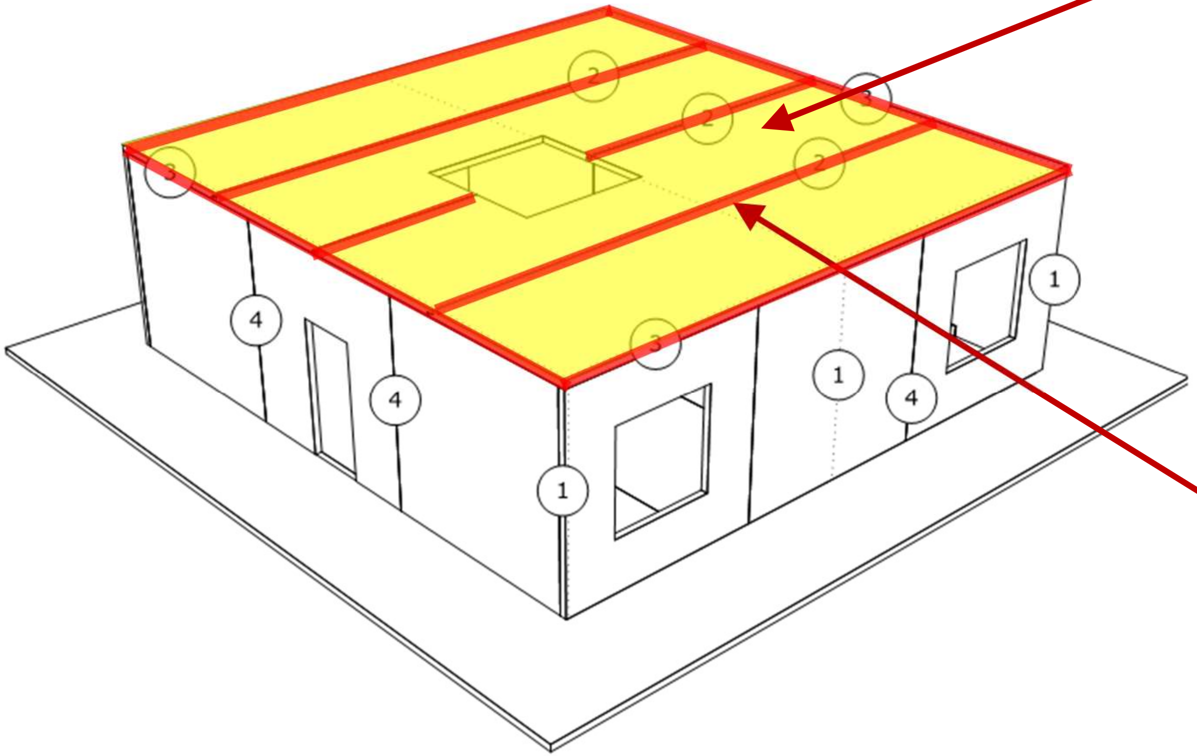
2021 Special Design Provisions for Wind and Seismic



Top Changes Relevant to CLT Lateral Systems:

- New unified nominal shear capacity
- New CLT Shear Wall requirements
- **New CLT Diaphragm requirements**

CLT Diaphragms



Strength of CLT should never govern

Strength of connections (covered by NDS and proprietary fastener Evaluation Reports) governs design

2021 Special Design Provisions for Wind and Seismic

4.5 Cross-Laminated Timber (CLT) Diaphragms

4.5.1 Application Requirements

CLT diaphragms shall be permitted to be used to resist lateral forces provided the deflection in the plane of the diaphragm, as determined by calculations, tests, or analogies drawn therefrom, does not exceed the maximum permissible deflection limit of attached load distributing or resisting elements. Permissible deflection shall be that deflection that will permit the diaphragm and any attached elements to maintain their structural integrity and continue to support their prescribed loads as determined by the applicable building code or standard.

4.5.2 Deflection

CLT diaphragm deflection shall be determined using principles of engineering mechanics.

4.5.3 Unit Shear Capacity

CLT diaphragms shall be designed in accordance with principles of engineering mechanics using design values for wood members and connections in accordance with NDS provisions.

The nominal unit shear capacity, v_n, of CLT diaphragms shall be based on the nominal shear capacity for dowel-type fastener connections used to transfer diaphragm shear forces, as calculated per 4.5.4, Item 1. ASD allowable shear capacity or LRFD factored shear resistance for the CLT diaphragm and diaphragm shear connections shall be determined in accordance with 4.1.1.

4.5.4 Additional CLT Diaphragm Design Requirements

CLT diaphragms shall meet the following additional requirements:

1. The nominal shear capacity for dowel-type fastener connections used to transfer diaphragm shear forces between CLT panels and between CLT panels and diaphragm boundary elements (chords and collectors) shall be taken as 4.5Z*, where Z* is Z multiplied by all applicable NDS adjustment factors except C_D, K_F, ϕ, and λ; and Z shall be controlled by Mode III_s or Mode IV fastener yielding in accordance with NDS 12.3.1.
2. Connections used to transfer diaphragm shear forces shall not be used to resist diaphragm tension forces.
3. Wood elements, steel parts, and wood or steel chord splice connections shall be designed for 2.0 times the diaphragm forces associated with the shear forces induced from the design loads.

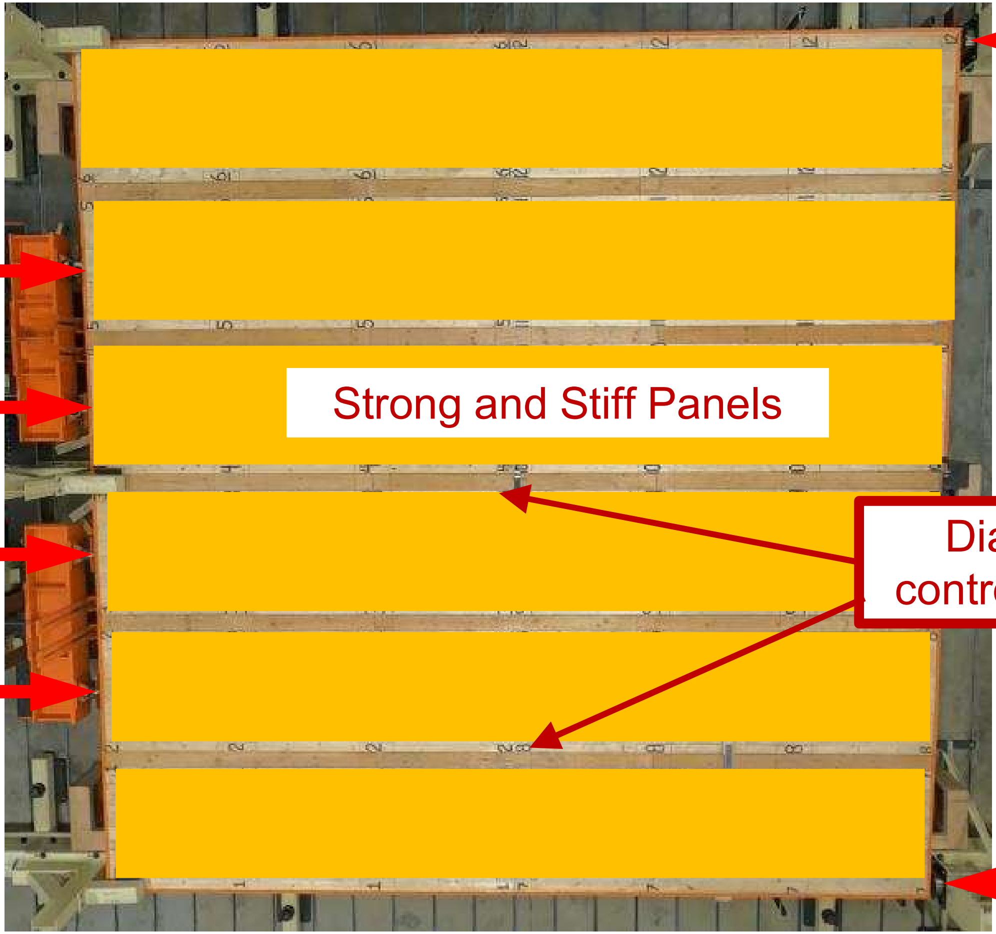
Exceptions:

1. Wood elements and wood splice connections shall be permitted to be designed for 1.5 times the diaphragm forces associated with the shear forces induced by the wind design loads.
2. Where dowel-type fasteners are used in chord splice connections and the connection is controlled by Mode III_s or Mode IV fastener yielding in accordance with NDS 12.3.1, fasteners in the connection shall be permitted to be designed for 1.5 and 1.0 times the diaphragm forces associated with the shear forces induced by the prescribed seismic and wind design loads, respectively.

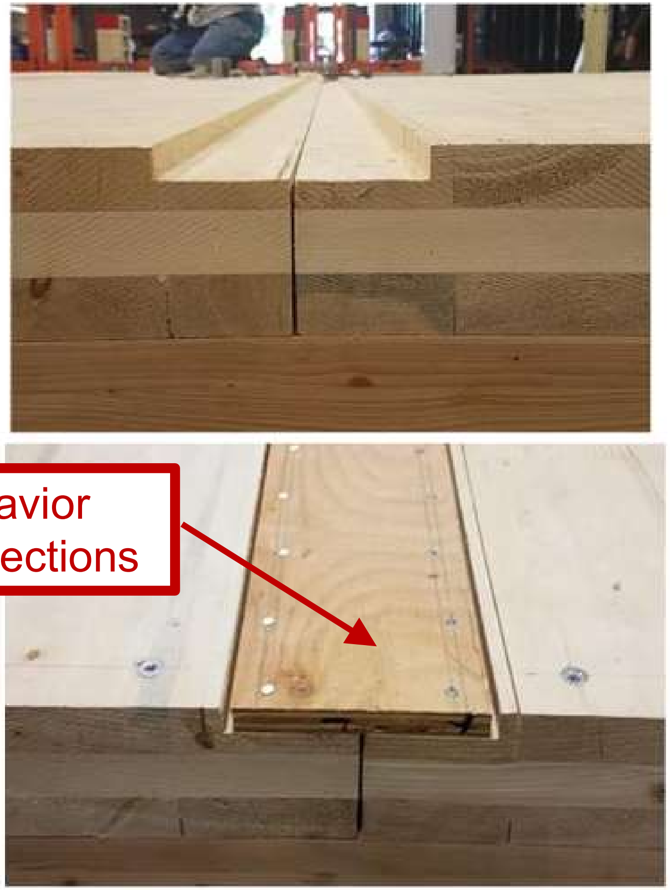
Diaphragm chord elements and chord splice connections using materials other than wood or steel shall be designed using provisions in NDS 1.4.

Only 1 page of requirements for CLT Diaphragms

24' x 24' CLT Diaphragm Test with Plywood Spline Joints by AWC



Diaphragm behavior controlled by connections



2021 Special Design Provisions for Wind and Seismic

4.5 Cross-Laminated Timber (CLT) Diaphragms

4.5.1 Application Requirements

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CLT diaphragm deflection shall be determined using principles of engineering mechanics.

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CLT diaphragms shall be designed in accordance with principles of engineering mechanics using design values for wood members and connections in accordance with NDS provisions.

The nominal unit shear capacity, v_n, of CLT diaphragms shall be based on the nominal shear capacity for dowel-type fastener connections used to transfer diaphragm shear forces, as calculated per 4.5.4, Item 1. ASD allowable shear capacity or LRFD factored shear resistance for the CLT diaphragm and diaphragm shear connections shall be determined in accordance with 4.1.1.

4.5.4 Additional CLT Diaphragm Design Requirements

CLT diaphragms shall meet the following additional requirements:

1. The nominal shear capacity for dowel-type fastener connections used to transfer diaphragm shear forces between CLT panels and between CLT panels and diaphragm boundary elements (chords and collectors) shall be taken as 4.5Z*, where Z* is Z multiplied by all applicable NDS adjustment factors except C_D, K_F, ϕ, and λ; and Z shall be controlled by Mode IIIs or Mode IV fastener yielding in accordance with NDS 12.3.1.
2. Connections used to transfer diaphragm shear forces shall not be used to resist diaphragm tension forces.
3. Wood elements, steel parts, and wood or steel chord splice connections shall be designed for 2.0 times the diaphragm forces associated with the shear forces induced from the design loads.

Exceptions:

1. Wood elements and wood splice connections shall be permitted to be designed for 1.5 times the diaphragm forces associated with the shear forces induced by the wind design loads.
2. Where dowel-type fasteners are used in chord splice connections and the connection is controlled by Mode III_s or Mode IV fastener yielding in accordance with NDS 12.3.1, fasteners in the connection shall be permitted to be designed for 1.5 and 1.0 times the diaphragm forces associated with the shear forces induced by the prescribed seismic and wind design loads, respectively.

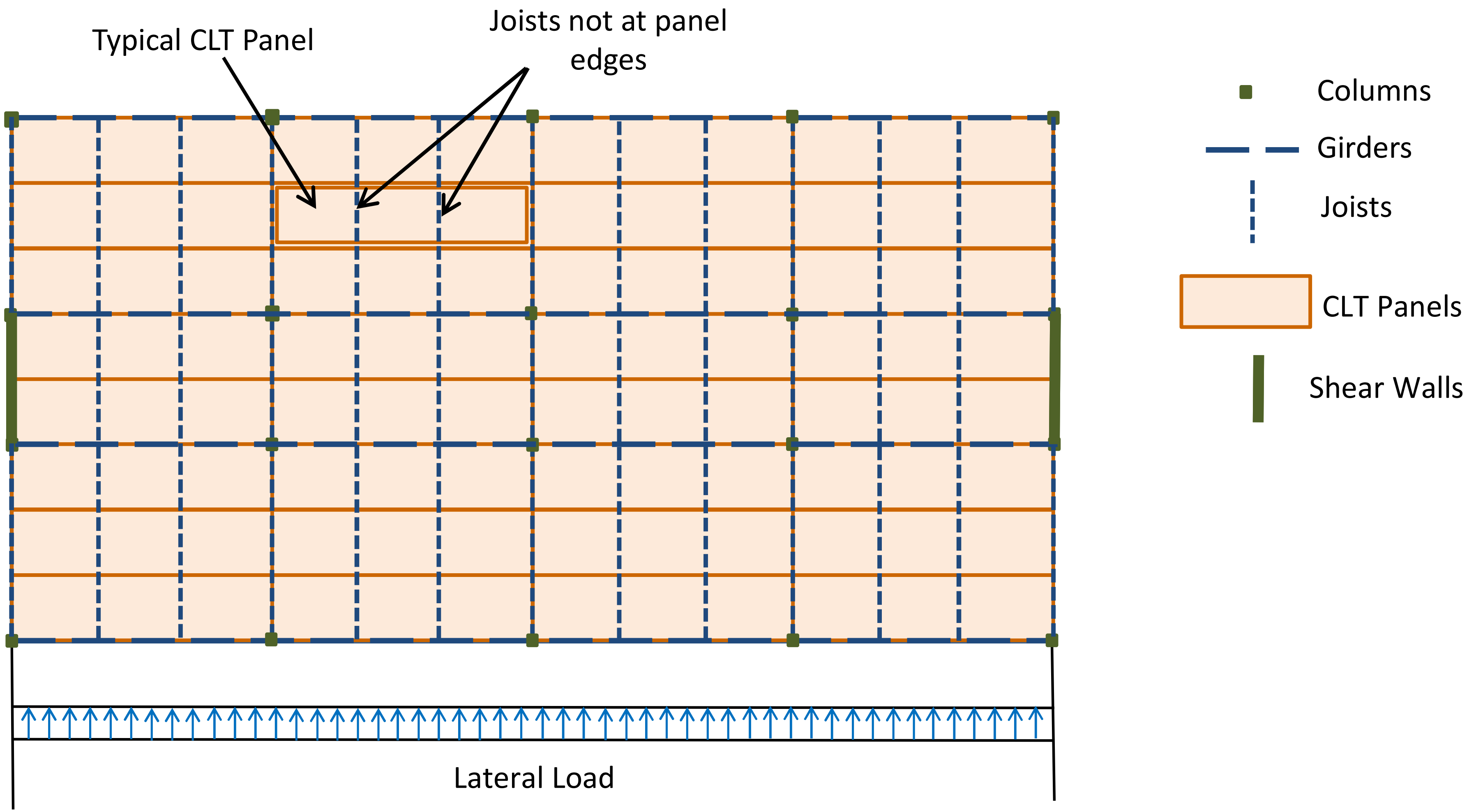
Diaphragm chord elements and chord splice connections using materials other than wood or steel shall be designed using provisions in NDS 1.4.

4.5.4 Additional CLT Diaphragm Design Requirements

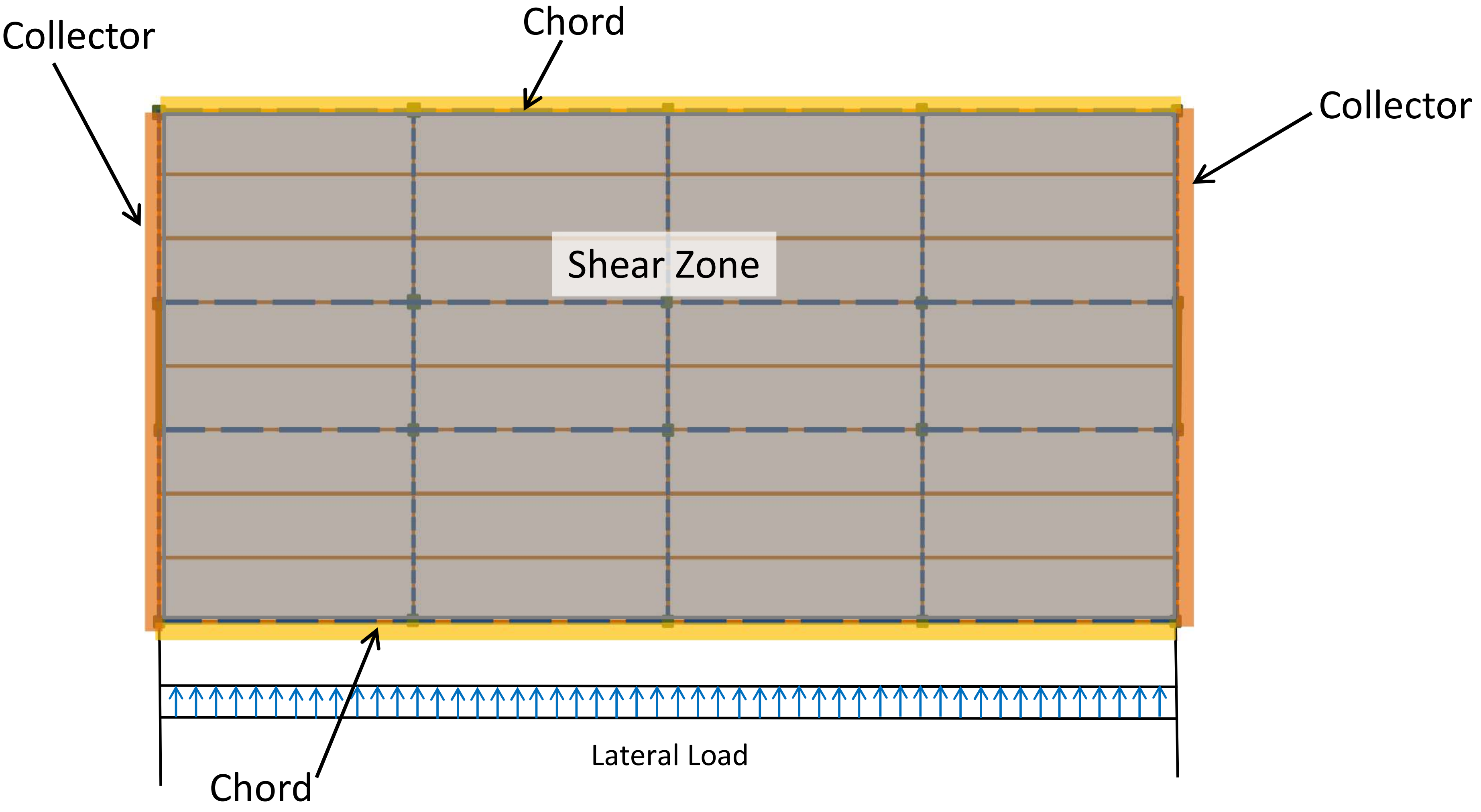
CLT diaphragms shall meet the following additional requirements:

1. The nominal shear capacity for dowel-type fastener connections used to transfer diaphragm shear forces between CLT panels and between CLT panels and diaphragm boundary elements (chords and collectors) shall be taken as 4.5Z*, where Z* is Z multiplied by all applicable NDS adjustment factors except C_D, K_F, ϕ, and λ; and Z shall be controlled by Mode IIIs or Mode IV fastener yielding in accordance with NDS 12.3.1.

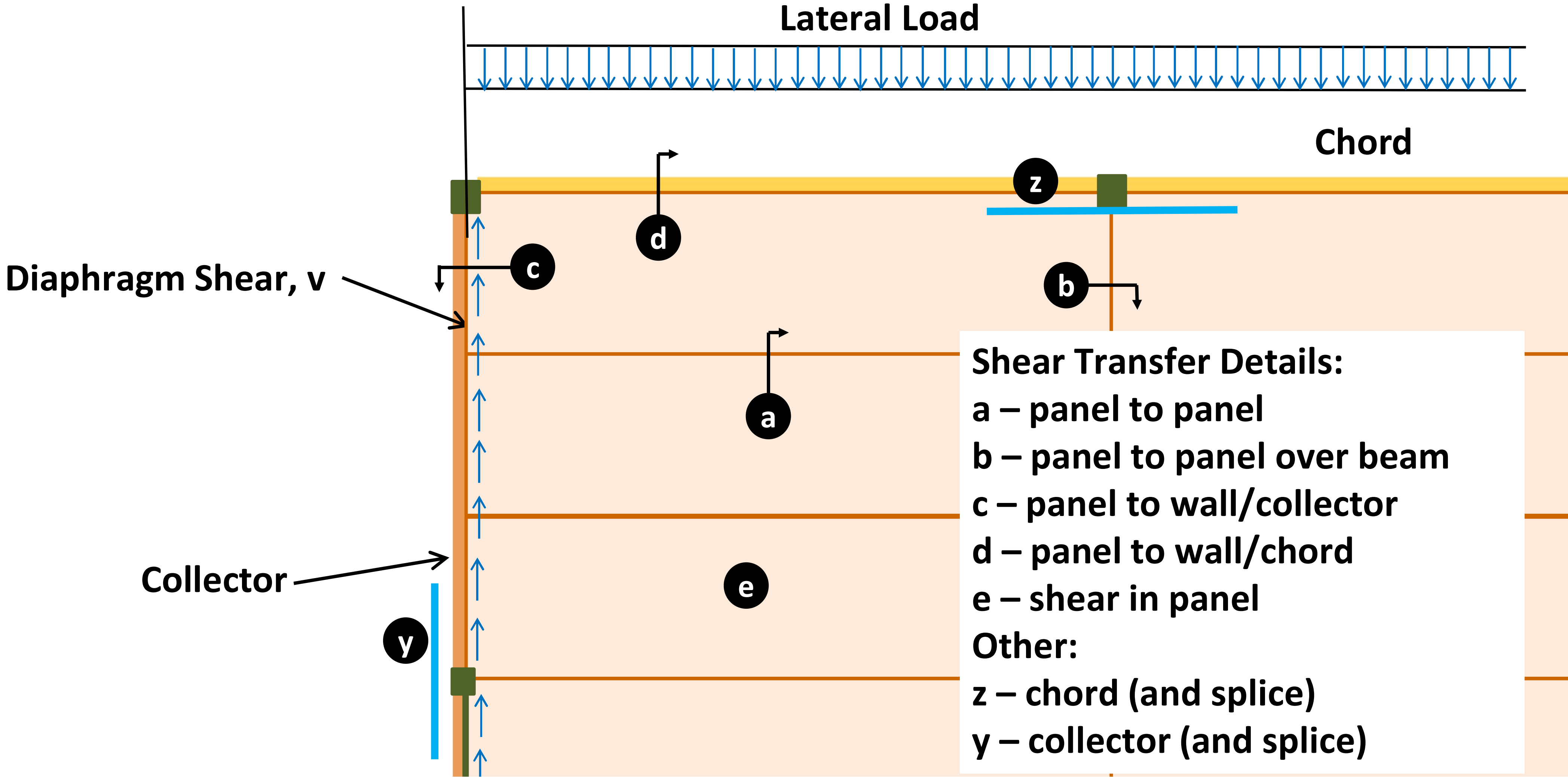
Generic CLT Floor/Roof Diaphragm



Generic CLT Floor/Roof Diaphragm



Generic CLT Floor/Roof Diaphragm



Shear Transfer Details:

a – panel to panel

b – panel to panel over beam

c – panel to wall/collector

d – panel to wall/chord

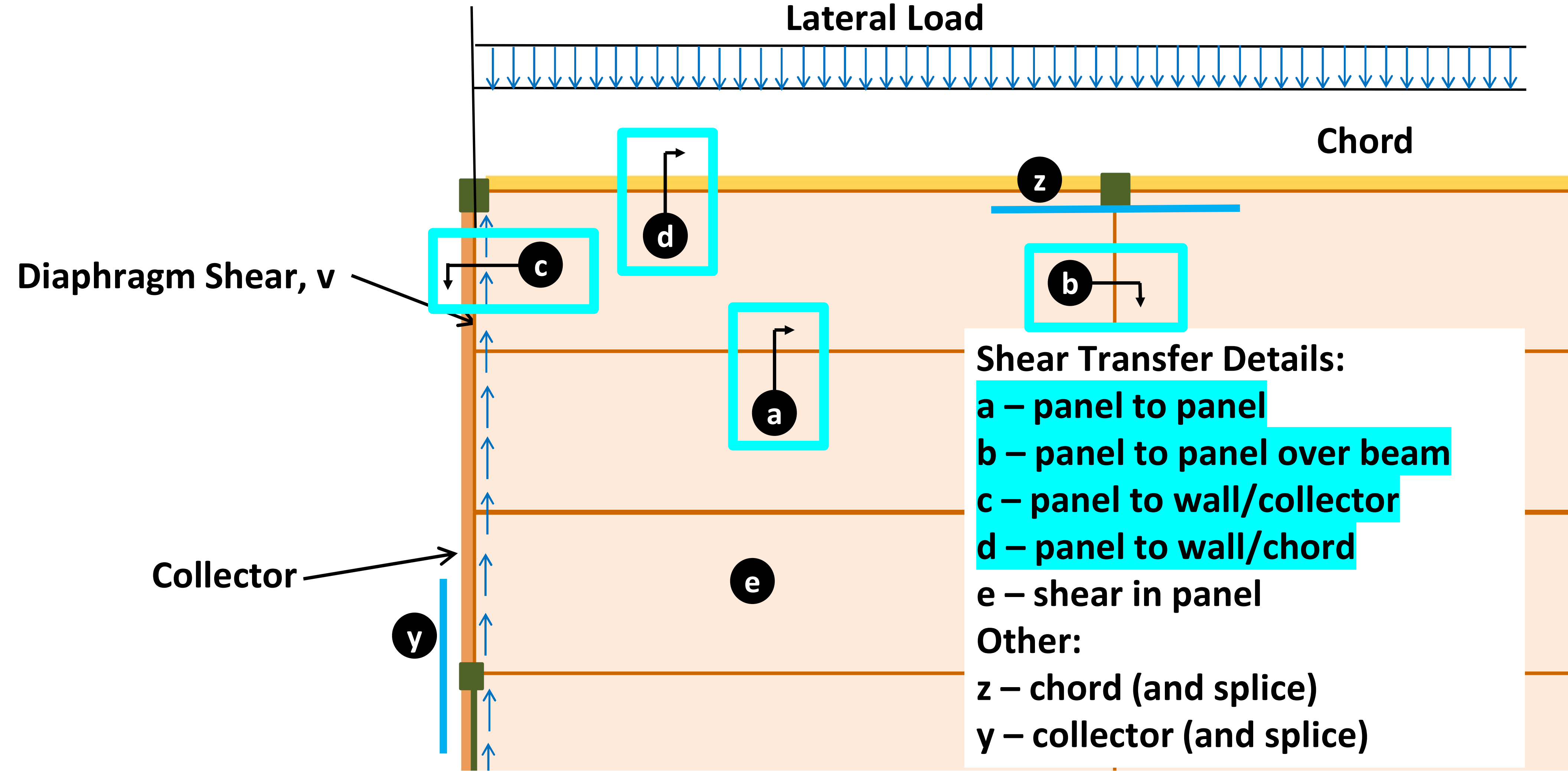
e – shear in panel

Other:

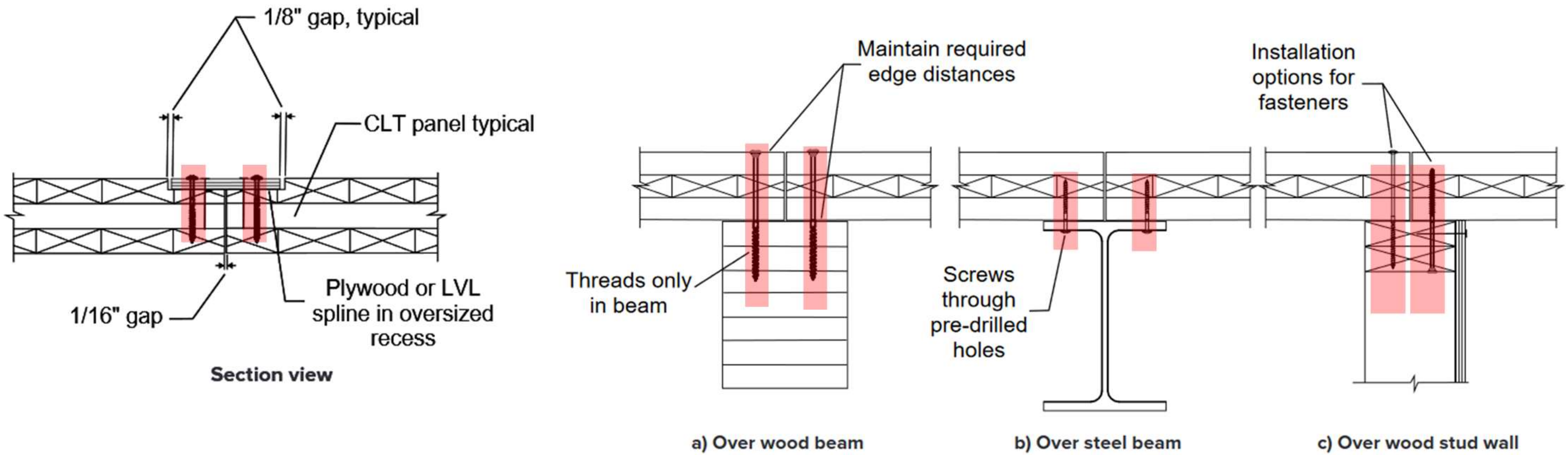
z – chord (and splice)

y – collector (and splice)

CLT Diaphragm Shear Transfer Connections



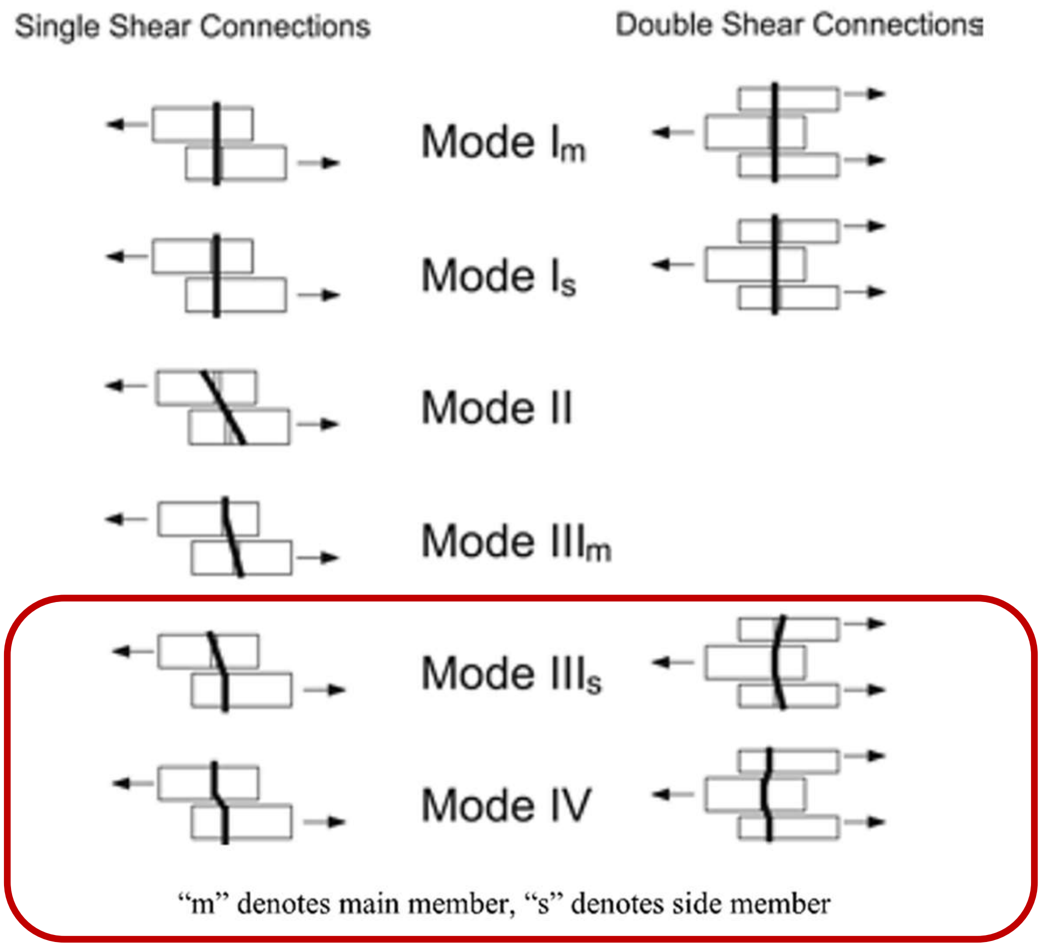
CLT Diaphragm Shear Transfer Connections



Diaphragm **shear transfer connections** at CLT panel edges:

- Use dowel-type fasteners in shear (nails, screws, bolts)
- Yield **Mode IIIs or IV** per NDS 12.3.1 must control capacity

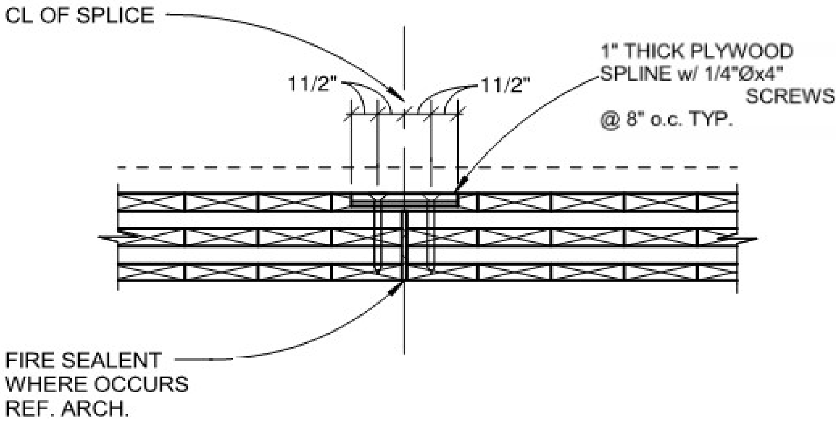
Connection Yield Modes Per the NDS

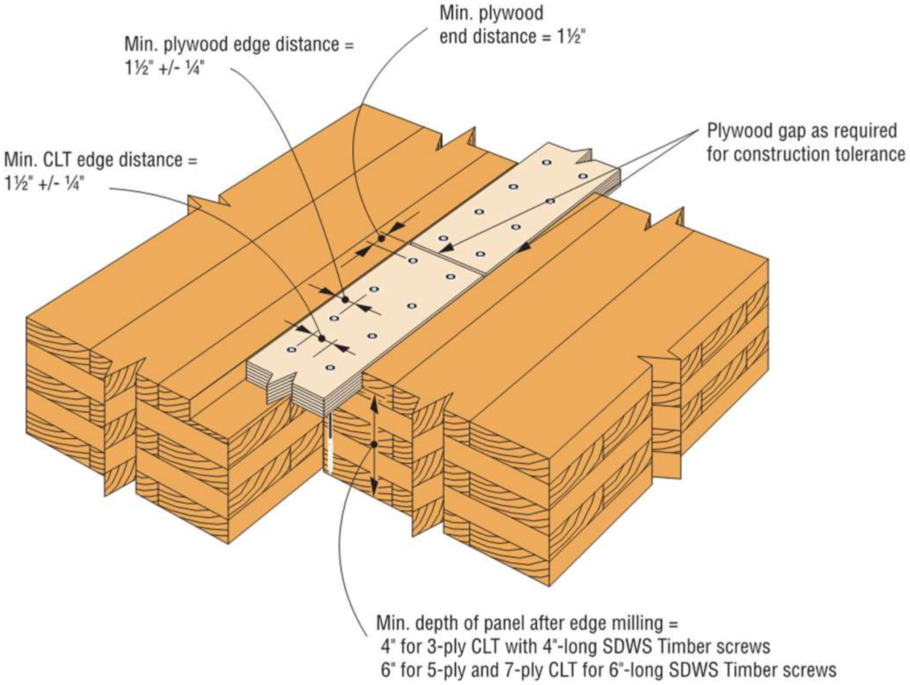


SB1

Panel to Panel Connection Styles

Top Surface Spline



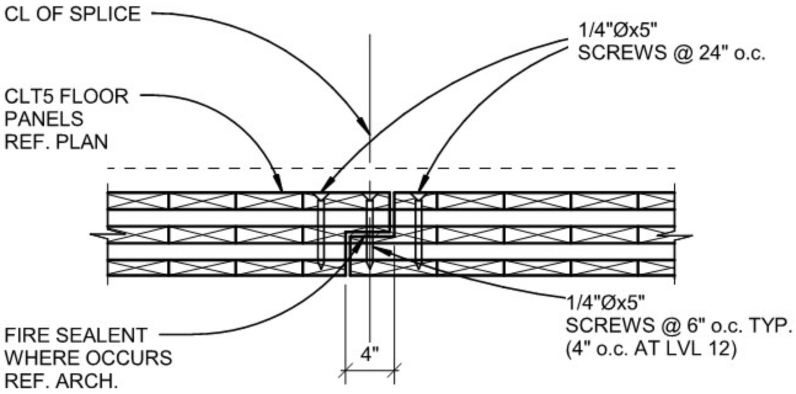


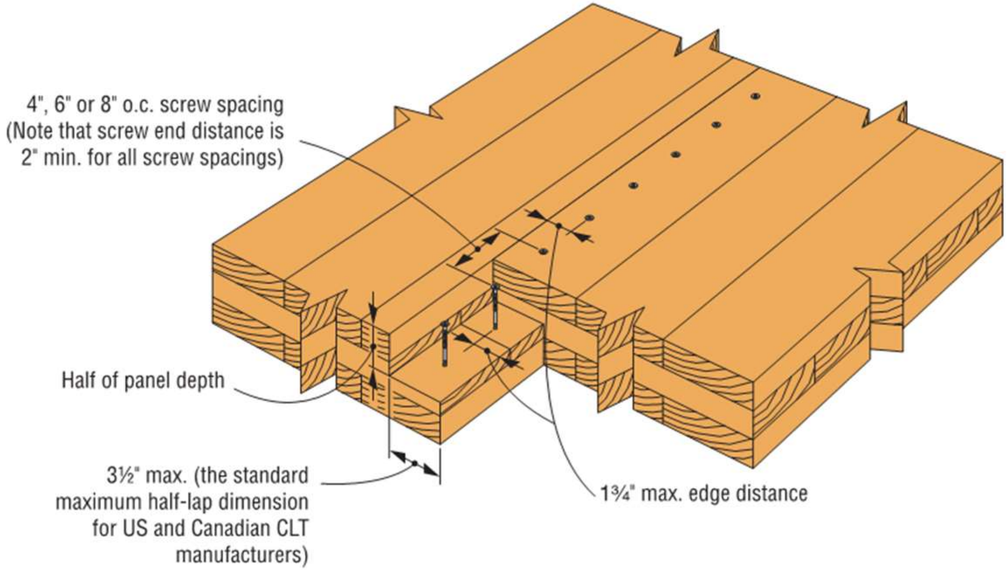
Source: Simpson Strong-Tie

SB2

Panel to Panel Connection Styles

Half-Lap





Source: Simpson Strong-Tie

CLT Diaphragm Shear Transfer Connection Design

Nominal capacity of CLT diaphragm shear transfer connection fastener:

$$Z_n = 4.5\, Z^*$$

Where Z^* is reference lateral capacity Z from NDS

multiplied by all applicable factors *except* C_D, K_F, ϕ, $\lambda = 1.0$

Source: 2021 SDPWS 4.5.4(1) and 2018 NDS Table 11.3.1

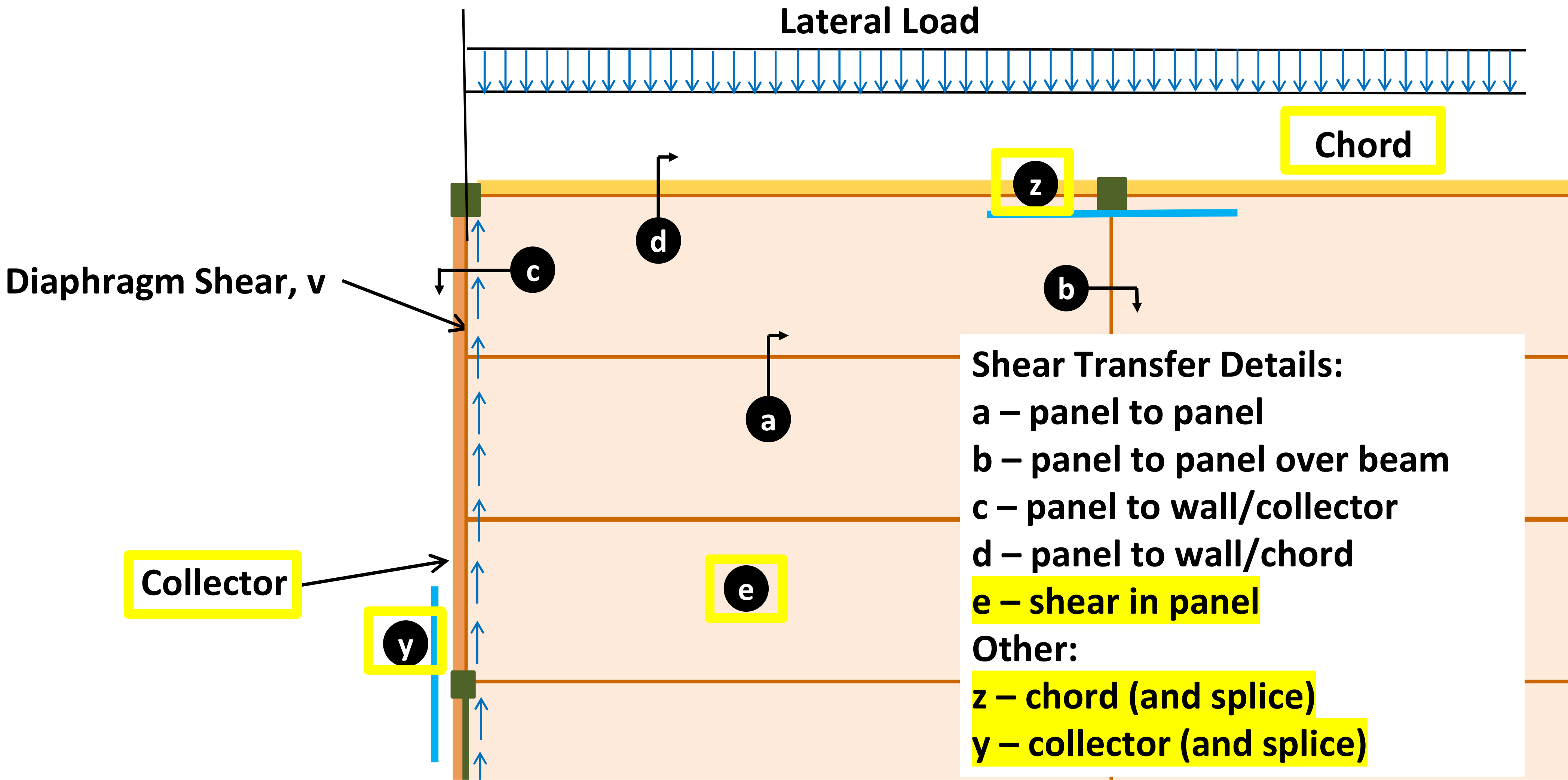
Table 11.3.1 Applicability of Adjustment Factors for Connections

	ASD Only	ASD and LRFD									LRFD Only		
	Load Duration Factor [1]	Wet Service Factor	Temperature Factor	Group Action Factor	Geometry Factor [3]	Penetration Depth Factor [3]	End Grain Factor [3]	Metal Side Plate Factor [3]	Diaphragm Factor [3]	Toe-Nail Factor [3]	Format Conversion Factor K_F	Resistance Factor ϕ	Time Effect Factor
Lateral Loads													
Dowel-type Fasteners (e.g. bolts, lag screws, wood screws, nails, spikes, drift bolts, & drift pins) $Z^* = \boxed{Z \ \text{x}}$	1.0	C_M	C_t	C_g	C_Δ	-	C_{eg}	-	1.0	C_{tn}	1.0	1.0	1.0

Also 1.0 for CLT Diaphragm Shear Transfer Connections

Source 2021 SDPWS 4.5.4(1) and 2018 NDS Table 11.3.1

Other CLT Diaphragm Components



Other CLT Diaphragm Components

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2. Where dowel-type fasteners are used in chord splice connections and the connection is controlled by Mode III_s or Mode IV fastener yielding in accordance with NDS 12.3.1, fasteners in the connection shall be permitted to be designed for 1.5 and 1.0 times the diaphragm forces associated with the shear forces induced by the prescribed seismic and wind design loads, respectively.

Diaphragm chord elements and chord splice connections using materials other than wood or steel shall be designed using provisions in NDS 1.4.

3. Wood elements, steel parts, and wood or steel chord splice connections shall be designed for 2.0 times the diaphragm forces associated with the shear forces induced from the design loads.

Exceptions:

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Other CLT Diaphragm Components

Amplified Diaphragm Design Forces ≤ Design Capacity

$$\gamma \cdot v \leq v'$$

v = wind or seismic force demand

v' = Adjusted capacity calculated per the NDS *not 4.5 Z**

$\gamma =$ 2.0 for wood and steel components, except:

1.5 for wood members resisting wind loads

1.5 for chord splice connections controlled by Mode IIIs or IV (seismic)

1.0 for chord splice connections controlled by Mode IIIs or IV (wind)

See* ***2021 SPDWS 4.5.4* *for the full information*

Additional Resources

Additional Resources

Available from woodworks.org

https://www.woodworks.org/resources/clt-diaphragm-design-for-wind-and-seismic-resistance/

WoodWorks Wood Products Council

CLT Diaphragm Design for Wind and Seismic Resistance

Using SDPWS 2021 and ASCE 7-22

Cross-laminated timber (CLT) has become increasingly prominent in building construction and can be seen in buildings throughout the world. Specifically, the use of CLT floor and roof panels as a primary gravity force-resisting component has become relatively commonplace. Now, with availability of the 2021 *Special Design Provisions for Wind and Seismic* (SDPWS 2021) from the American Wood Council (AWC), U.S. designers have a standardized path to utilize CLT floor and roof panels as a structural diaphragm. Prior to publication of this document, projects typically had to receive approval to use CLT as a structural diaphragm on a case-by-case basis from the local Authority Having Jurisdiction (AHJ).

This paper highlights important provisions of SDPWS 2021 for CLT diaphragm design and recommendations developed by the authors in the more extensive *CLT Diaphragm Design Guide*, based on SDPWS 2021, published by WoodWorks – Wood Products Council.

AWC SDPWS 2021

SDPWS 2021 is the first edition to provide direct provisions for CLT to be used as an element in a diaphragm or shear wall. To differentiate between CLT and light-frame lateral force-resisting systems, it adopts the terminology *sheathed wood-frame* for light-frame diaphragms (SDPWS §4.2) and shear walls (SDPWS §4.3), and includes new sections for CLT diaphragms (SDPWS §4.5) and shear walls (SDPWS §4.6). SDPWS 2021 is referenced in the 2021 International Building Code (IBC).

Shear Capacity

SDPWS 2021 has a single nominal shear capacity for each set of construction details, v_n, defined in §4.1.4 for use with both wind and seismic design. From this nominal shear capacity, the Allowable Stress Design (ASD) and Load and Resistance Factor Design (LRFD) wind and seismic design capacities are determined by dividing by the ASD reduction factor, Ω_D, or multiplying by a resistance factor, ϕ_D, for LRFD design as summarized in Table 1. For sheathed wood-frame diaphragms, the SDPWS

Photo: KPFF

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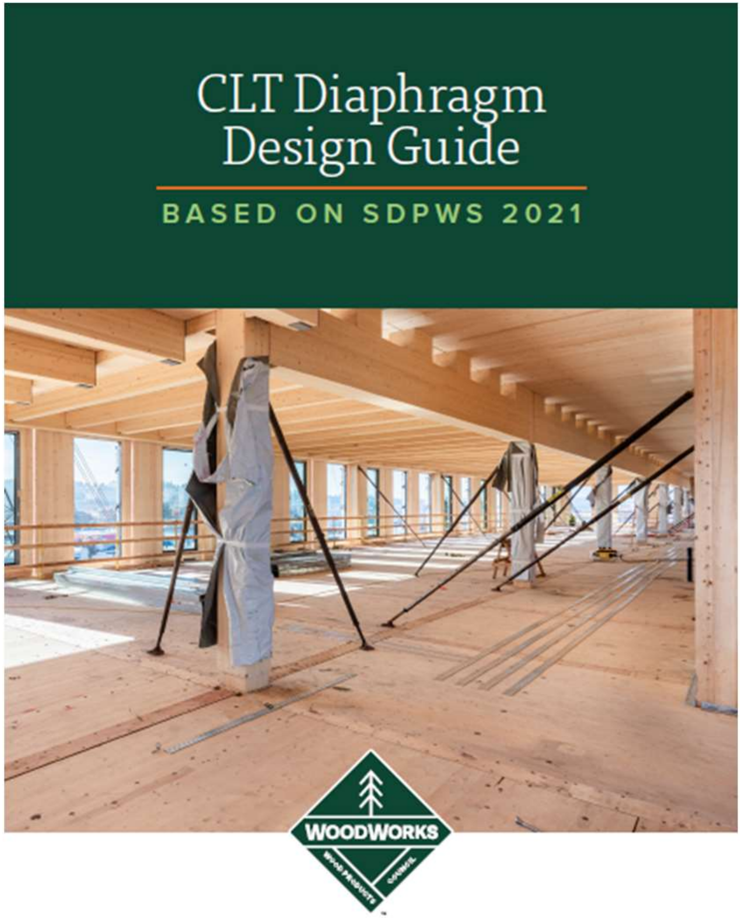
Additional Resources



https://www.woodworks.org/resources/clt-diaphragm-design-guide/

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USDA

Questions? Ask me anything.

Mike Romanowski, SE

Regional Director | CA-South, AZ, NM

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Please take our survey!

901 East Sixth, Thoughtbarn-Delineate Studio, Leap!Structures, photo Casey Dunn