CLT Floor and Roof Diaphragms for Seismic and Wind Resistance

Presented May 27, 2021

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Senior Technical Director – Mass Timber

WoodWorks – Wood Products Council

Architect Hacker, Photo: Structurlam

John W. Olver Design Building

At UMass Amherst

Photo Credit: Alex Schreyer

Cheney Park Apartments CLT floor on Panelized Light Frame Walls

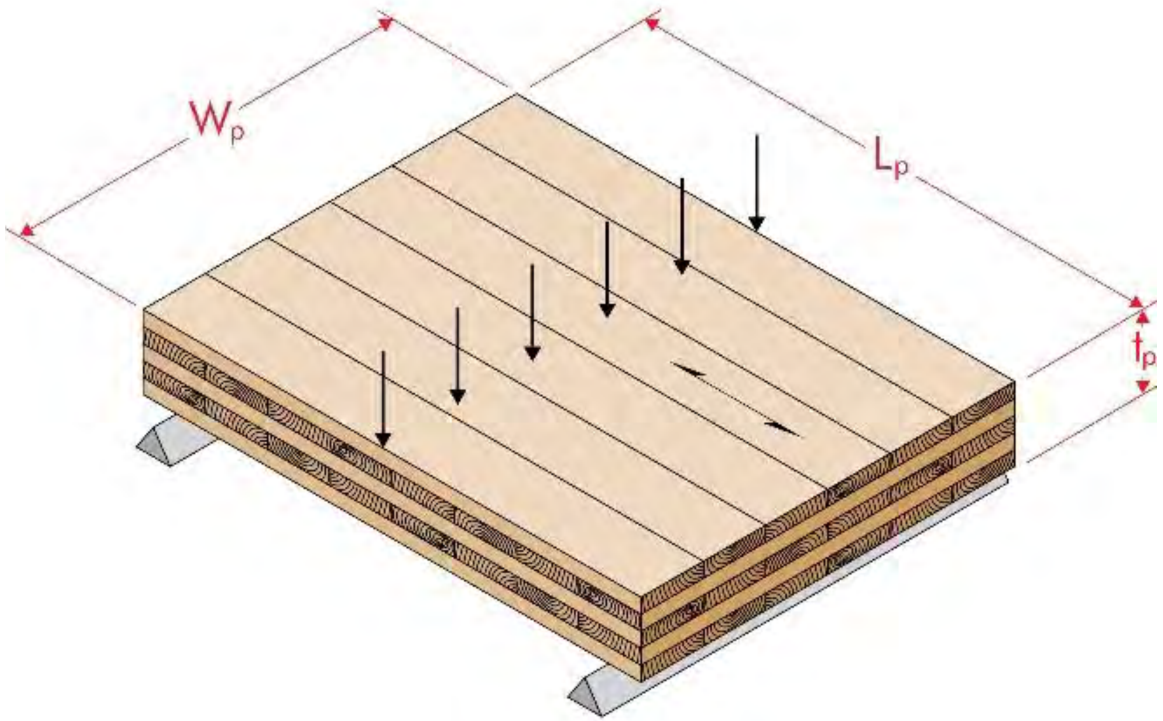

Photo Credit: WoodWorks

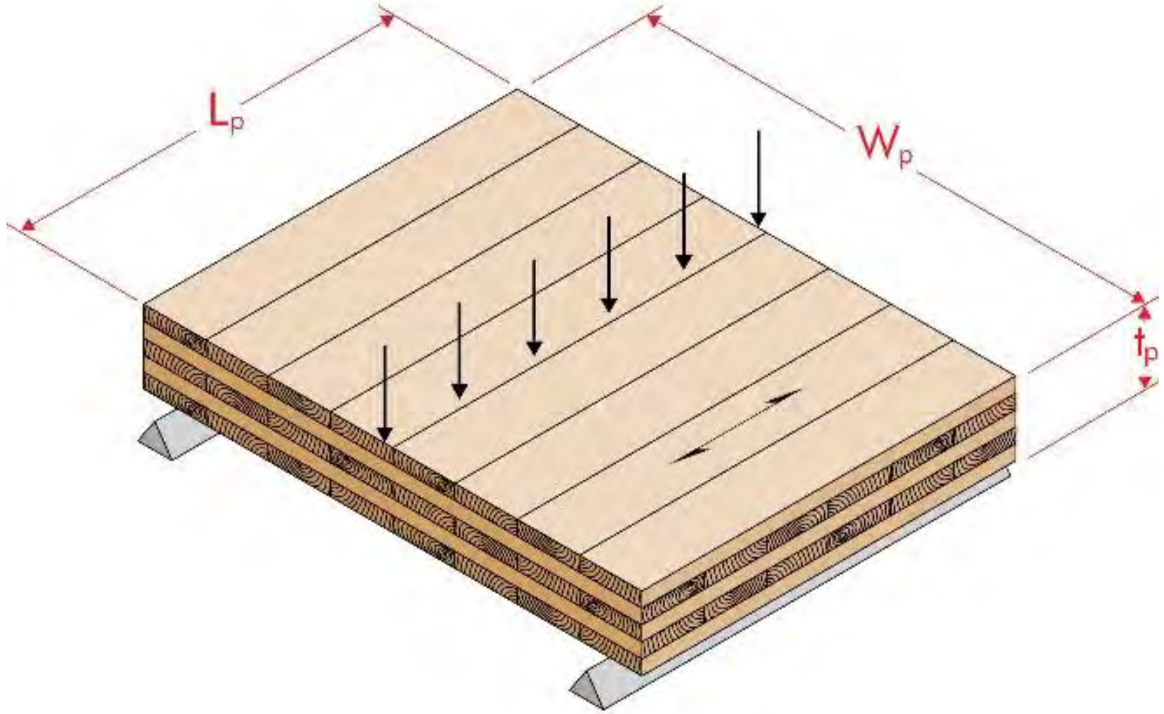

Photo Credit: WoodWorks

CLT Building Code Acceptance

2015 International Building Code

FLATWISE Panel Loading



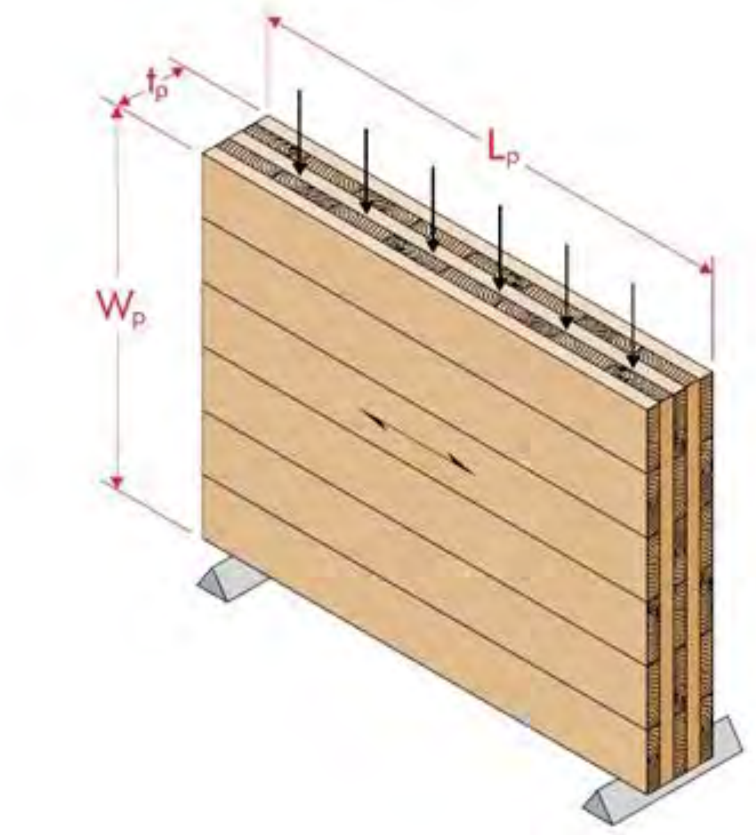


Span in MAJOR Strength Direction
"Parallel" Direction
Use subscript '0' in Notation

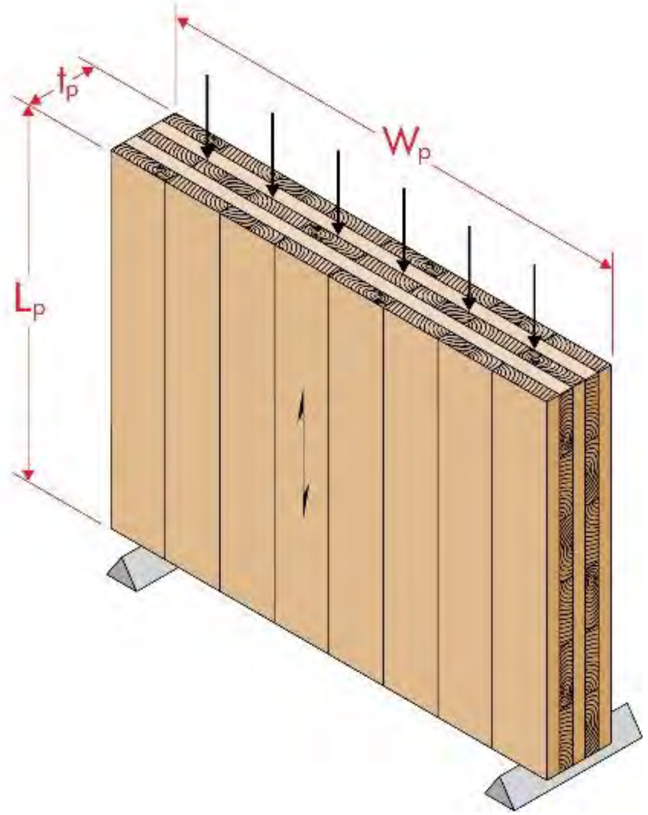
Span in MINOR Strength Direction
"Perpendicular" Direction
Use subscript '90' in Notation

Reference & Source: ANSI/APA PRG 320

EDGEWISE Panel Loading



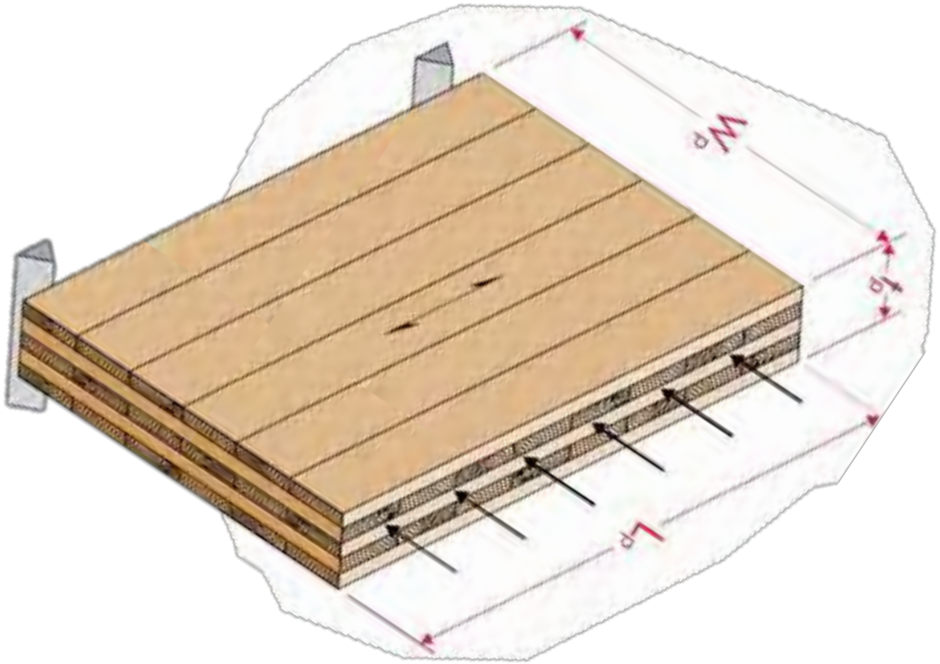
Span in MAJOR Strength Direction



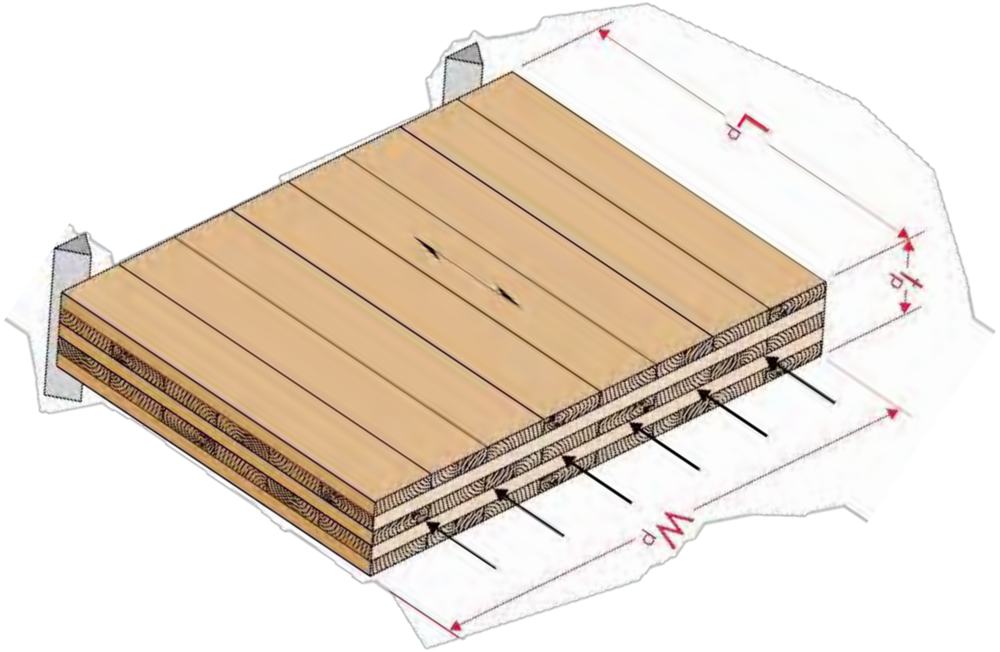
Span in MINOR Strength Direction

Reference & Source: ANSI/APA PRG 320

EDGEWISE Panel Loading



Span in MAJOR Strength Direction



Span in MINOR Strength Direction

Reference & Source: ANSI/APA PRG 320

CLT Lateral (Seismic & Wind) Design

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

ASCE/SEI 7-10 or 7-16

SDPWS 2015

CLT in 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*

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*

145 to 290 PSI Edgewise Shear Capacity

= 1.7 to 3.5 kips/ft (ASD)

per inch of thickness!

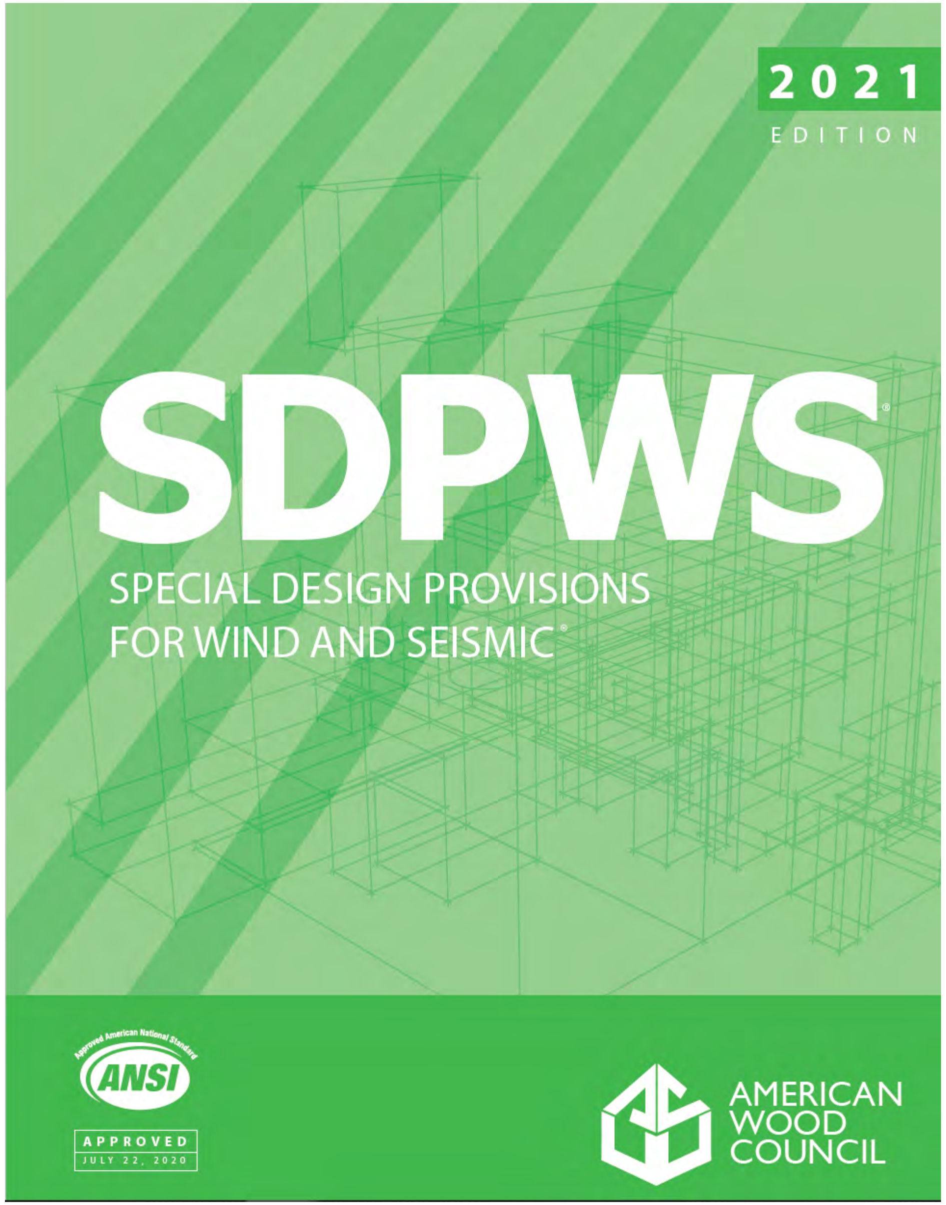
Consult with the Manufacturers for Values

Multiply by ***Cd = 1.6***

for short term ASD strength

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

2021 Special Design Provisions for Wind and Seismic



- Free view at AWC.org

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.

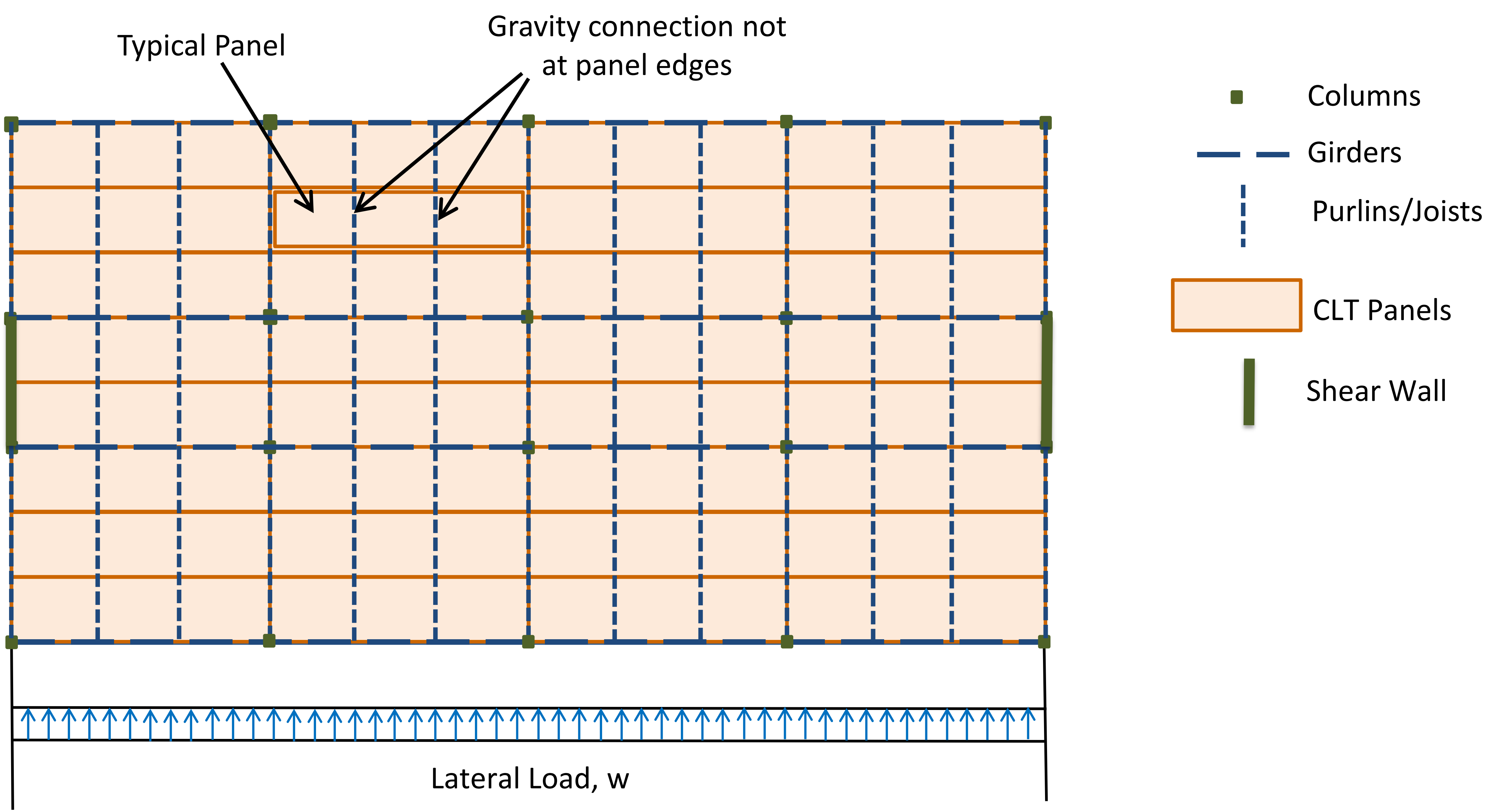
- Unit shear capacity based on dowel-type fastener connections
- Fastener Z value controlled by Mode III_s or IV per NDS
- Wood elements, steel parts and chord splice connections designed for 2.0 times forces induced from design loads

Exceptions:

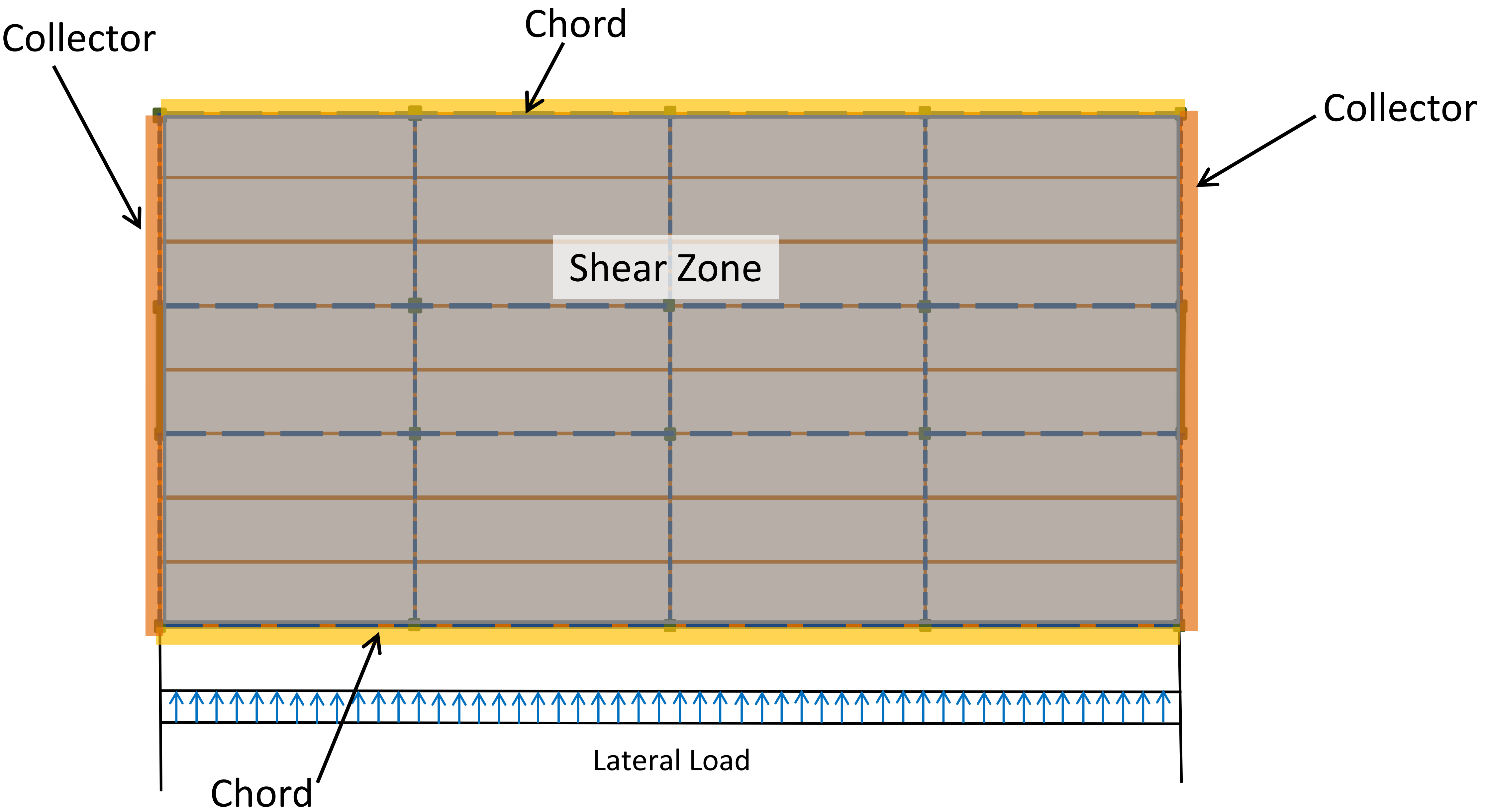
1) Wood elements and chord splice connections for wind (1.5 times)

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

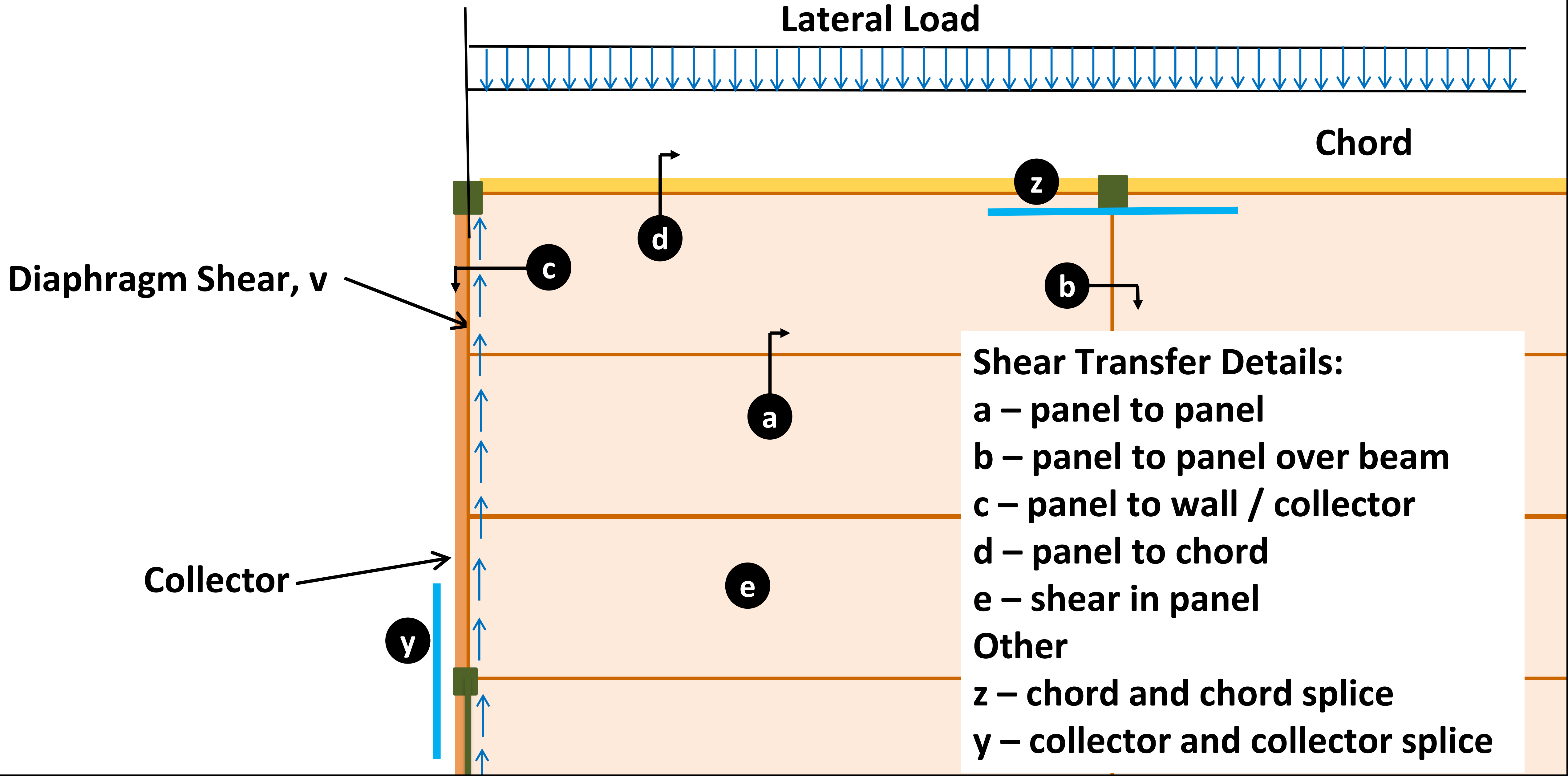
Generic Mass Timber Floor System



Example CLT Diaphragm Design



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

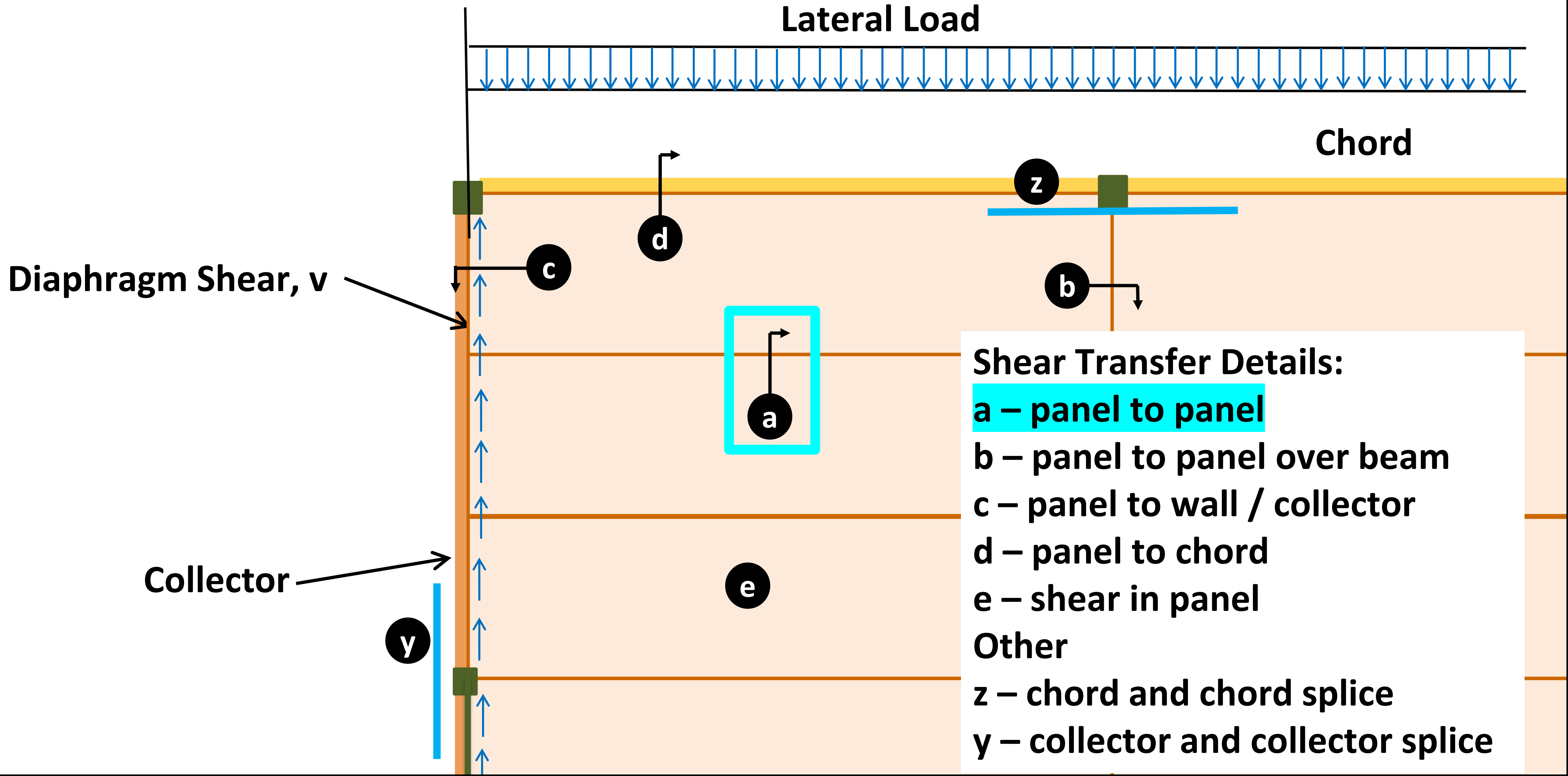
e – shear in panel

Other

z – chord and chord splice

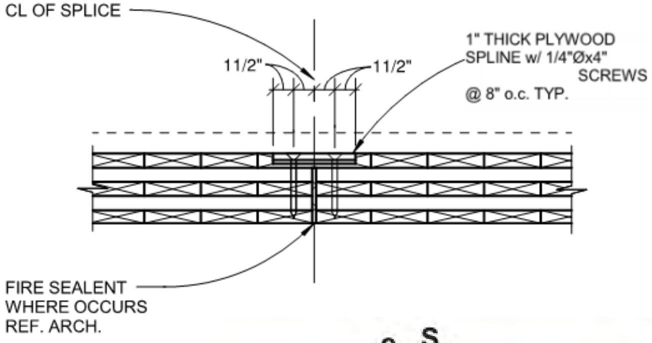
y – collector and collector splice

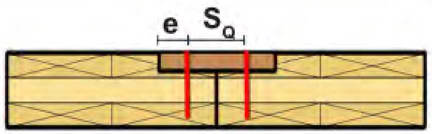
Example CLT Diaphragm Design

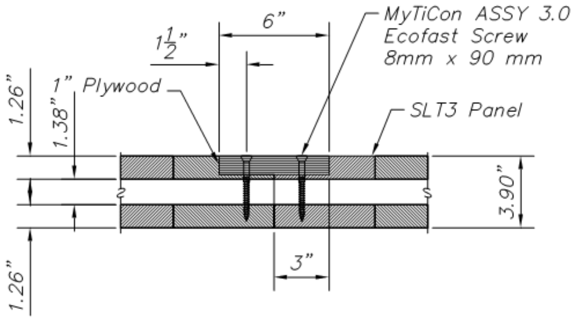


Panel to Panel Connection Styles

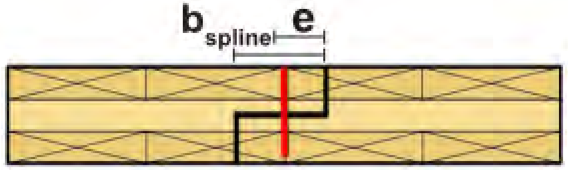
Surface Spline

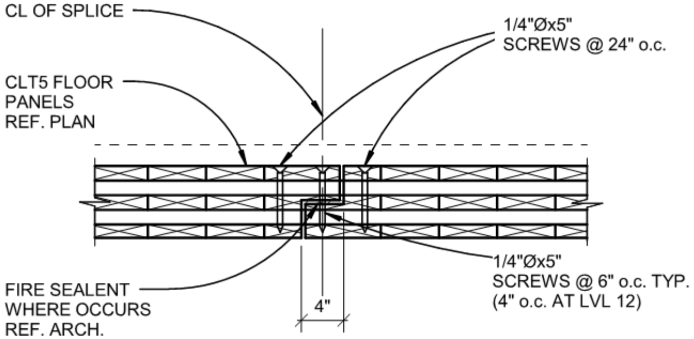






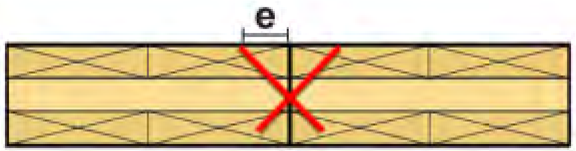
Half Lap





Load Sharing…
not load bearing

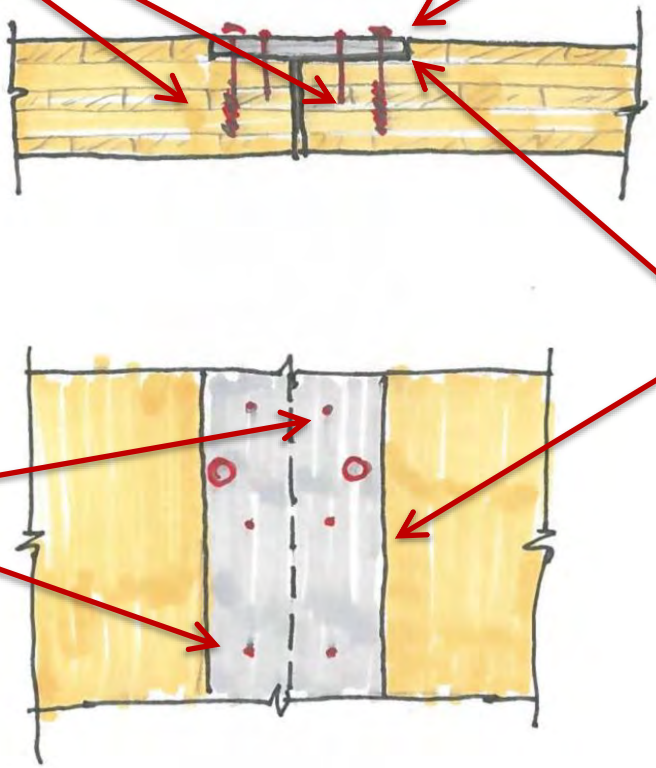
Butt Joint



An Efficient Panel to Panel Connection

Self-Tapping Screws as "erection bolts" @ ~ 24" o.c

5 ½" to 6" plywood strip ~ ¾" or 1" Thick

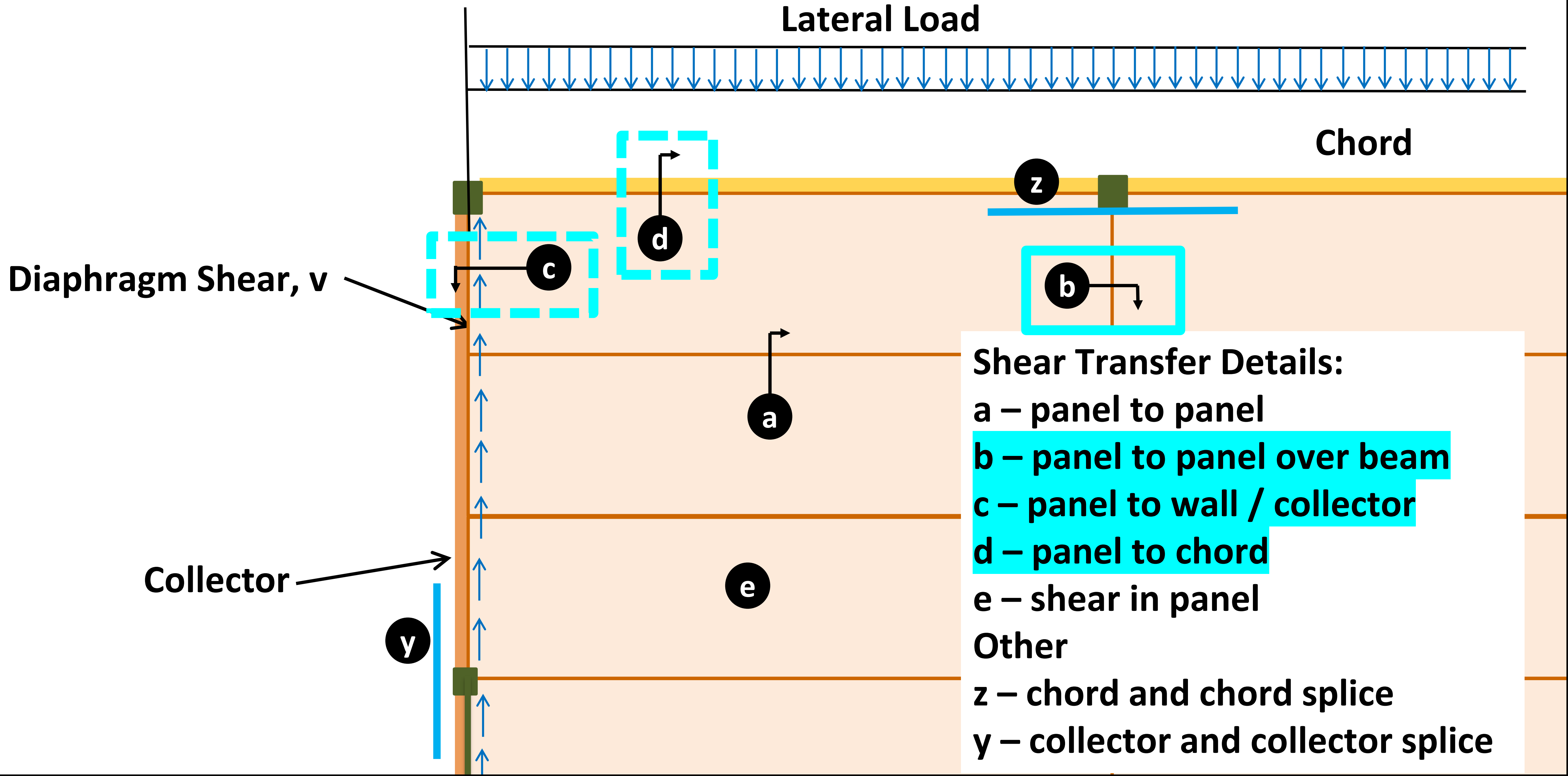


Nails at spacing required for shear transfer

Oversize rabbet cut in CLT (width of groove) 1/8" or more, each side

Graphics: ASPECT Structural Engineers

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

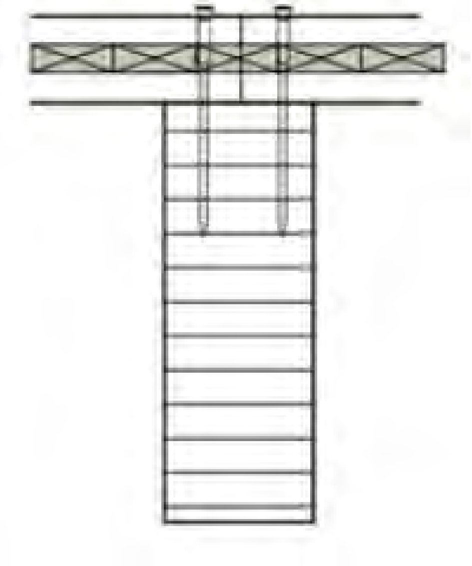
e – shear in panel

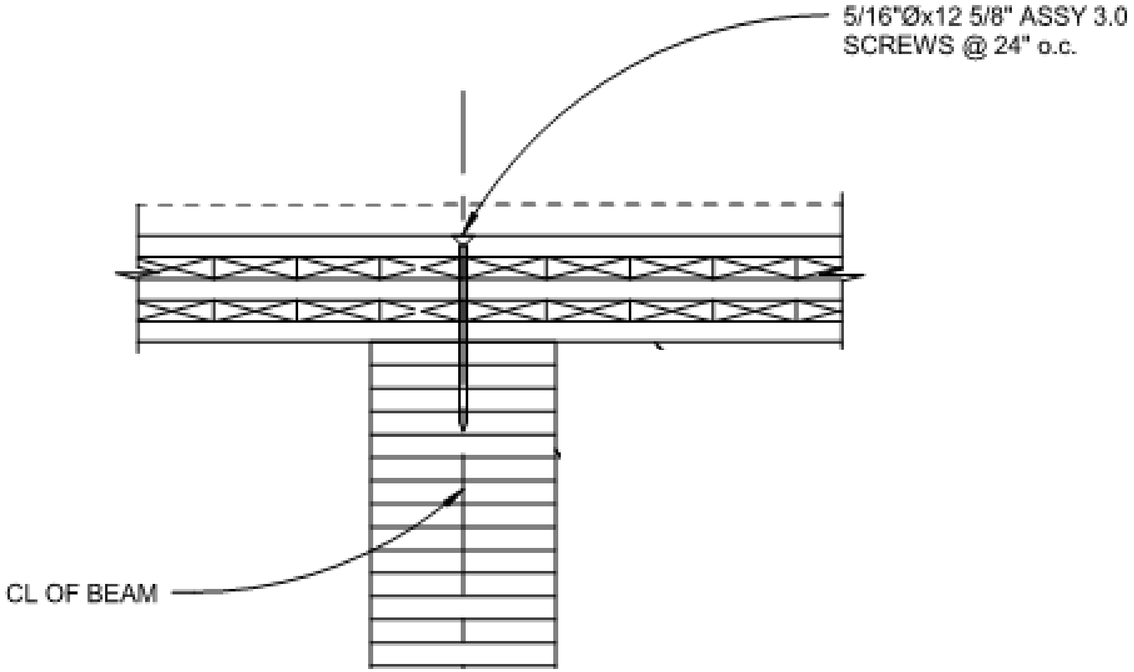
Other

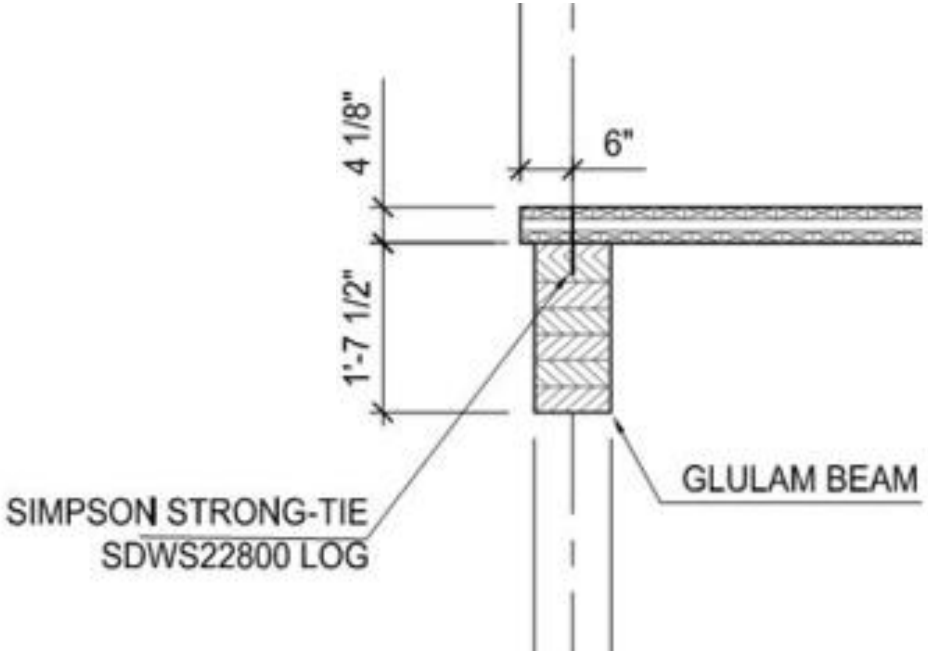
z – chord and chord splice

y – collector and collector splice

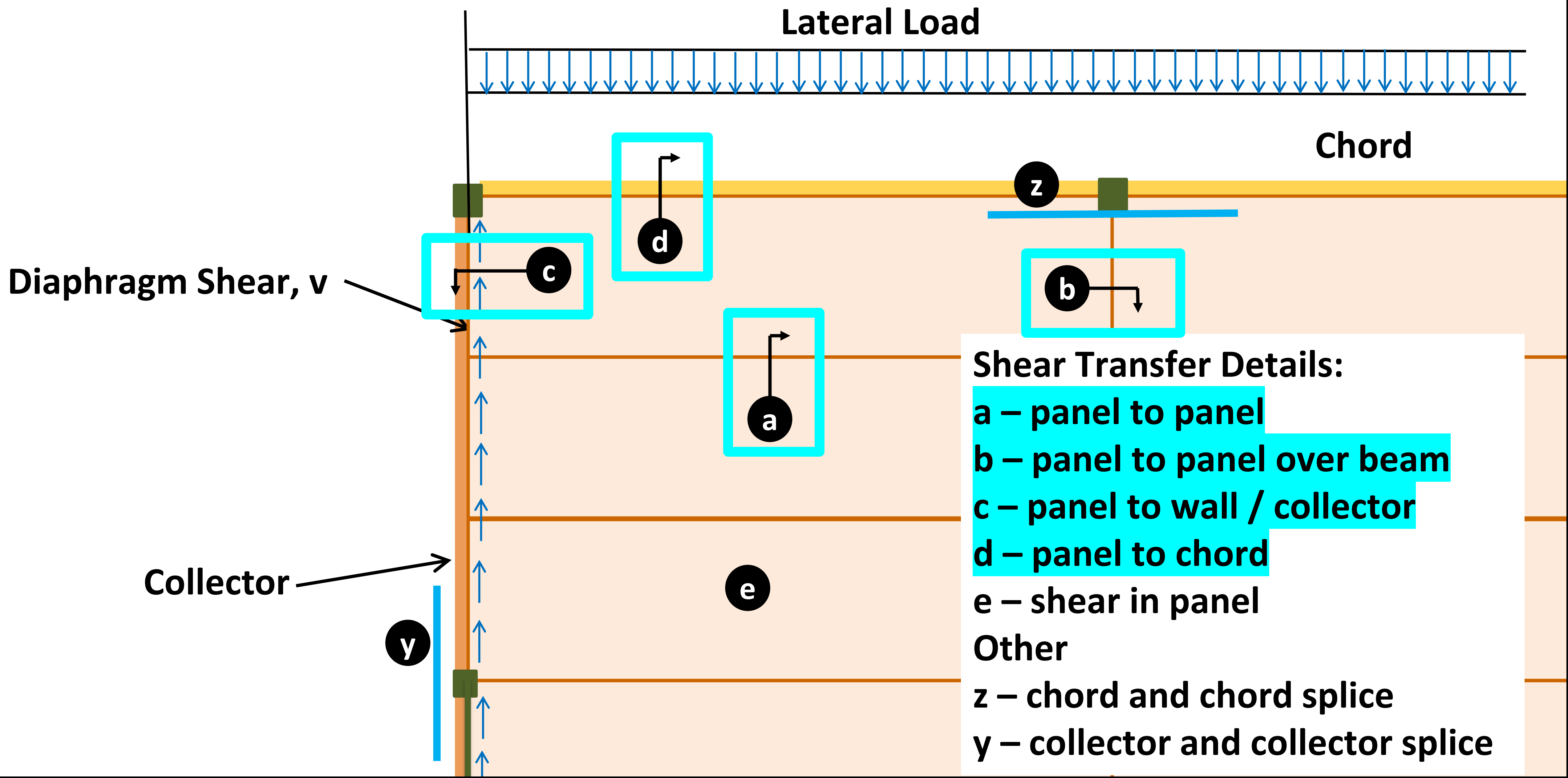
Panel to Beam Connection Styles







CLT Diaphragm Shear Transfer Connections

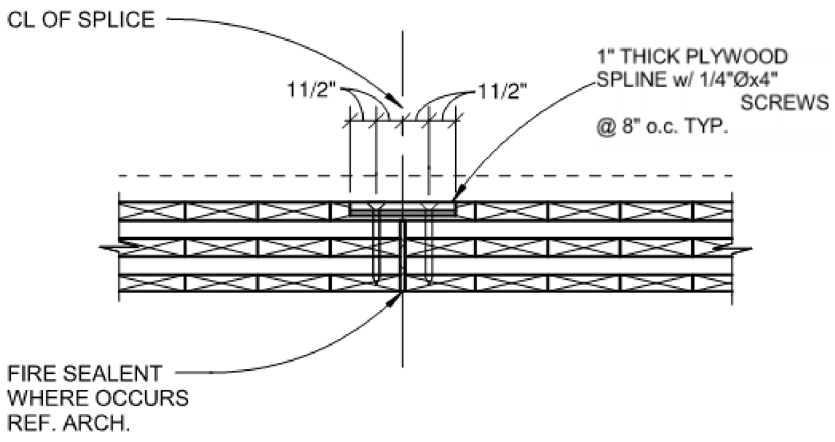


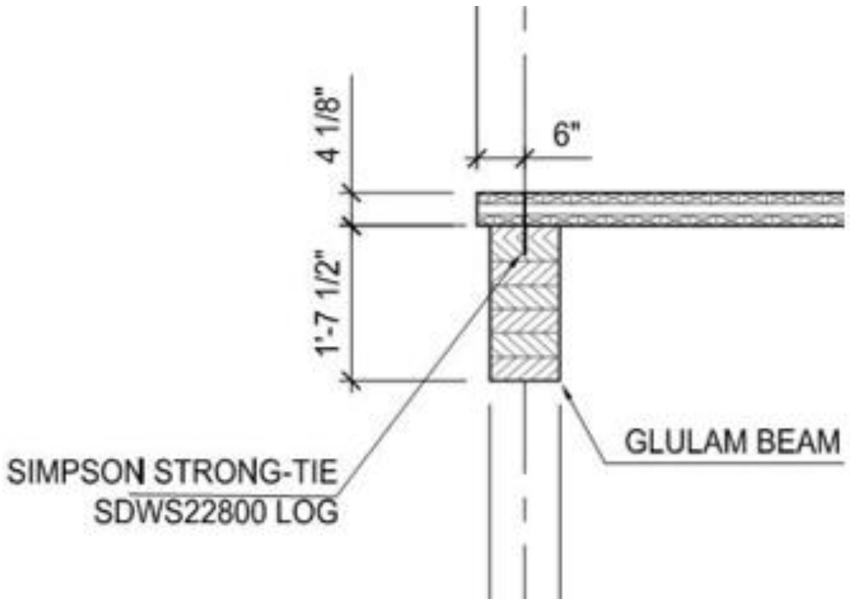
CLT Diaphragm Shear Connection Design

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

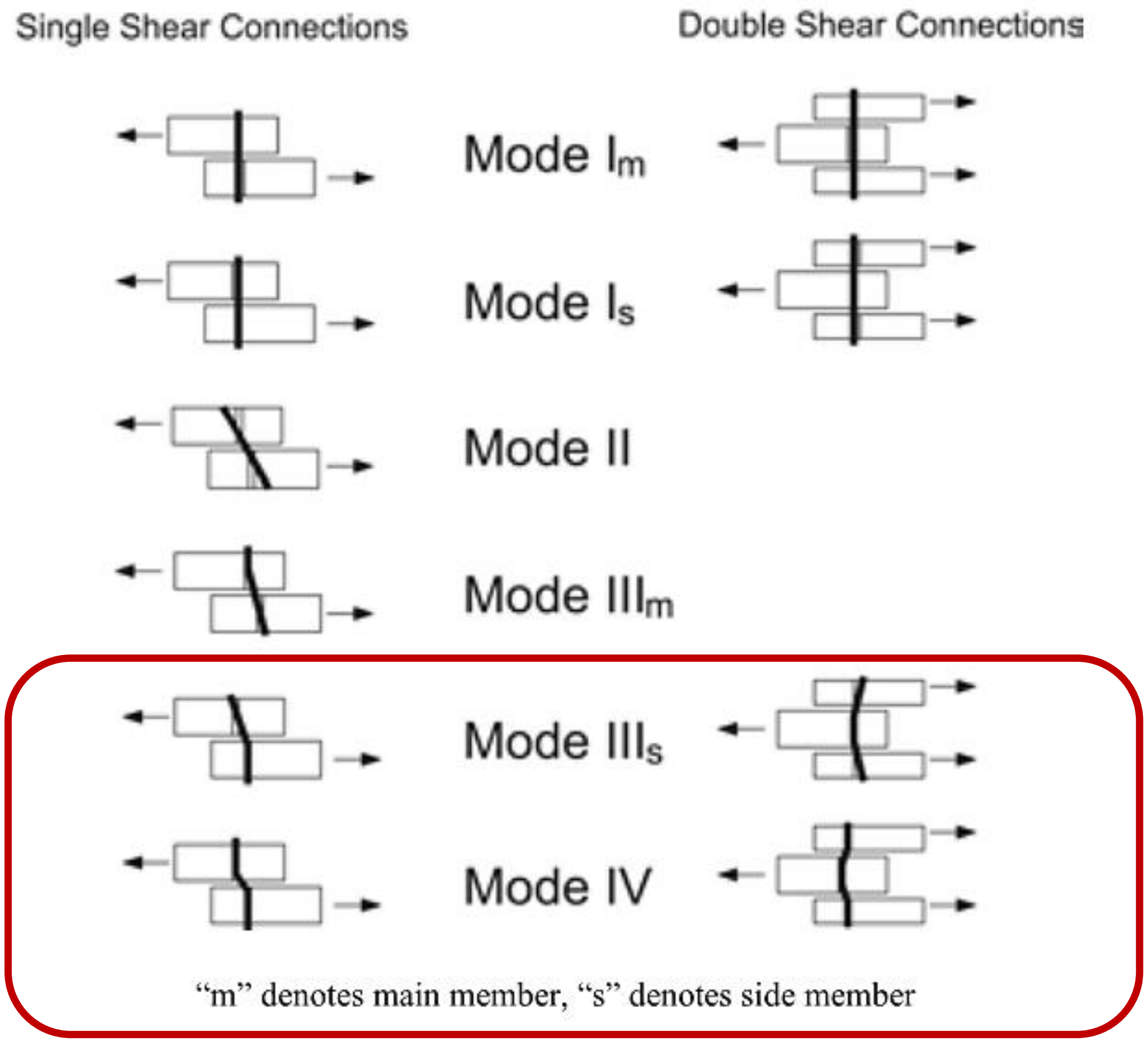




SDPWS 2021 Section 4.5.3

Connection Yield Modes Per the NDS

CLT Diaphragm Shear Capacity



CLT Diaphragm Shear Connection Design

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

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	Resistance Factor	Time Effect Factor
											K_F	ϕ	
Lateral Loads													
Dowel-type Fasteners (e.g. bolts, lag screws, wood screws, nails, spikes, drift bolts, & drift pins) $Z^* = \boxed{Z\ x}$	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

CLT Diaphragm Shear Connection Design

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

$$v_n = Z_n/\mathrm{S} = 4.5\ Z^*/\mathrm{S}$$

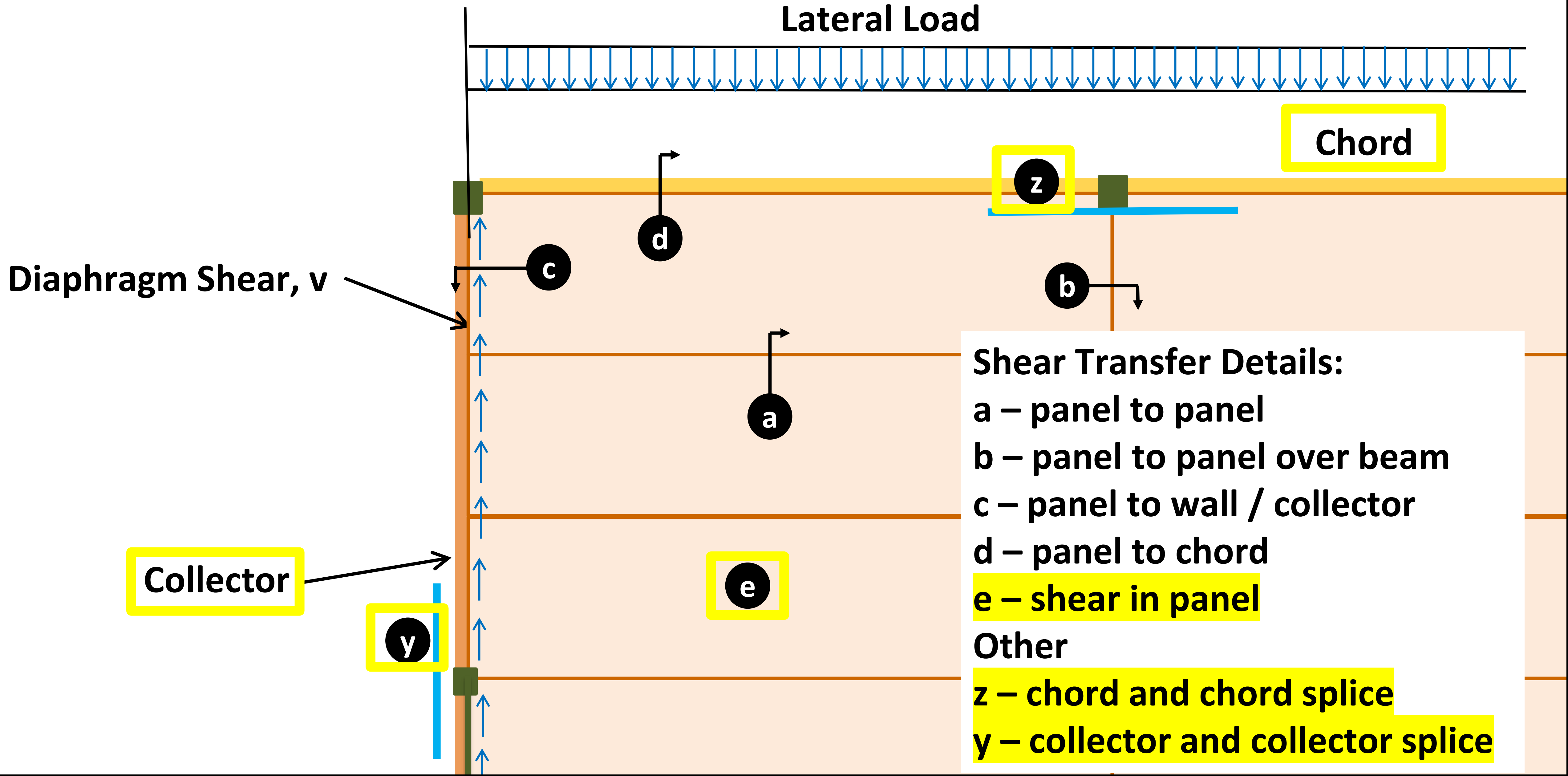
Required unit shear strength ≤ Design unit shear capacity

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

LRFD $$v = v_u \leq \phi_d v_n$$ ϕ_d = 0.5 (seismic) = 0.8 (wind)

SDPWS 2021 Section 4.1.4 and 4.5.4(1)

Other CLT Diaphragm Components



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

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:

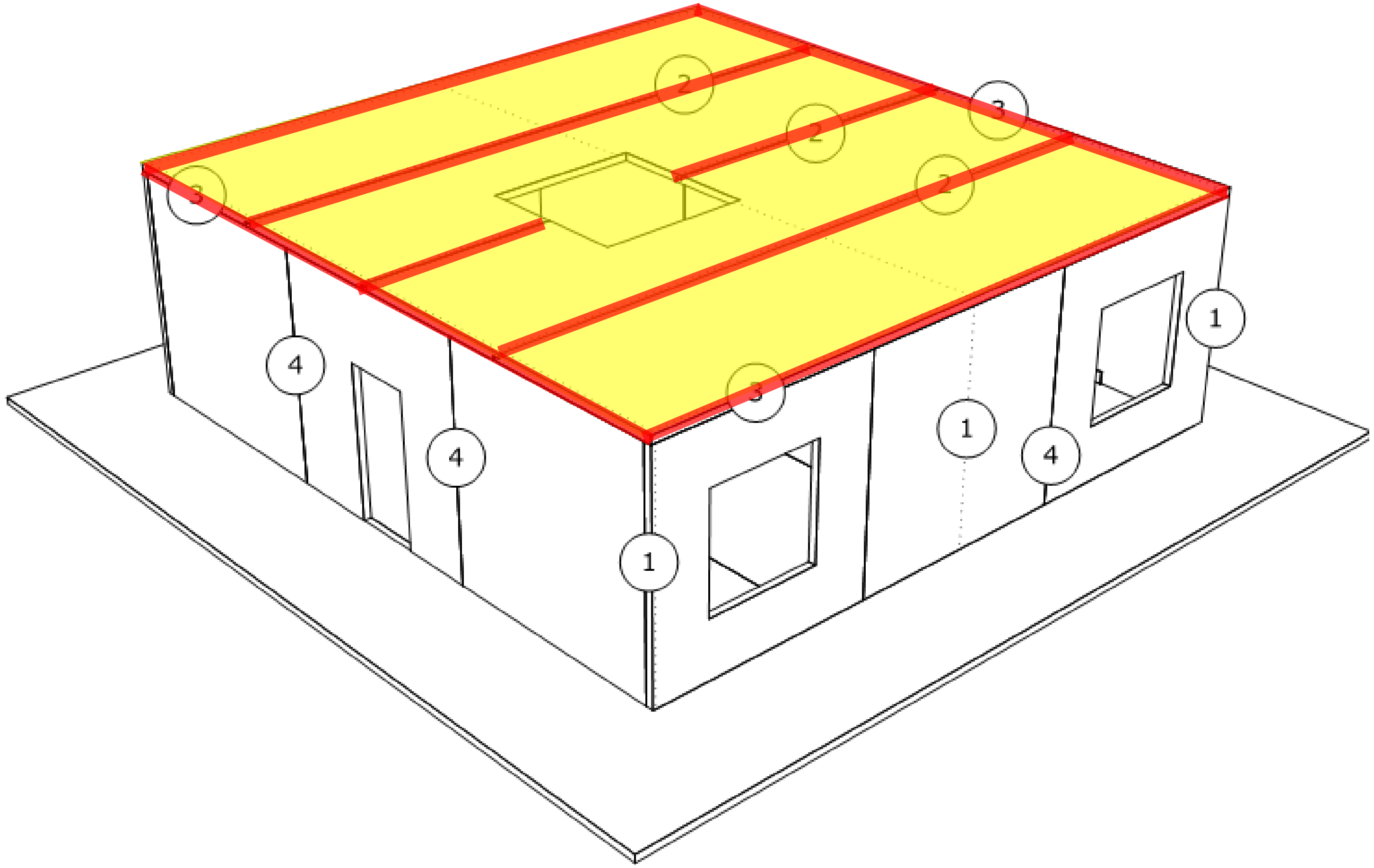
1.5 wood members resisting wind loads

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

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

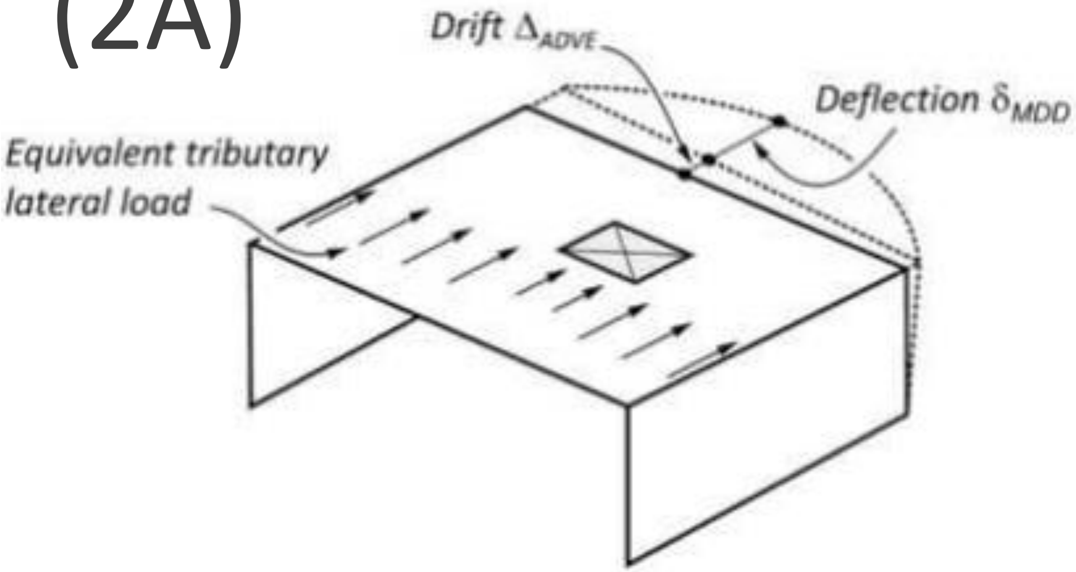
*See **SDPWS 2021 Section 4.5.4** for the full information*

CLT Diaphragms



Is the Diaphragm Rigid or Flexible?

(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:

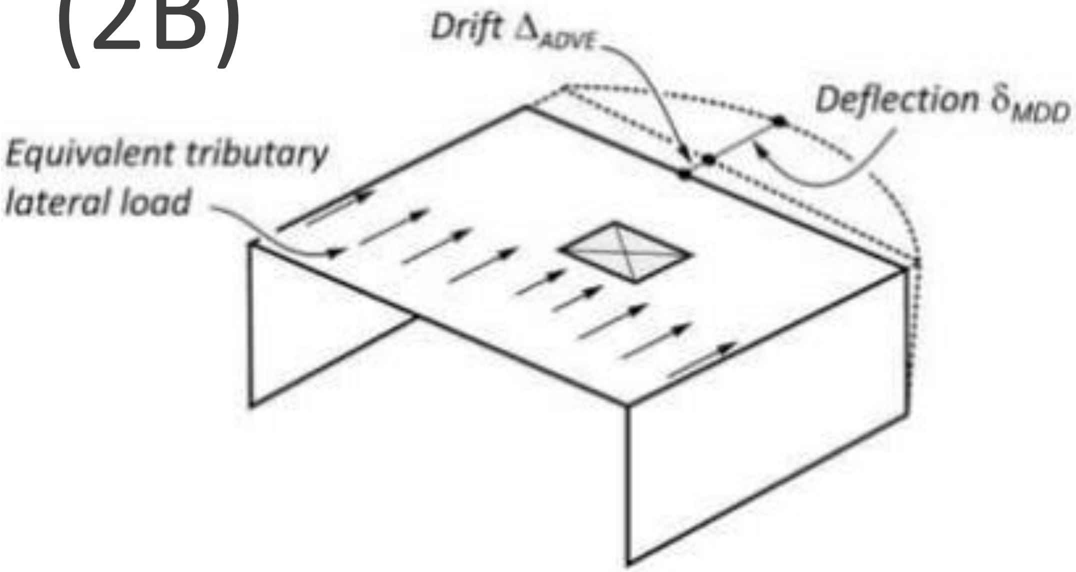
$$\frac{\delta_{MDD}}{\Delta_{ADVE}} > 2 \qquad (12.3\text{-}1)$$

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

(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.

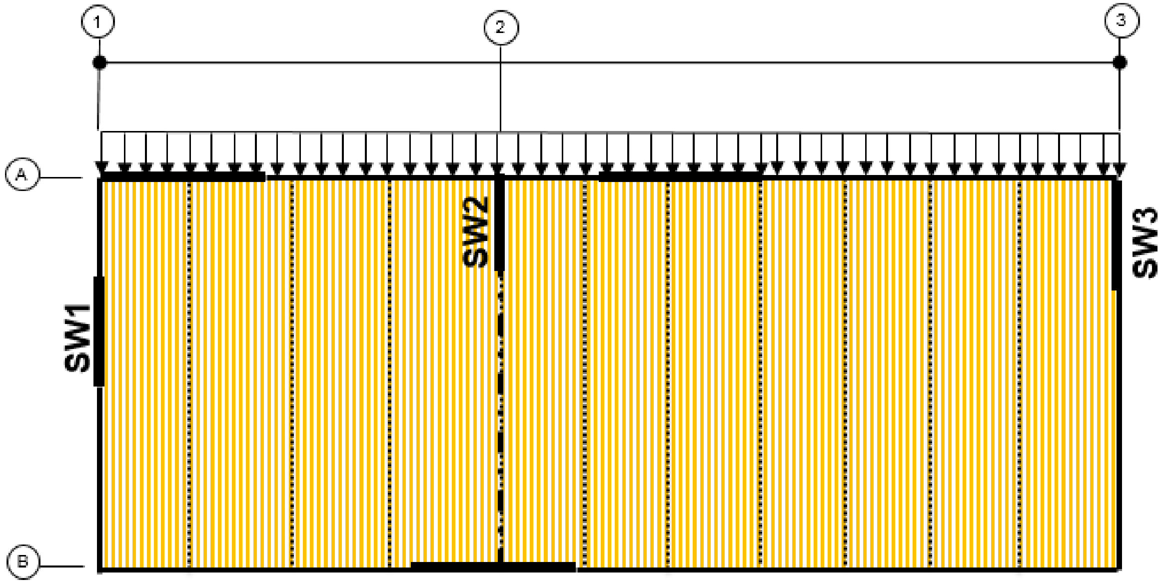
Rigid by Calculation

IBC 1604.4

CLT Diaphragm Deflection Requirements

SDPWS 2021 Section 4.5.2 Requirement:

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



2015 White Paper on CLT Diaphragms

CROSS LAMINATED TIMBER

Horizontal Diaphragm Design Example

Our aim for this white paper is to provide a practical design method to determine the strength of a Cross Laminated Timber horizontal diaphragm and deflection due to lateral wind or seismic loads.

CLT HORIZONTAL DIAPHRAGM DESIGN

The design approach is based on compliance with engineered design of CLT in accordance with the 2015 International Building Code, reference standards, and other published information includ...

literature.

Applicable Building Code, reference standards, and ... sources:

- *ICC, 2015 International Building Code*
- *ANSI/AWC NDS-2015 National Design Specification (NDS) for Wood Construction with Commentary*
- *AWC SDPWS-2015 Special Design Provisions for Wind and Seismic*
- *ANSI/APA PRG 320 – 2012 Standard for Performance-rated Cross-laminated Timber*
- *FP Innovations, US CLT (Cross-Laminated Timber) Handbook 2013*
- *ASCE 7-10 Minimum Design Loads for Buildings and Other Structures*
- *AISC 360-10 Specification for Structural Steel Buildings*
- *APA Product Report PR-L314 - CrossLam by Structurlam Products LP, February 20, 2014*

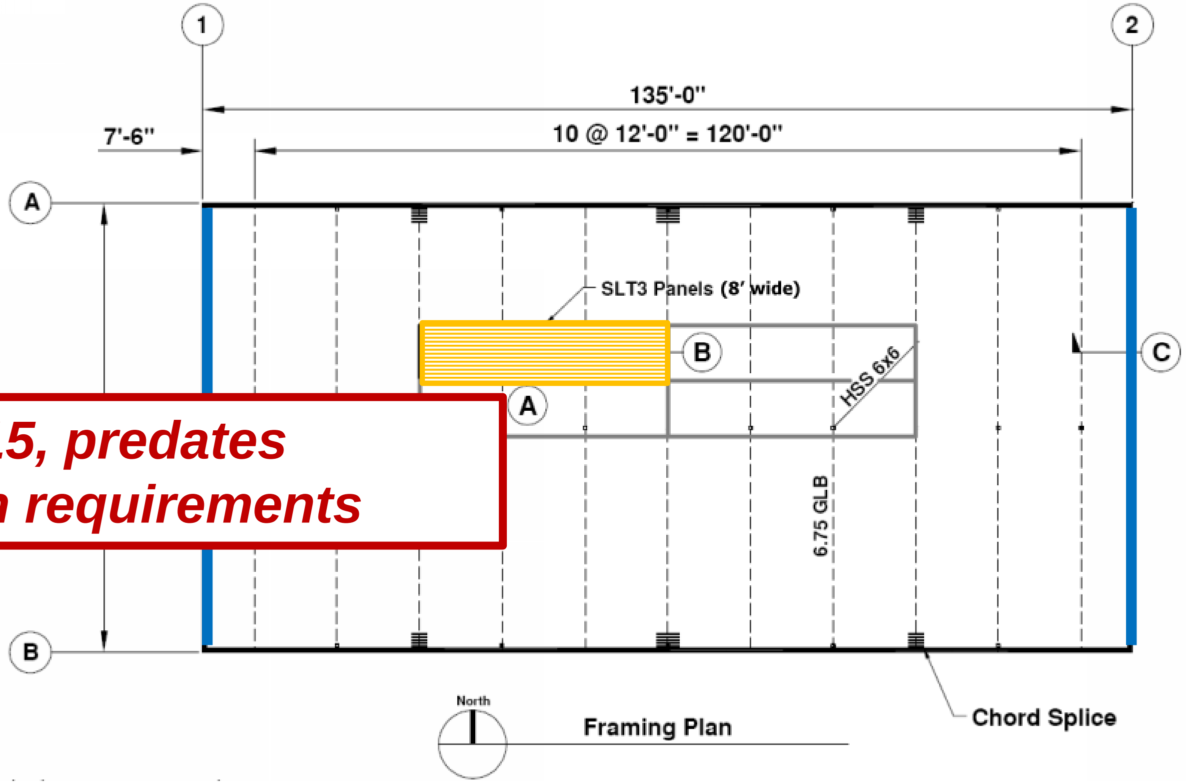
Kris Spickler P.E.
Heavy Timber Group
Structurlam Products LP
Granite Bay, CA

Surrey, BC

Philip Line, P.E.
American Wood Council
Leesburg, VA
www.awc.org

Martin Pohll P.E., S.E.
Martin Pohll Structural Engineering
Rancho Murieta, CA

Developed in 2015, predates SDPWS 2021 design requirements



Available from structurlam.com

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

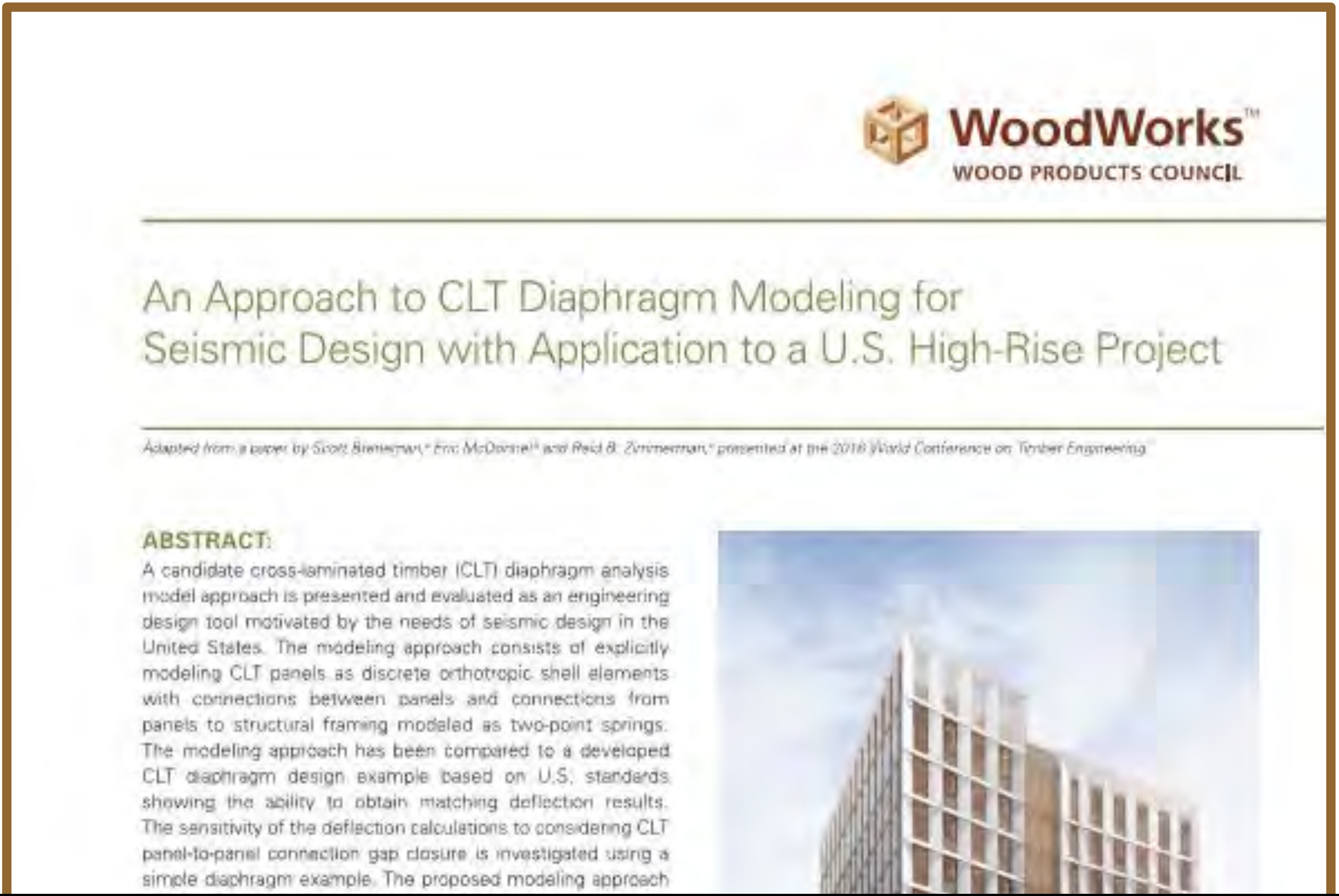
$$\delta_{dia} = \underbrace{\frac{5vL^3}{8EAW}}_{\text{Chord Flexure}} + \underbrace{\frac{vL}{4G_v t_v}}_{\text{Panel Shear}} + \underbrace{\boxed{CLe_n}}_{\text{Connector Slip}} + \underbrace{\frac{\sum(x\Delta_c)}{2W}}_{\text{Chord Slip}}$$

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

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

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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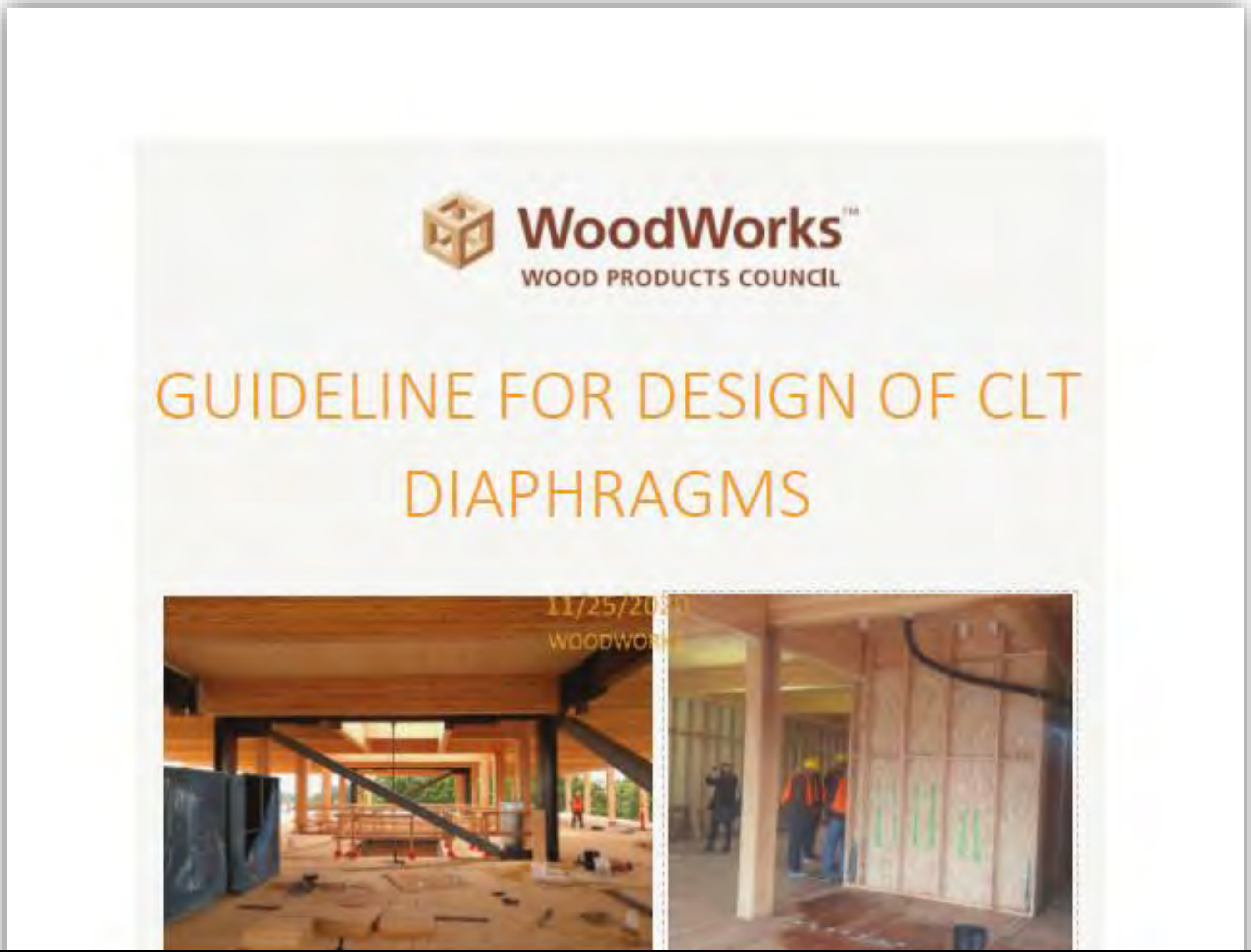
An Approach to CLT Diaphragm Modeling for Seismic Design with Application to a U.S. High-Rise Project

Adapted from a paper by Scott Breneman, Eric McDonnell and Reid B. Zimmerman, presented at the 2016 World Conference on Timber Engineering

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

WoodWorks CLT Diaphragm Guideline with Examples



Under Development By:

WoodWorks
WOOD PRODUCTS COUNCIL

Holmes Structures

kpff

SWINERTON
MASS TIMBER

Funded By:

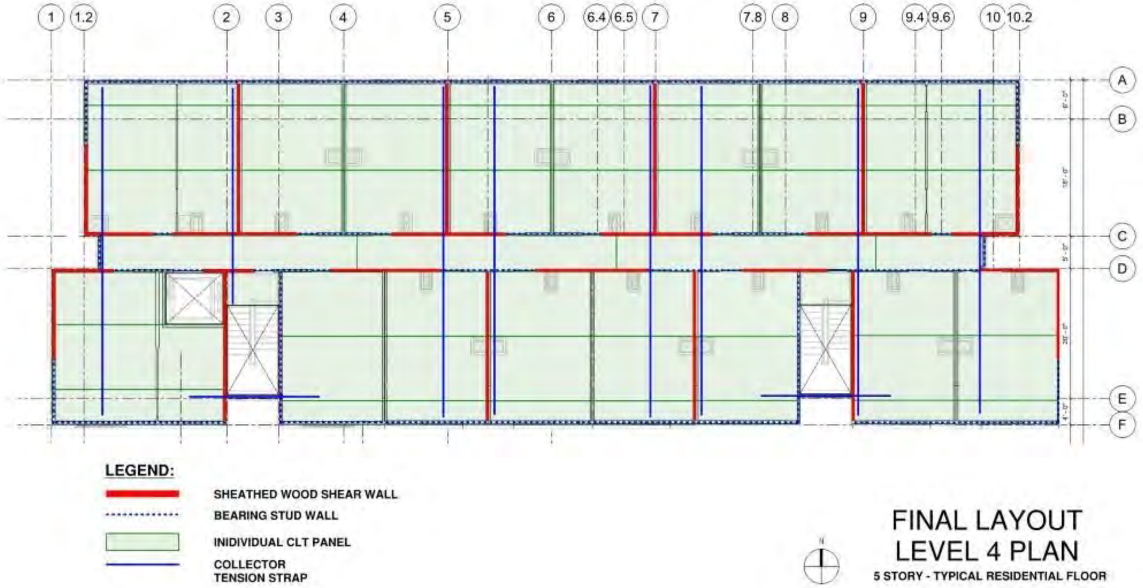
U.S. Endowment
for Forestry and Communities

USDA

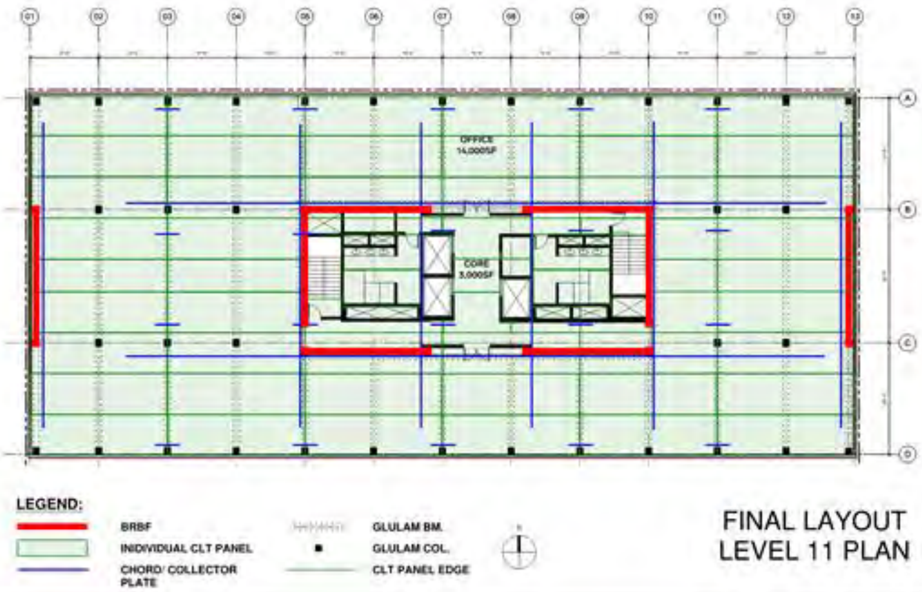
WoodWorks CLT Diaphragm Guideline with Examples

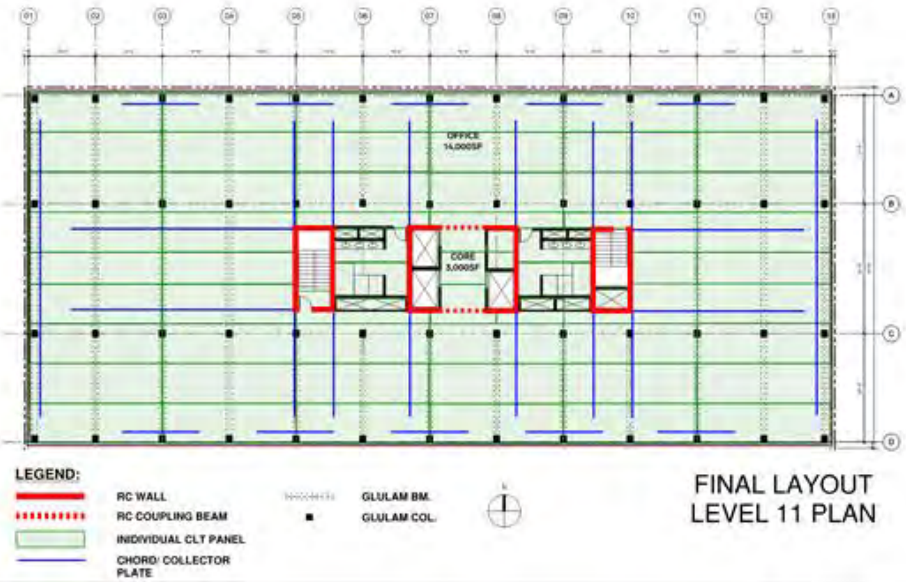
3 Examples

High and Low Seismic & Wind



Example from Holmes Structures





Thank You! Questions?

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