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CLT Diaphragm Design: New Code Provisions and Design Examples

Presented 12/9/2020
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Architect Hacker, Photo: Structurlam

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Course Description

The use of cross-laminated timber (CLT) as structural floor and roof panels has seen incredible growth in the US over the past decade. However, its use as part of a seismic and wind force-resisting system—either as a diaphragm or shear wall—has not been codified to date. This has resulted in designing CLT diaphragms through alternative means or using a structural topping, such as a layer of wood structural panels or concrete, as the diaphragm. This webinar will introduce new provisions for CLT diaphragm design, in the American Wood Council's 2021 Special Design Provisions for Wind and Seismic (SDPWS), which will be the code-referenced standard to provide guidance on CLT diaphragms. Following a discussion of the new SDPWS provisions, CLT diaphragm detailing options and design examples will be presented in order to apply practical design techniques and discuss structural detailing challenges and solutions.

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Learning Objectives

- Develop an understanding of structural design challenges as it pertains to designing CLT while meeting the intent of the code.
- Discuss new provisions contained in the 2021 SDPWS related to the design of CLT diaphragms.
- Examine common panel to panel detailing options in CLT diaphragms to understand the impact of detailing on the relative strength, stiffness, costs and constructability.
- Describe some detailing challenges and solutions for chord and collector conditions in CLT diaphragms.

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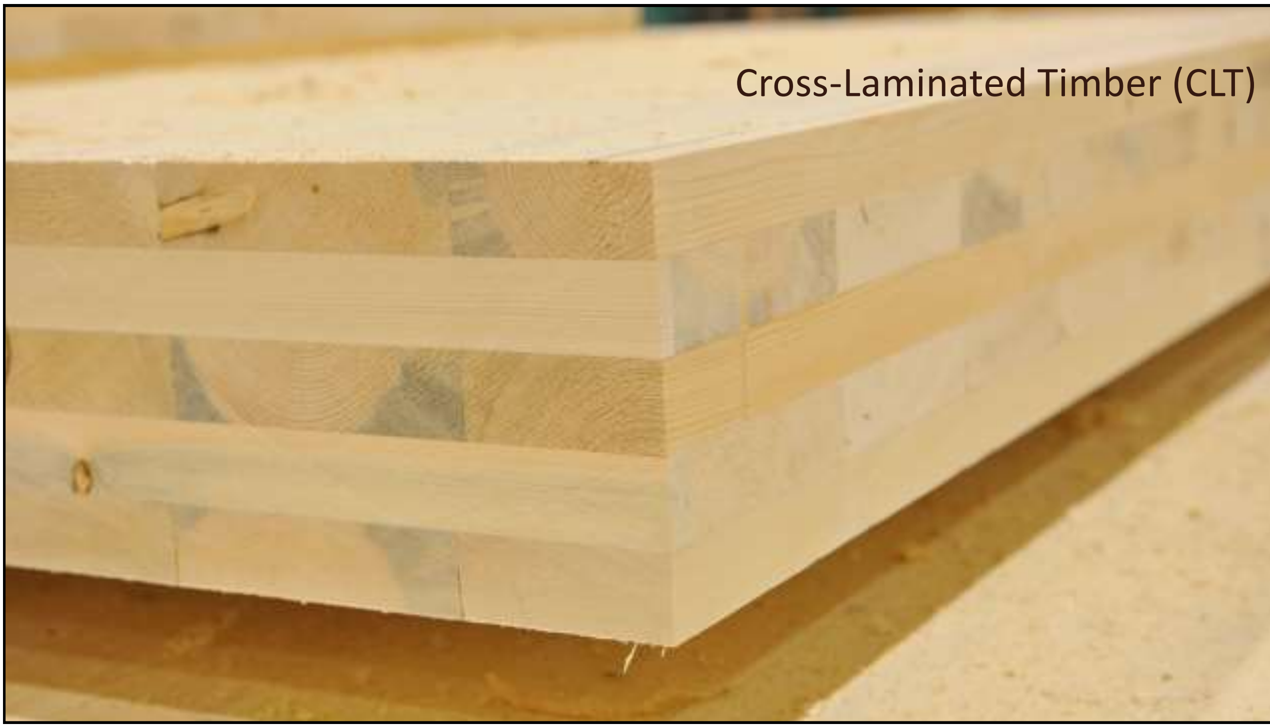

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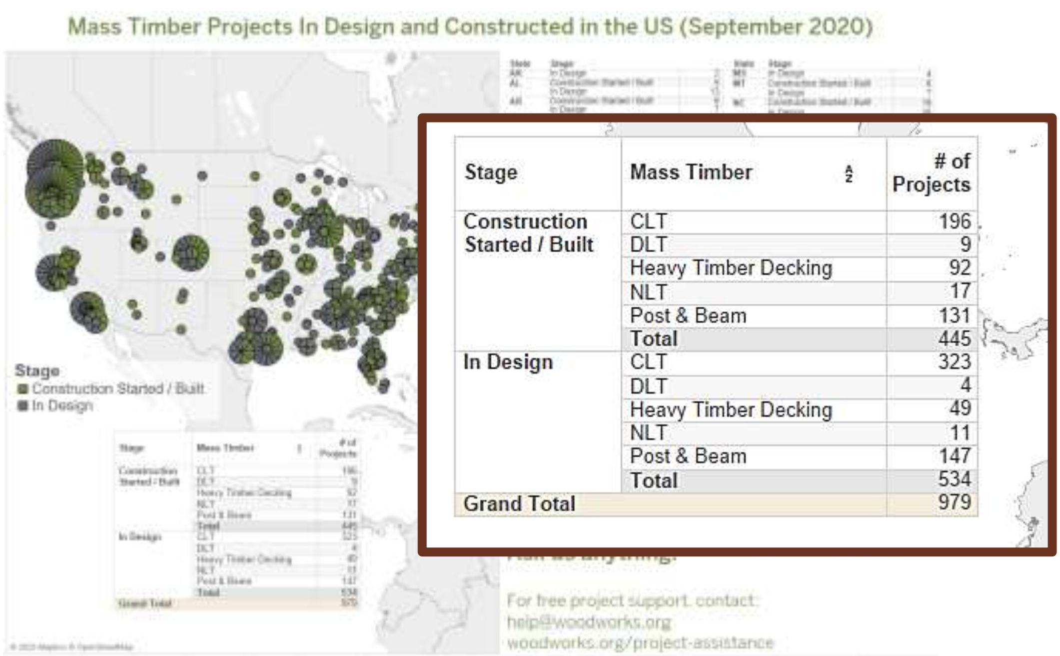

Stage	Mass Timber	# of Projects
Construction Started / Built	CLT	196
	DLT	9
	Heavy Timber Decking	92
	NLT	17
	Post & Beam	131
	Total	445
In Design	CLT	323
	DLT	4
	Heavy Timber Decking	49
	NLT	11
	Post & Beam	147
	Total	534
Grand Total		979

https://www.woodworks.org/publications-media/building-trends-mass-timber/

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Cheney Park Apartments
CLT floor on Panelized Light Frame Walls


Photo Credit: WoodWorks


Photo Credit: WoodWorks

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Barracuda Condos
Madison WI


Photo Credit: WoodWorks

Public Library
Brentwood CA

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CLT Building Code Acceptance

2015 International Building Code

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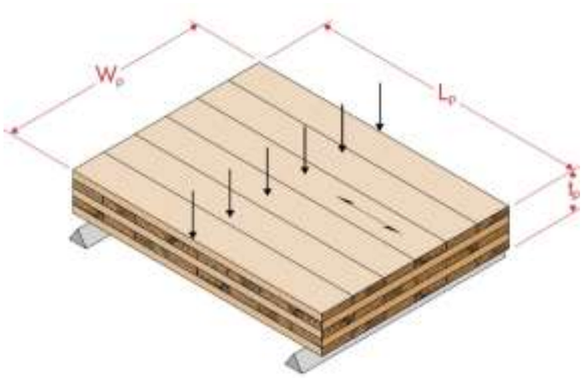
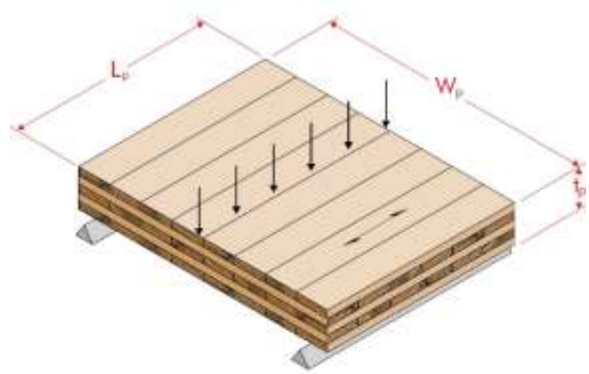
FLATWISE Panel Loading



Span in MAJOR Strength Direction
"Parallel" Direction
Use subscript '0' in Notation



Span in MINOR Strength Direction
"Perpendicular" Direction
Use subscript '90' in Notation

Reference & Source: ANSI/APA PRG 320

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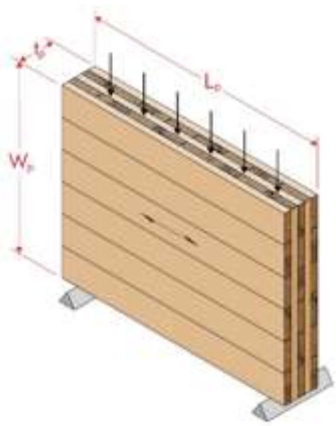
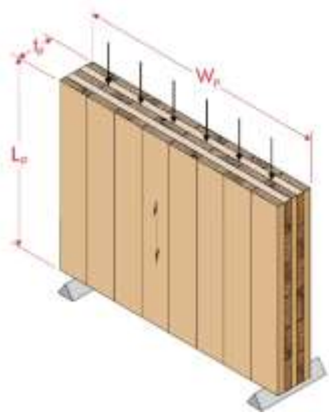
EDGEWISE Panel Loading



Span in MAJOR Strength Direction



Span in MINOR Strength Direction

Reference & Source: ANSI/APA PRG 320

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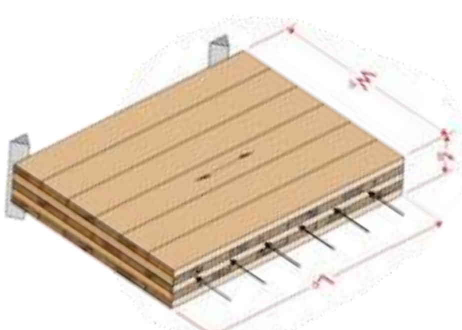
EDGEWISE Panel Loading



Span in MAJOR Strength Direction

Span in MINOR Strength Direction

Reference & Source: ANSI/APA PRG 320

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CLT Seismic Design

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

ASCE/SEI 7-10 or 7-16

SDPWS 2015

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CLT in In-Plane (Edgewise) Strength

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

CLT LAYUP	CLT PANEL THICKNESS DESIGNATION	FACE LAMINATION ORIENTATION (psi) ∥	FACE LAMINATION ORIENTATION (psi) ⊥	FACE LAMINATION ORIENTATION (lbf/ft of width) ∥	FACE LAMINATION ORIENTATION (lbf/ft of width) ⊥
V2M1	99 V	175	235	8,200	11,000
	169 V	175	235	14,000	18,800
	239 V	175	235	19,800	26,600
	309 V	175	235	25,600	34,300
V2M1.1	105V	195	290	9,700	14,400
	175V	270	290	22,400	24,000
	245V	270	290	31,300	33,600
	316V	270	290	40,200	43,200

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

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

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

Source: *APA Product Report PR-L306*

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

Consult with the Manufacturers for Values

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

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

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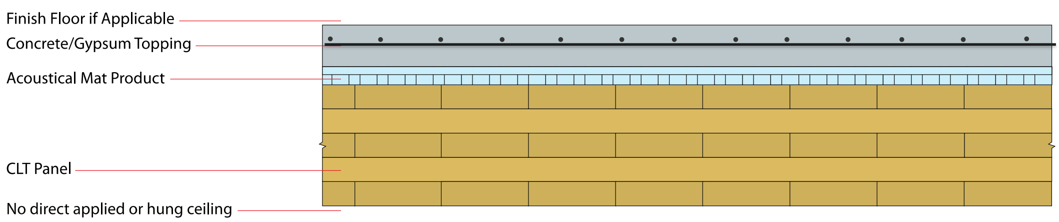
Diaphragm Strategies with Horizontal CLT

Option 1: Structural Topping as Horizontal Diaphragm
(1A) Structural Concrete Topping



Careful detailing to provide adequate load path, minimum rebar cover, etc.

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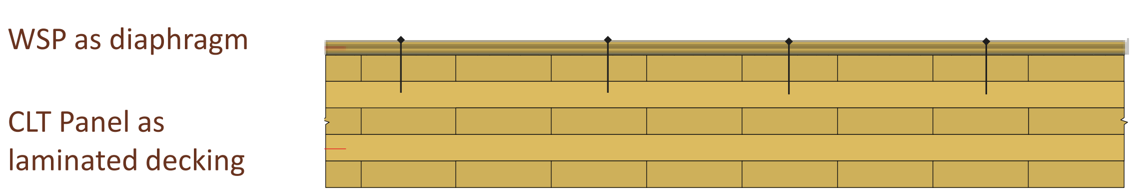
Diaphragm Strategies with Horizontal CLT

Option 1: Structural Topping as Horizontal Diaphragm
(1B) Wood Structural Panel Topping



Classify as blocked WSP diaphragm per SDPWS 2015 4.2.7.1?
19/32" thick 4ft by 8ft panel vs 4 1/8" thick 8ft by 24 ft panel?

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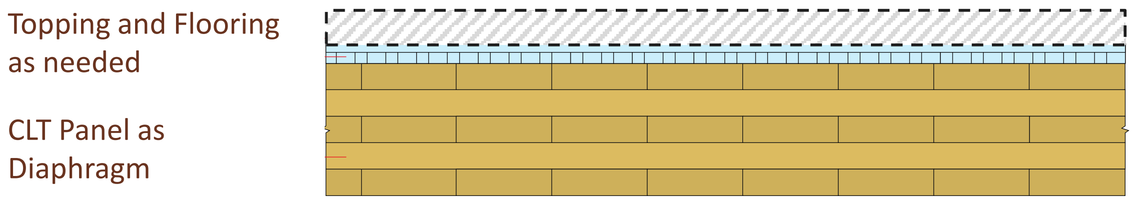
Diaphragm Strategies with Horizontal CLT

Option 2: CLT as a Diaphragm via Engineering Principles



CLT Diaphragms not Recognized in IBC 2018 and Reference Standards.
Guidance documents and Precedents Available.

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Special Design Provisions for Wind & Seismic 2021 Update

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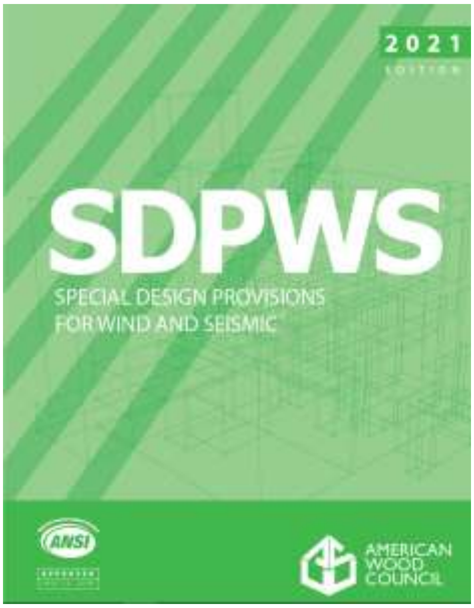
2021 Special Design Provisions for Wind and Seismic



- Referenced in 2021 International Building Code
- CLT diaphragm provisions in Section 4.5

  Target minimum nominal unit shear capacity of 2.8 times ASD unit shear capacity for seismic

  ✓Nominal unit shear capacity based on dowel-type fasteners with Z value controlled by Mode III_s or IV yield per NDS

  ✓Wood elements, steel parts and chord splice connections designed for increased forces to meet the minimum strength objective

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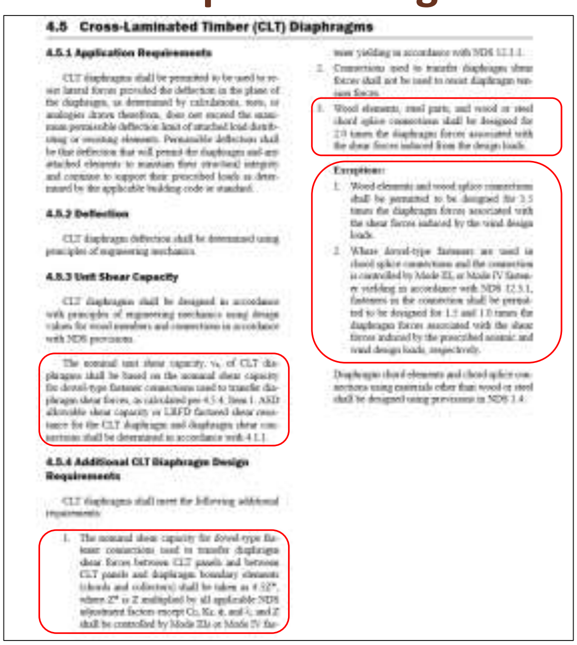
2021 Special Design Provisions for Wind and Seismic



4.5 Cross-Laminated Timber (CLT) Diaphragms

4.5.1 Application Requirements

4.5.2 Deflection

4.5.3 Unit Shear Capacity

4.5.4 Additional CLT Diaphragm Design Requirements

Exceptions:

- Unit shear capacity based on dowel-type fastener connections
- Fastener Z value controlled by Mode III_s or IV per NDS
- Wood elements, steel parts and chord splice connections designed for 2.0 times forces induced from design loads

  Exceptions:

  1) Wood elements and chord splice connections for wind (1.5 times)

  2) Mode III_s or IV dowels in chord splice connections (1.5 times for seismic, 1.0 times for wind)

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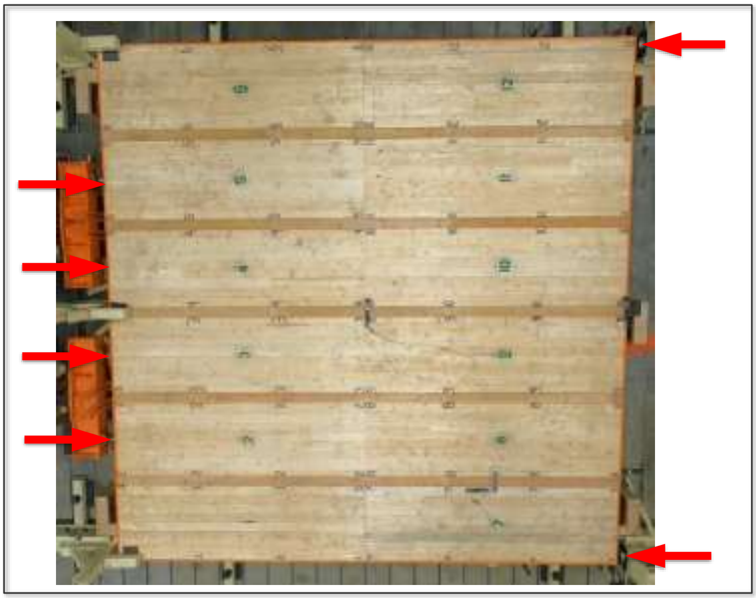
24' x 24' CLT Diaphragm Test with Plywood Spline



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2021 Special Design Provisions for Wind and Seismic

4.1.4 Shear Capacities

4.1.4.1 For seismic design of diaphragms and shear walls, the ASD allowable shear capacity shall be determined by dividing the nominal shear capacity in 4.1.2 by the ASD reduction factor of 2.8 and the LRFD factored shear resistance shall be determined by multiplying the nominal shear capacity by a resistance factor, ϕ_D, of 0.50. No further increases shall be permitted.

4.1.4.2 For wind design of diaphragms and shear walls, the ASD allowable shear capacity shall be determined by dividing the nominal shear capacity in 4.1.2 by the ASD reduction factor of 2.0 and the LRFD factored shear resistance shall be determined by multiplying the nominal shear capacity by a resistance factor, ϕ_D, of 0.80. No further increases shall be permitted.

- 4.5.4…Nominal shear capacity for dowl-type fastener connections:

  $= 4.5Z^*$

  Where Z^* is Z multiplied by all applicable adjustment factors except C_D, K_F, ϕ, λ

- 4.1.4.1 Seismic Design

  ASD: Nominal/2.8

  LRFD: (Nominal)(0.5)

- 4.1.4.2 Wind Design

  ASD: Nominal/2.0

  LRFD: (Nominal)(0.8)

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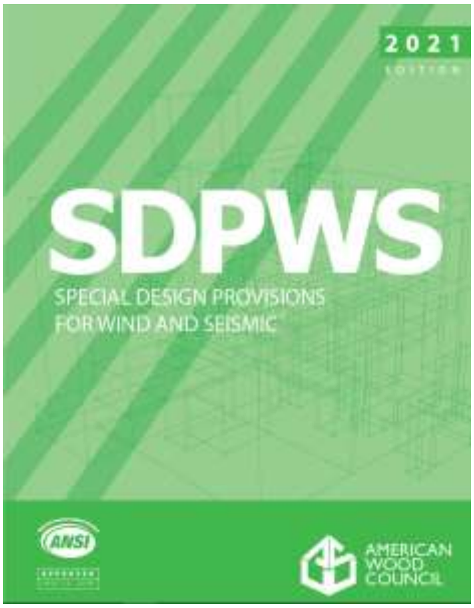
2021 Special Design Provisions for Wind and Seismic



- Free view at AWC.org

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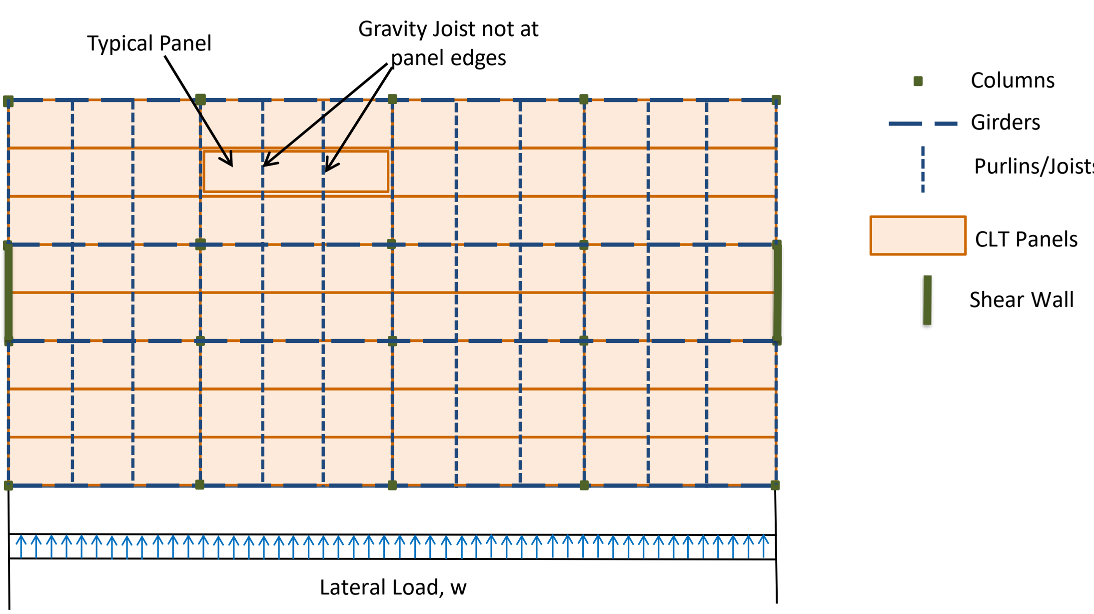
Generic Mass Timber Floor System



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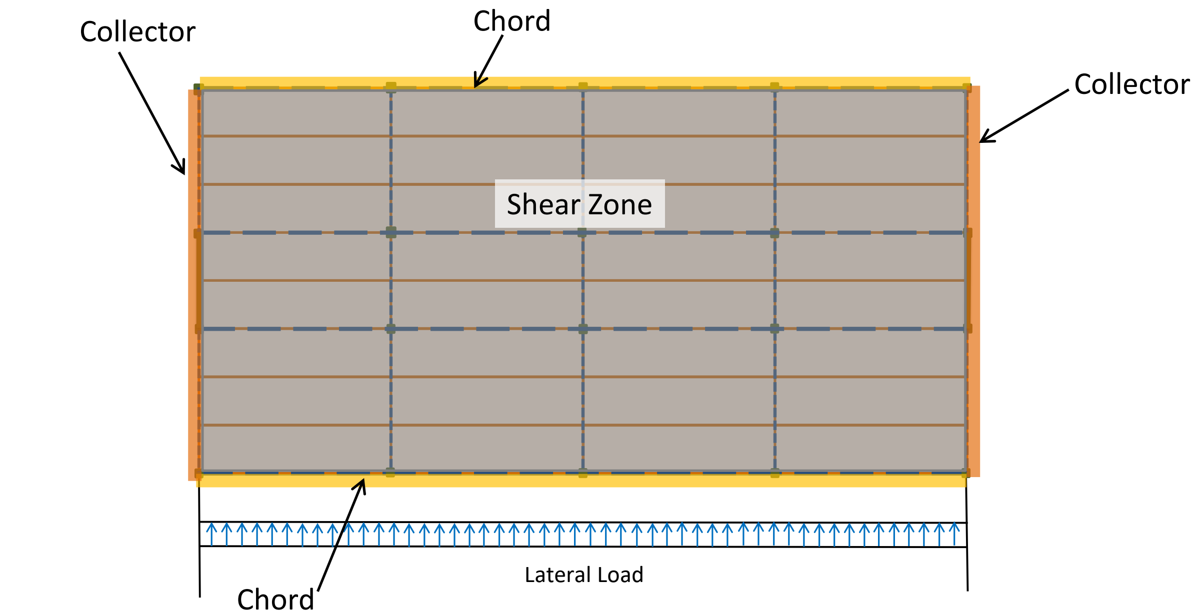
Example CLT Diaphragm Design



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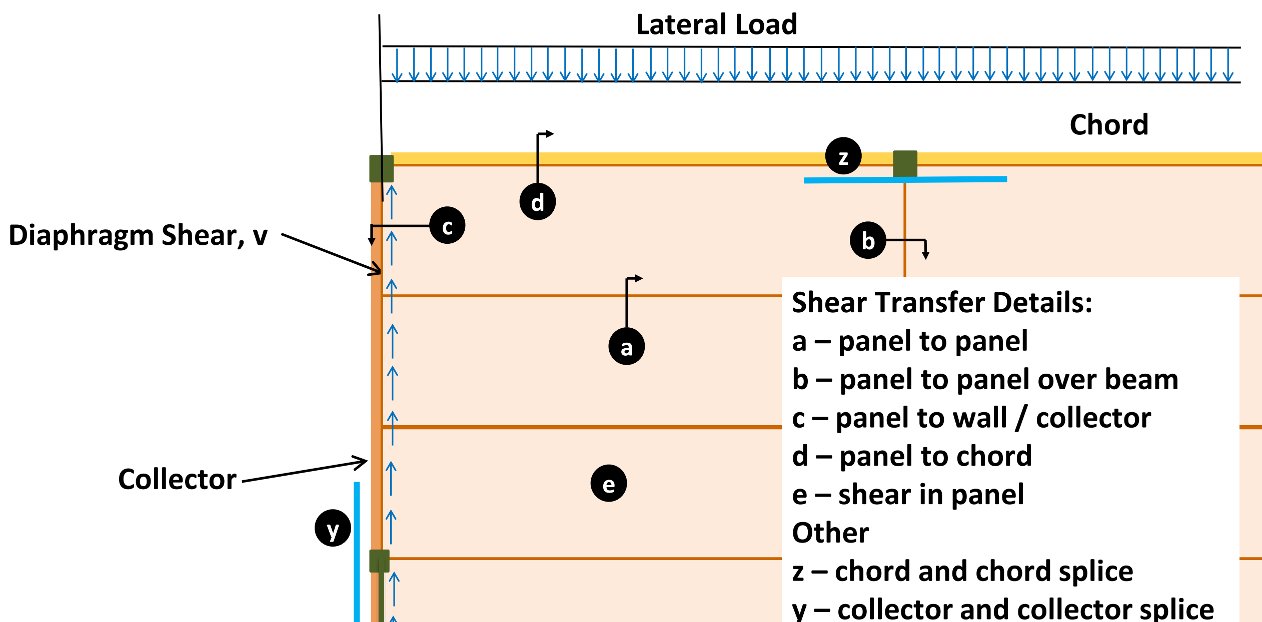
Example CLT Diaphragm Design



Shear Transfer Details:
a – panel to panel
b – panel to panel over beam
c – panel to wall / collector
d – panel to chord
e – shear in panel
Other
z – chord and chord splice
y – collector and collector splice

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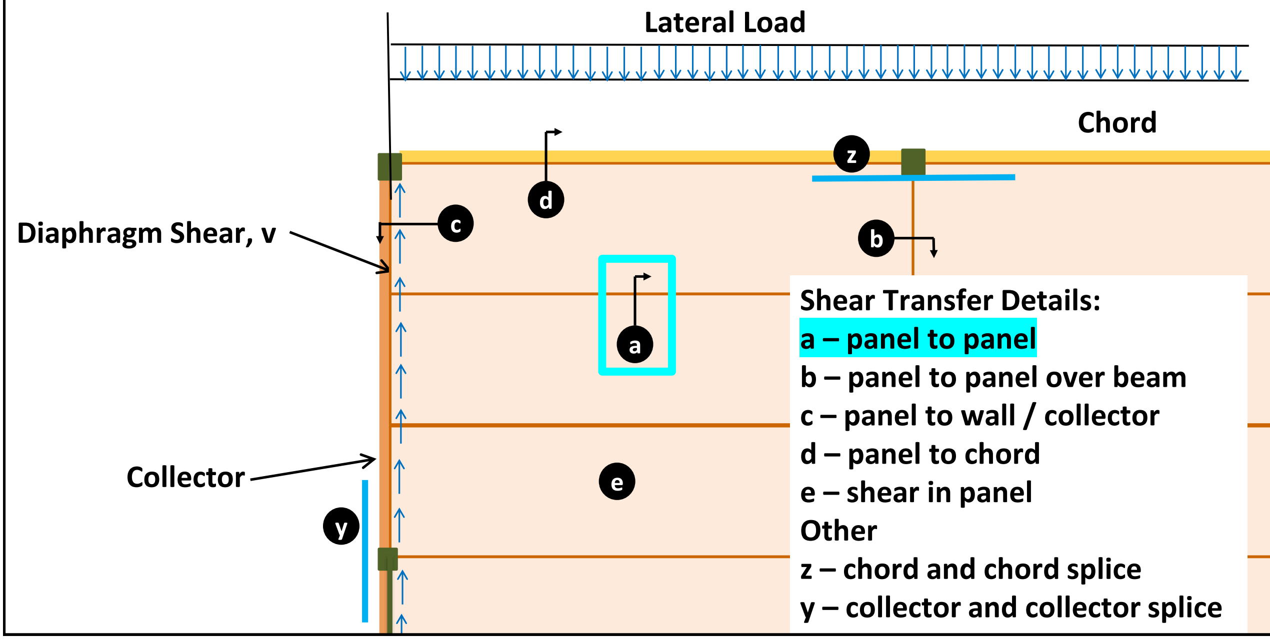
Example CLT Diaphragm Design



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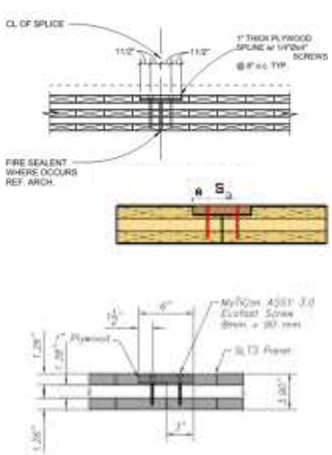
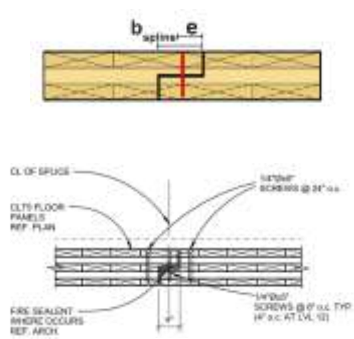
Panel to Panel Connection Styles

Surface Spline

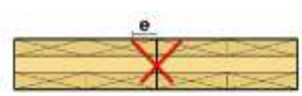


Half Lap



Load Sharing…
not load bearing

Butt Joint



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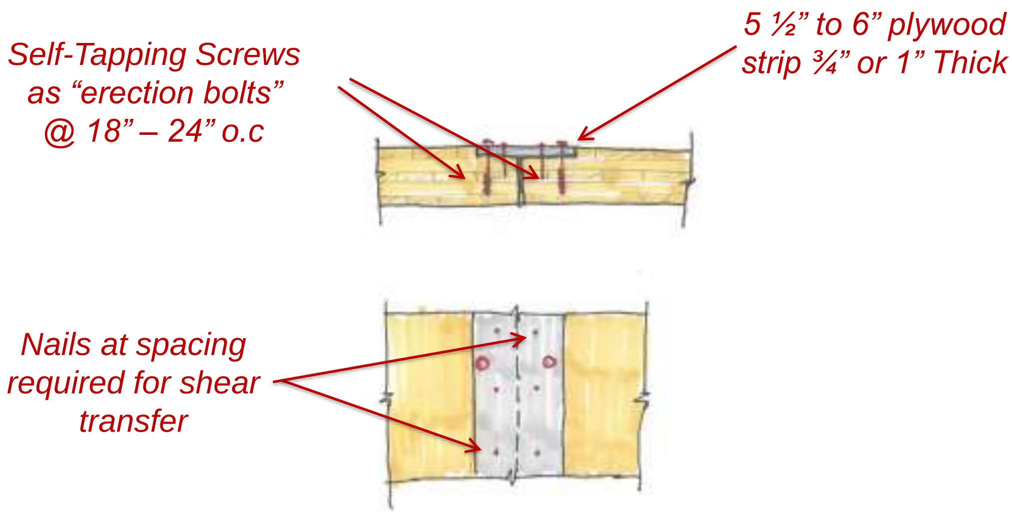
An Efficient Panel to Panel Connection



Graphics: ASPECT Structural Engineers

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Connection Styles

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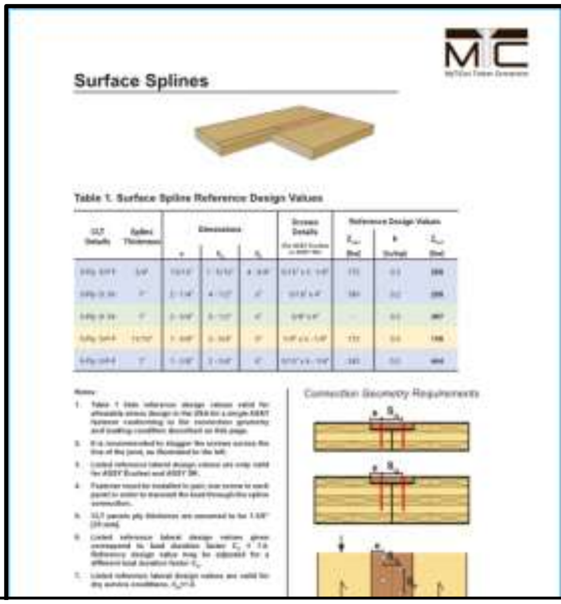
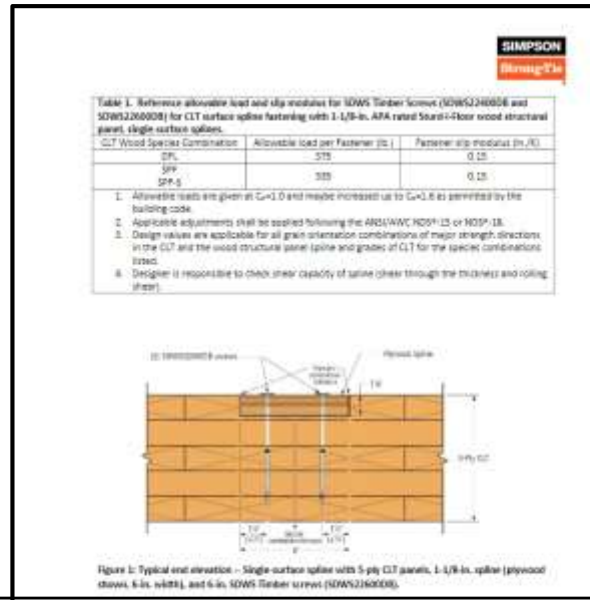
Fastener Vendor Design Support





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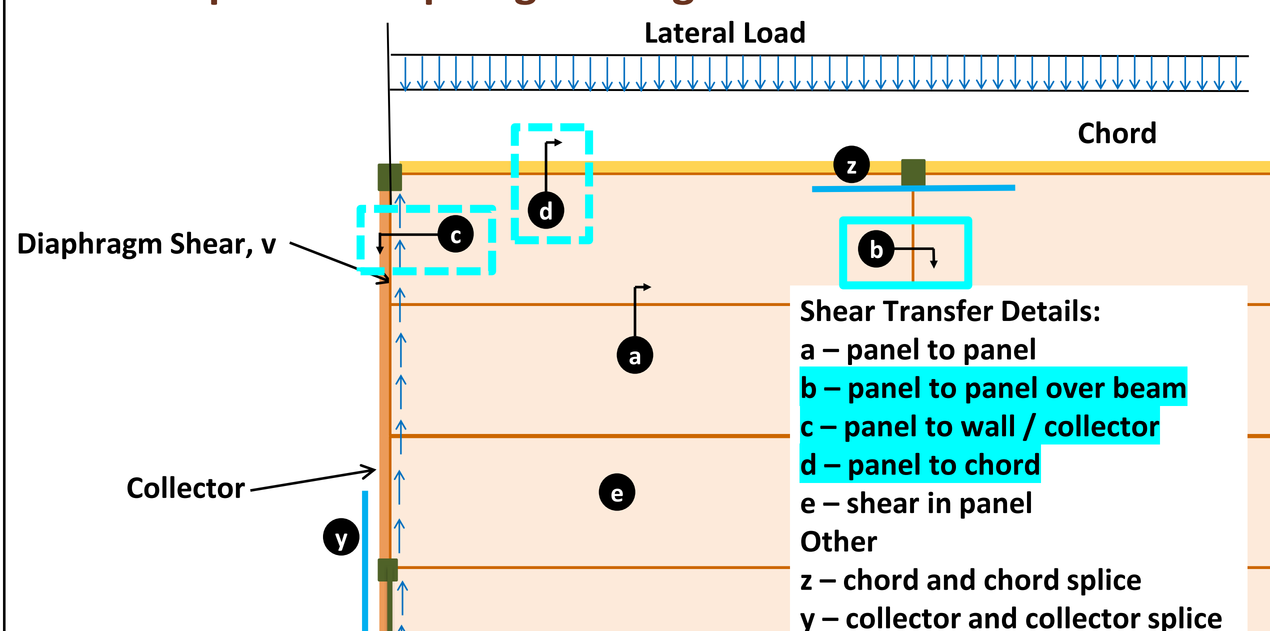
Example CLT Diaphragm Design



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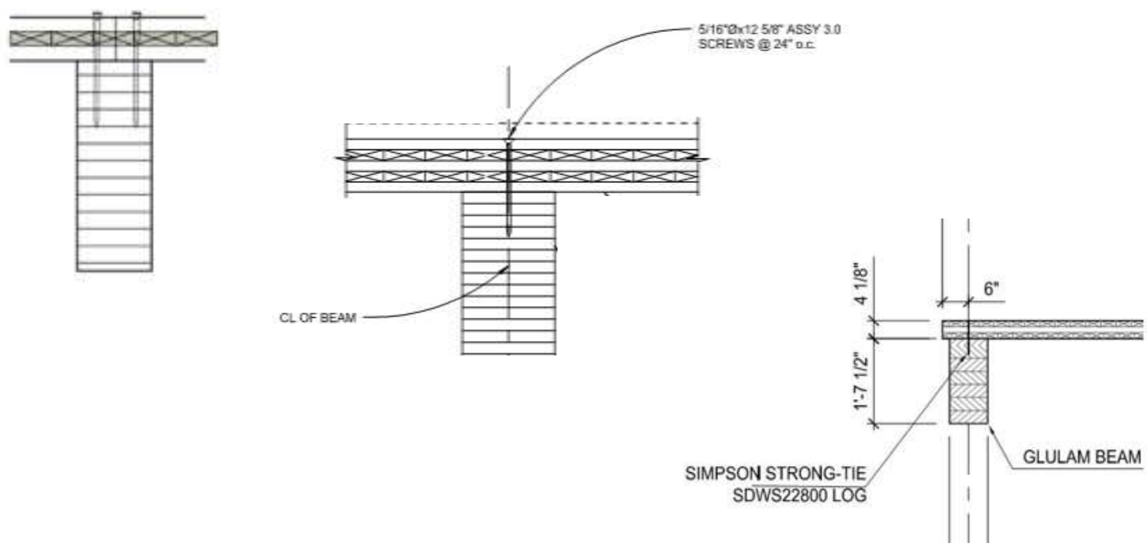
Panel to Beam Connection Styles



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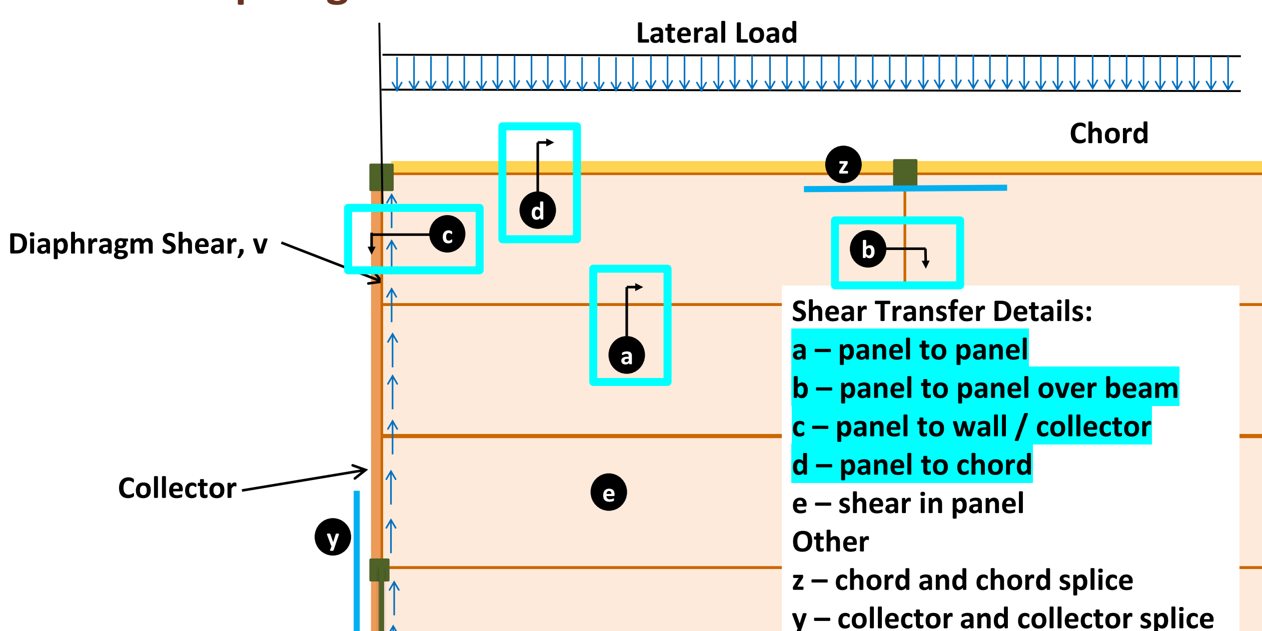
CLT Diaphragm Shear Transfer Connections



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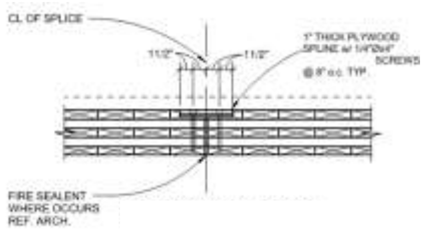
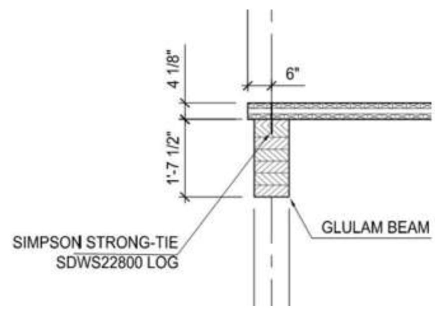
CLT Diaphragm Shear Connection Design

CLT Diaphragm Shear Capacity

Diaphragm **shear connections** at CLT panel edges:
- Use dowel-type fasteners in shear (nails, screws, bolts)
- Yield **Mode IIIs or Mode IV** per NDS 12.3.1 controls capacity





SDPWS 2021 Section 4.5.3

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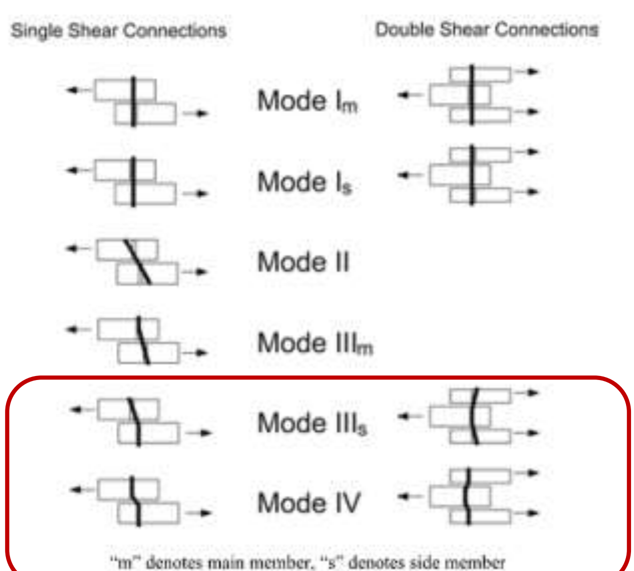
Connection Yield Modes Per the NDS

CLT Diaphragm Shear Capacity



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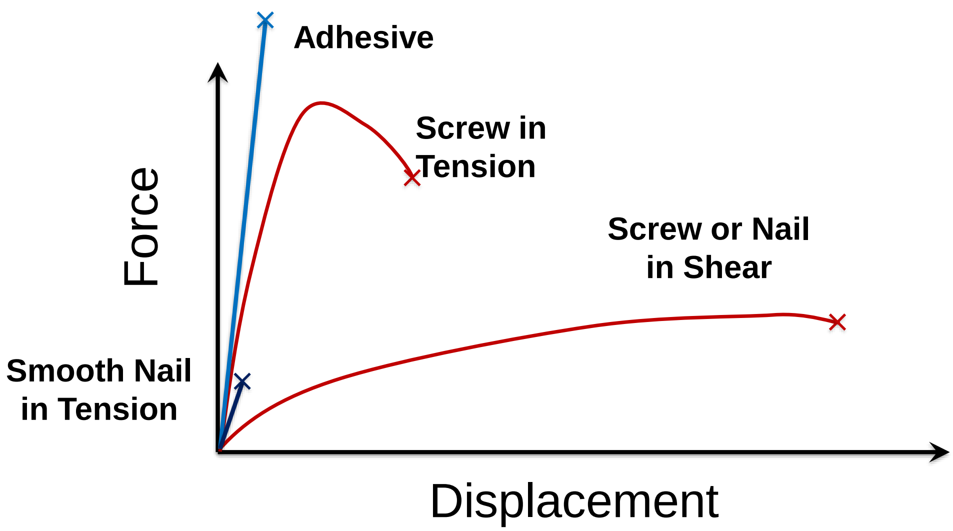
Conceptual Fastener Behavior

CLT Diaphragm Shear Capacity



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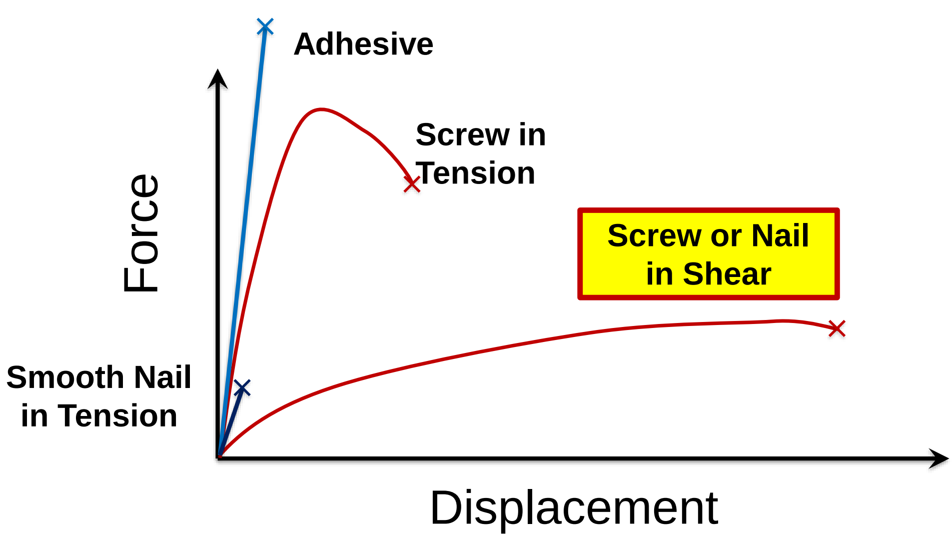
Conceptual Fastener Behavior

CLT Diaphragm Shear Capacity

Well behaved seismic systems have ductile failure modes.



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CLT Diaphragm Shear Connection Design

CLT Diaphragm Shear Capacity

Nominal capacity of CLT diaphragm shear connection fastener:

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

Where Z^* is reference lateral capacity Z of NDS multiplied by all applicable factors except C_D, K_F, ϕ, $\lambda = 1.0$

SDPWS 2021 Section 4.5.4(1) and NDS Table 11.3.1

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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^* = Z x	1.0	C_M	C_t	1.0	C_Δ	-	C_{eg}	-	1.0	C_{tn}	1.0	1.0	1.0

Also 1.0 for CLT Diaphragm Shear Connections

SDPWS 2021 Section 4.5.4(1) and NDS Table 11.3.1

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CLT Diaphragm Shear Connection Design

CLT Diaphragm Shear Capacity

Fastener with regular spacing, S, nominal unit shear connection capacity is:

$$v_n = Z_n/S = 4.5\ Z^*/S$$

Required unit shear strength ≤ Design unit shear capacity

ASD $\quad v = v_{ASD} \leq \dfrac{v_n}{RF} \quad RF$ = 2.8 (seismic), = 2.0 (wind)

LRFD $\quad v = v_u \leq \phi v_n \quad \phi$ = 0.5 (seismic), = 0.8 (wind)

SDPWS 2021 Section 4.1.4 and 4.5.4(1)

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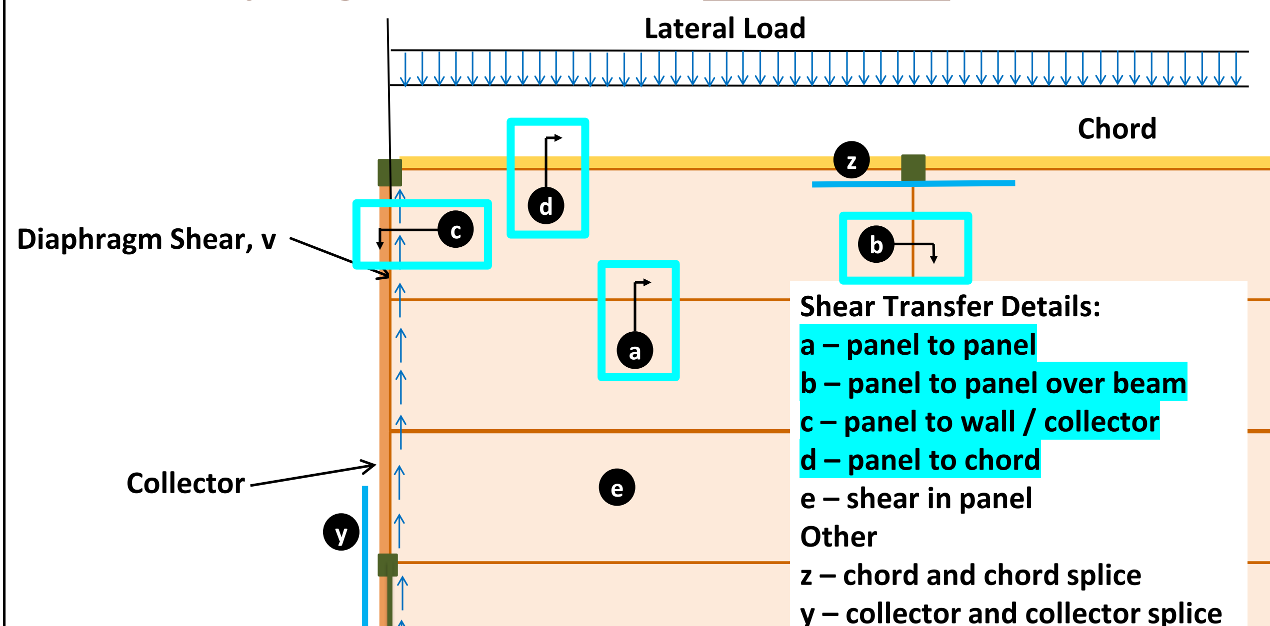
CLT Diaphragm Shear Transfer Connections



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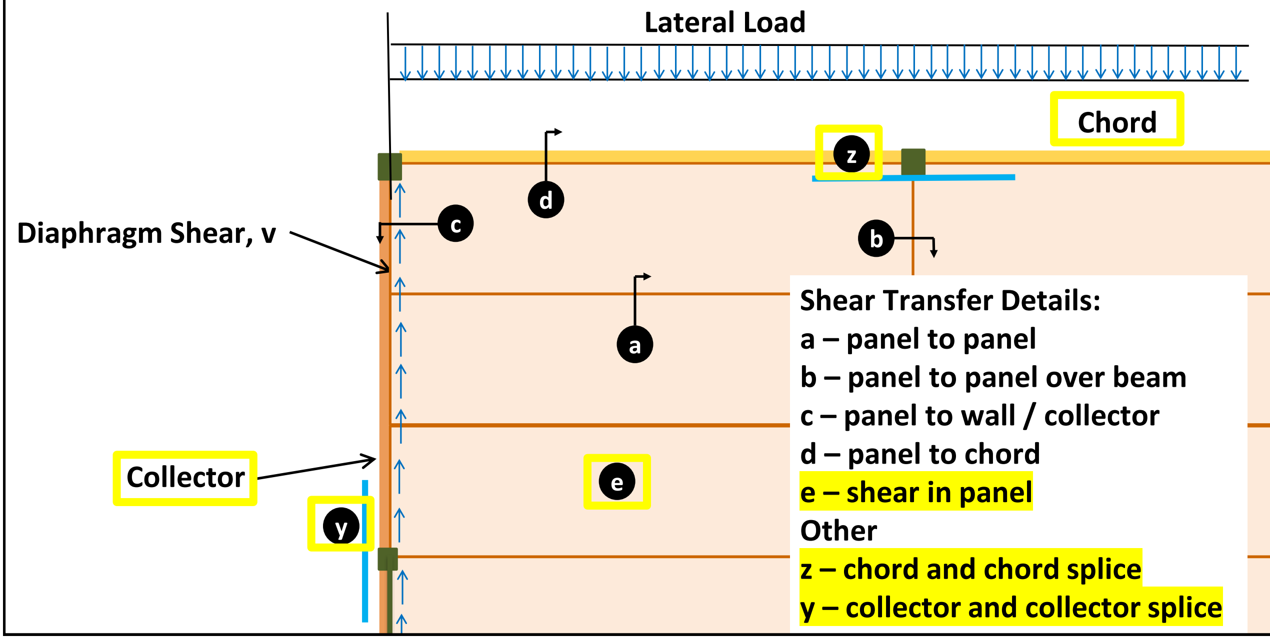
Other CLT Diaphragm Components



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Other CLT Diaphragm Components

Additional Design Requirements

Engineering goal: Design CLT panels, diaphragm chord members and chord splices such that diaphragm develops target shear capacity in ductile manner:

Approach 1: Capacity Based Design

Amplified nominal capacity of shear connections

$$\alpha \cdot v_n \leq v'$$

Design capacity of other components

SDPWS Approach

Approach 2: Overstrength Approach

Amplified applied wind or seismic forces

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

Design capacity of other components

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Other CLT Diaphragm Components

Additional Design Requirements

Amplified Diaphragm Design Forces ≤ Design Capacity

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

v = wind or seismic force demand

v' = Adjusted capacity calculated per the NDS

$\gamma =$ 2.0 for wood and steel components, except:
1.5 wood members resisting wind loads
1.5 chord splice connections controlled by Mode IIIs or IV (seismic)
1.0 chord splices connections controlled by Mode IIIs or IV (wind)

*See **SDPWS 2021 Section 4.5.4** for the full information*

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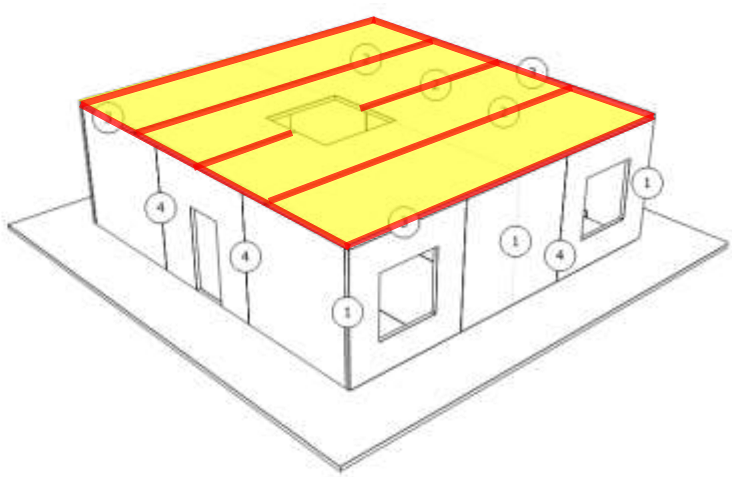
CLT Diaphragms



Is the Diaphragm Rigid or Flexible?

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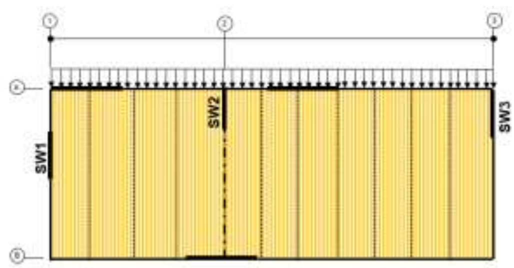
Lateral Load Distribution using CLT Diaphragms

Option 1:
Simplified Seismic Design

Regular structure, ≤ 3 stories & other limitations per ASCE 7 12.14
Can Assume Flexible if ASCE 7 12.14.1.1.8 met



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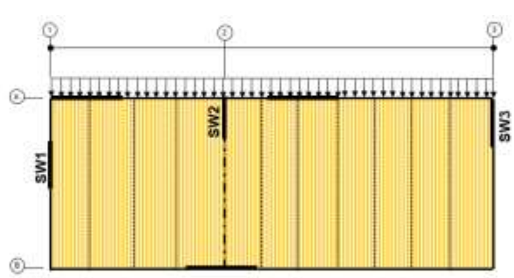
Lateral Load Distribution using CLT Diaphragms

Option 2:
Idealize as Flexible (2A) or Rigid (2B)

as Justified by Calculated Diaphragm Deflections



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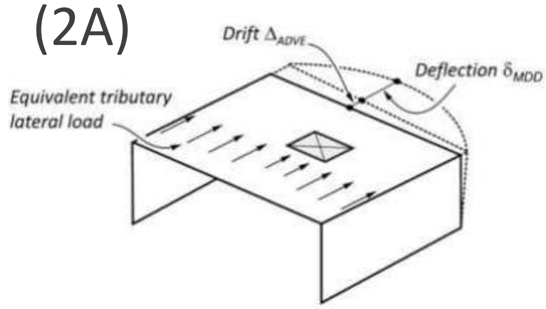
(2A)



12.3.1.3 Calculated Flexible Diaphragm Condition. Diaphragms not satisfying the conditions of Sections 12.3.1.1 or 12.3.1.2 are permitted to be idealized as flexible provided:

$$\frac{\delta_{MDD}}{\Delta_{ADVE}} > 2 \qquad (12.3\text{-}1)$$

where δ_{MDD} and Δ_{ADVE} are as shown in Fig. 12.3-1. The loading used in this calculation shall be that prescribed in Section 12.8.

Flexible by Calculation

ASCE 7 12.3.1.3

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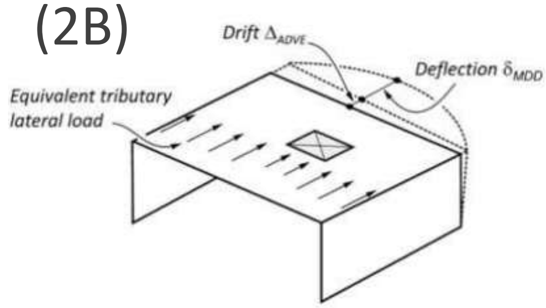
(2B)



IBC1604.4: A diaphragm is rigid for the purpose of distribution of story shear and torsional moment when the lateral deformation of the diaphragm ***is less than*** or equal to two times the average story drift.

Rigid by Calculation

IBC 1604.4

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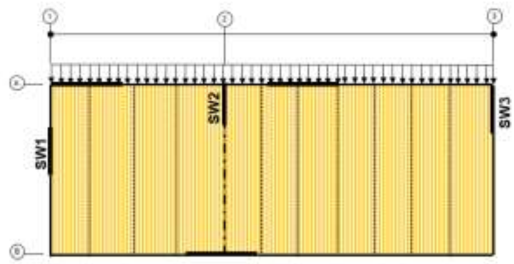
Lateral Load Distribution using CLT Diaphragms

Option 3:
Enveloped Diaphragm Design

Check both flexible and rigid diaphragm behavior (3A)

Or Check conservatively flexible and conservatively stiff semi-rigid behavior (3B)



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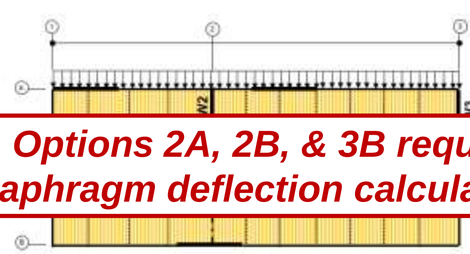
Lateral Load Distribution using CLT Diaphragms

Option 1 – Simplified Seismic Method
Option 2A – Flexible by Calculation
Option 2B – Rigid by Calculation
Option 3A – Envelope (Flex & Rigid)
Option 3B – Envelope (Semi-rigid)



Options 2A, 2B, & 3B require diaphragm deflection calculations

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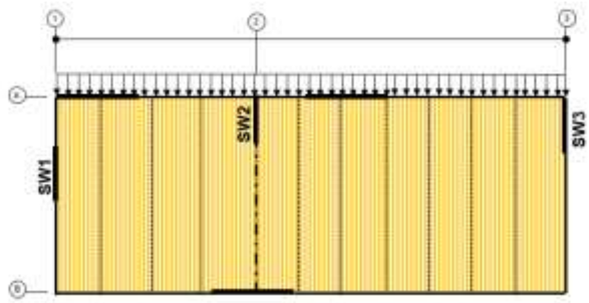
CLT Diaphragm Deflection Requirements

SDPWS 2021 Section 4.5.2 Requirement:

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



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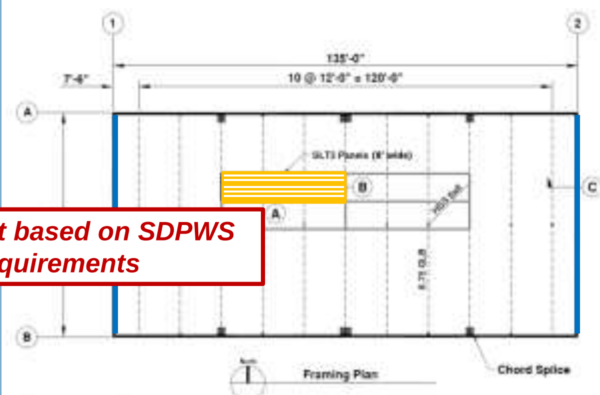
2015 White Paper on CLT Diaphragms

Developed in 2015, not based on SDPWS 2021 design requirements



Available from structurlam.com

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2015 White Paper on CLT Diaphragms

- Design example following SDPWS 2015, US CLT Handbook
- Includes Modified 4-term wood panel sheathed diaphragm equation in SDPWS 2015

$$\delta_{dia} = \underbrace{\frac{5vL^3}{8EAW}}_{\text{Chord Flexure}} + \underbrace{\frac{vL}{4G_v t_v}}_{\text{Panel Shear}} + \underbrace{\boxed{CLe_n}}_{\text{Connector Slip}} + \underbrace{\frac{\sum(x\Delta_c)}{2W}}_{\text{Chord Slip}}$$

$$C = \frac{1}{2}\left(\frac{1}{P_L} + \frac{1}{P_W}\right)$$

P_L is panel length
P_W is panel width
e_n is connector slip at diaphragm edge

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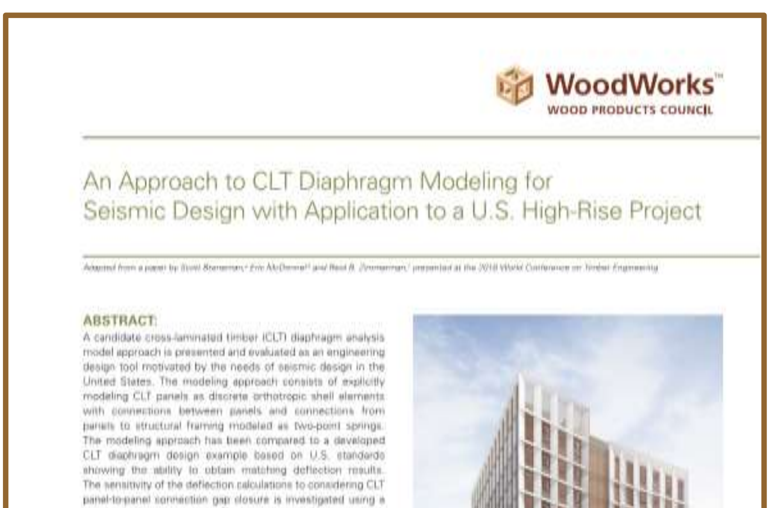
WoodWorks Solutions Paper on CLT Modeling

http://www.woodworks.org/wp-content/uploads/Approach-to-CLT-Diaphragm-Modeling-for-Seismic-WoodWorks-Jan-2017.pdf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An Approach to CLT Diaphragm Modeling for Seismic Design with Application to a U.S. High-Rise Project

ABSTRACT:
A candidate cross-laminated timber (CLT) diaphragm analysis model approach is presented and evaluated as an engineering design tool motivated by the needs of seismic design in the United States. The modeling approach consists of explicitly modeling CLT panels as discrete orthotropic shell elements with connections between panels and connections from panels to structural framing modeled as two-point springs. The modeling approach has been compared to a developed CLT diaphragm design example based on U.S. standards showing the ability to obtain matching deflection results. The sensitivity of the deflection calculations to considering CLT panel-to-panel connection gap closure is investigated using a simple diaphragm example. The proposed modeling approach

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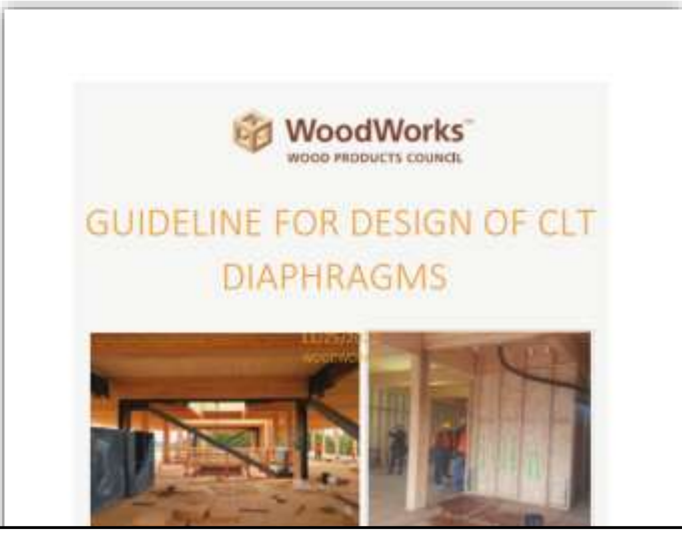
WoodWorks CLT Diaphragm Guideline with Examples



Under Development By:

WoodWorks WOOD PRODUCTS COUNCIL

Holmes Structures

kpff

SWINERTON MASS TIMBER

Funded By:

U.S. Endowment for Forestry and Communities

USDA

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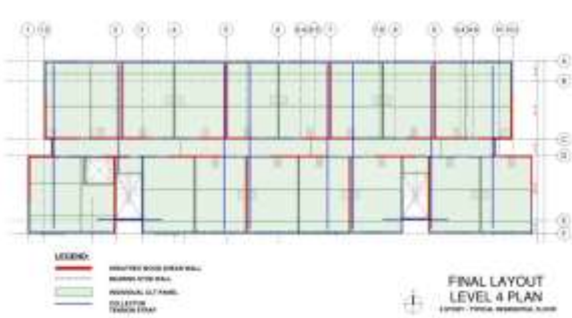
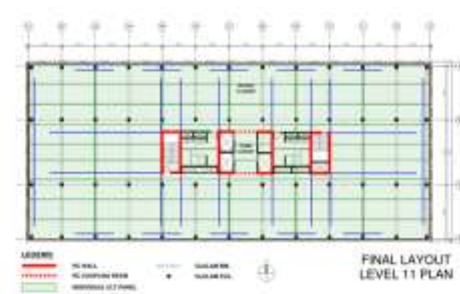
WoodWorks CLT Diaphragm Guideline with Examples

3 Examples
High and Low Seismic & Wind



Example from Holmes Structures



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WoodWorks CLT Diaphragm Guideline with Examples

Design Tools

Spline Material	Fastener	Nominal Diaphragm Shear Connection Capacity vn = 4.5Z*, @ Spacing, S (plf) 12" O.C.	6" O.C.	4" O.C.	3" O.C.	2" O.C.
CLT SG = 0.36						
General Sheathing (23/32)	8d Common Nail	255	510	765	1020	1530
General Sheathing (23/32)	10d Common Nail	296	592	888	1184	1776
General Sheathing (23/32)	Screw Type 1	266	531	797	1062	1593
General Sheathing (23/32)	Screw Type 2	321	641	[illegible]	[illegible]	[illegible]
Struct 1 Sheathing (23/32)	8d Common Nail	311	623	[illegible]	[illegible]	[illegible]
Struct 1 Sheathing (23/32)	10d Common Nail	359	718	[illegible]	[illegible]	[illegible]
Struct 1 Sheathing (23/32)	Screw Type 1	316	631	[illegible]	[illegible]	[illegible]
Struct 1 Sheathing (23/32)	Screw Type 2	385	771	[illegible]	[illegible]	[illegible]
General Sheathing (7/8)	10d Common Nail	336	672	[illegible]	[illegible]	[illegible]
General Sheathing (7/8)	16d Common Nail	379	758	[illegible]	[illegible]	[illegible]
General Sheathing (7/8)	Screw Type 1	295	590	[illegible]	[illegible]	[illegible]
General Sheathing (7/8)	Screw Type 2	360	721	1081	1441	2162
Struct 1 Sheathing (7/8)	10d Common Nail	414	829	1243	1657	2486
Struct 1 Sheathing (7/8)	16d Common Nail	464	928	1392	1855	2783
Struct 1 Sheathing (7/8)	Screw Type 1	358	715	1073	1430	2145
Struct 1 Sheathing (7/8)	Screw Type 2	441	[illegible]	[illegible]	[illegible]	[illegible]
General Sheathing (1 1/8)	10d Common Nail	405	[illegible]	[illegible]	[illegible]	[illegible]
General Sheathing (1 1/8)	16d Common Nail	452	[illegible]	[illegible]	[illegible]	[illegible]
General Sheathing (1 1/8)	Screw Type 1	347	695	1042	1390	2085
General Sheathing (1 1/8)	Screw Type 2	430	860	1290	1720	2581
Struct 1 Sheathing (1 1/8)	10d Common Nail	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

Expanded Deflection Estimates

$$\delta_{dia} = \frac{5vL^3W}{8EAd^2} + \frac{vL}{4G_v t_v} + \frac{L}{2}\left(\frac{e_{f\parallel}}{P_\perp} + \frac{e_{f\perp}}{P_\parallel}\right) + \frac{\sum(x\Delta_c)}{2d}$$

Available Early 2021

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Additional Resources – WoodWorks.org

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Additional Resources – WoodWorks.org

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Additional Resources – WoodWorks.org

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Questions?

This concludes The American Institute of Architects Continuing Education Systems Course

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