Cross-Laminated Timber (CLT) Shear Wall

2020 NEHRP Provisions Training Materials

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1

6.1 Overview - Cross-Laminated Timber (CLT) Shear Wall Example

- This example features the seismic design of cross-laminated timber shear walls used in a three-story, six-unit townhouse cross-laminated timber building of platform construction
- The CLT shear wall design in this example includes:
  - Check of CLT shear wall shear strength
  - Check of CLT shear wall hold-down size and compression zone length for overturning
  - Check of CLT shear wall deflection for conformance to seismic drift

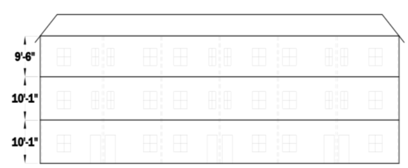

Figure 6-2. Elevation

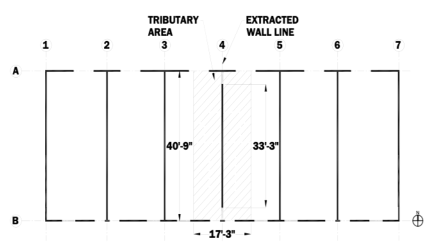

Figure 6-3. Typical Floor Plan (first story openings shown)

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2

6.1 Overview - Useful Design Aid Resources

- The following documents are used in this example
  - ASCE/SEI 7-22 Minimum Design Loads and Associated Criteria for Buildings and Other Structures
  - AWC (2020). Special Design Provisions for Wind and Seismic (SDPWS), SDPWS-21, American Wood Council
  - AWC (2017). National Design Specification (NDS) for Wood Construction, NDS-18, American Wood Council, Leesburg, VA, 2017
  - APA (2020). Standard for Performance-Rated Cross-Laminated Timber, ANSI/APA PRG 320-19, APA, 2020
  - FEMA (2020a). NEHRP Recommended Seismic Provisions for New Buildings and Other Structures, Volume I: Part 1 Provisions and Part 2 Commentary, 2020 Edition, FEMA P-2082-1, prepared by the Building Seismic Safety Council of the National Institute of Buildings Sciences for Federal Emergency Management Agency

3

6.2 Background

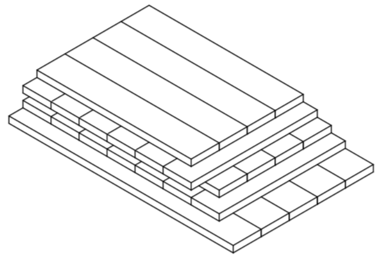
- NEHRP (2020a) proposed additions for ASCE/SEI 7-22 Table 12.2-1 featuring cross-laminated timber (CLT) shear walls

Seismic Force-Resisting System	Detailing Requirements, ASCE/SEI 7-22 Section	R	Ω_O	C_d	Structural System Limitations Including Structural Height, h_n (ft) Limits[d]				
					Seismic Design Category				
					B	C	D	E	F
A. BEARING WALL SYSTEMS									
Cross laminated timber shear walls	14.5	3	3	3	65	65	65	65	65
Cross laminated timber shear walls with shear resistance provided by high aspect ratio panels only	14.5	4	3	4	65	65	65	65	65

4

6.2 Background

- Cross-laminated timber (CLT)
  - Usually 3, 5 or 7 layers of dimension lumber stacked in alternating directions and bonded together with adhesive
  - Research and development for CLT began in the early 1990s in Europe
  - The first production facilities established in 1994 in Austria, Germany and Switzerland
  - The term coined in 2000 at the COST E5 conference in Italy



CLT panel with layers stacked in alternating (crossing) directions

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5

6.2 Background

- Cross-laminated timber (CLT)
  - Stadthaus, London, 2009
  - Residential
  - 9 stories
  - 9 weeks of CLT construction
  - 4 laborers
  - 1 supervisor

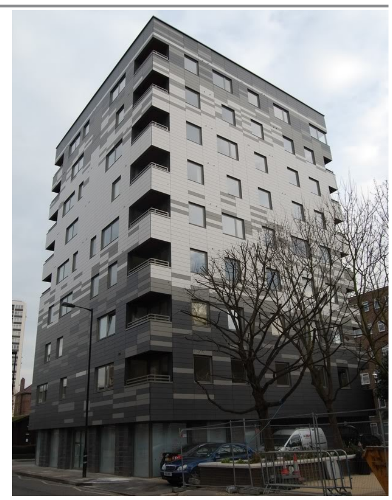

Photo credit: Will Pryce

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6.2 Background

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6.2 Background

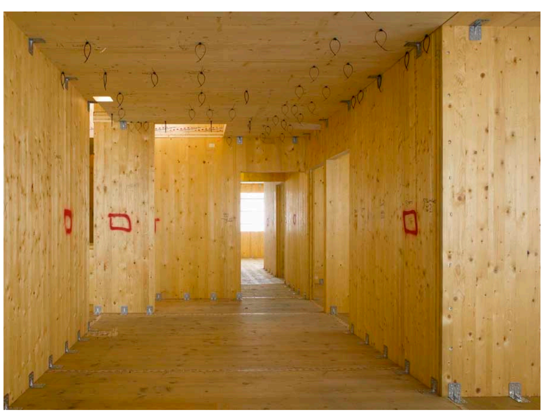
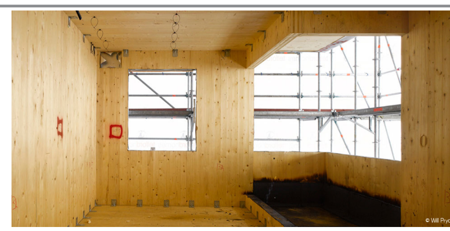
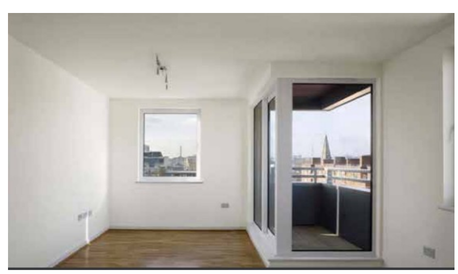


Photo credit: Will Pryce





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8

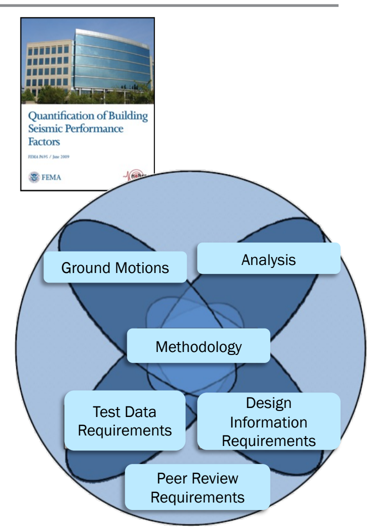
6.2 Background

Ft. Drum, NY (4-story), 2017; Courtesy Jeff Morrow, Lendlease

9

6.2 Background

- FEMA P-695: Quantification of Building Seismic Performance Factors
  - Peer review throughout
  - Archetypes
  - Design methodology
  - Nonlinear time history analysis
  - Performance evaluation (CMR & ACMR)
- Project Documentation: van de Lindt, J., Amini, M. O. , Rammer, D., Line, P., Pei, S., and Popovski, M. (2022) "Determination of Seismic Performance Factors for Cross-Laminated Timber Shear Walls Based on the FEMA P695 Methodology." General Technical Report FPL-GTR-281, Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory.



10

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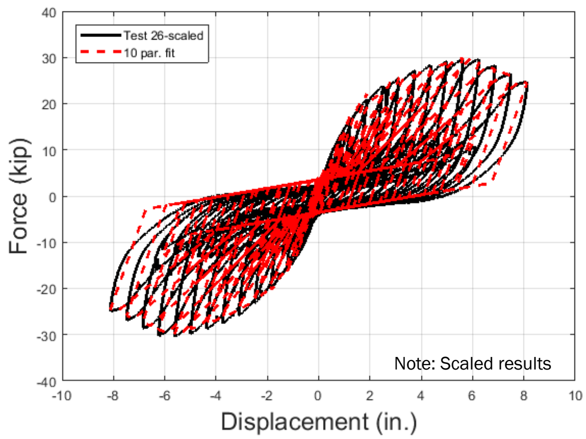

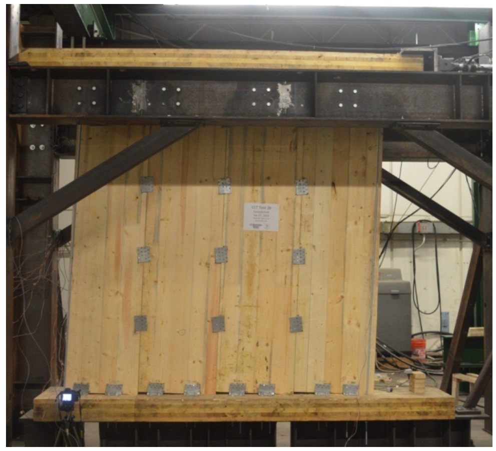

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11

6.2 Background

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12

6.2 Background



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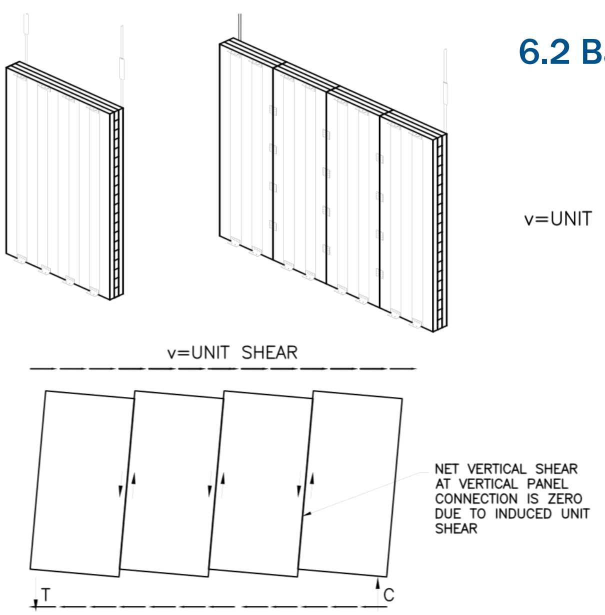

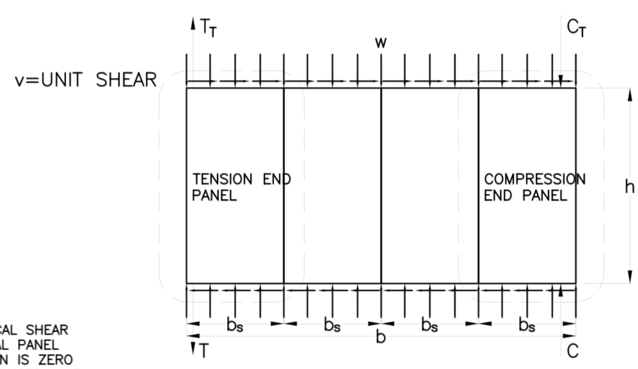

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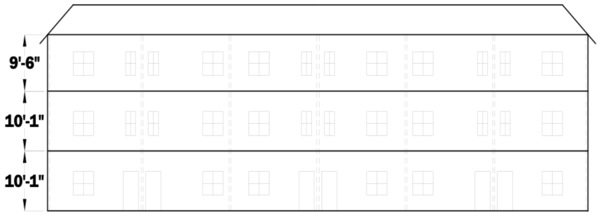


Figure 6-2. Elevation

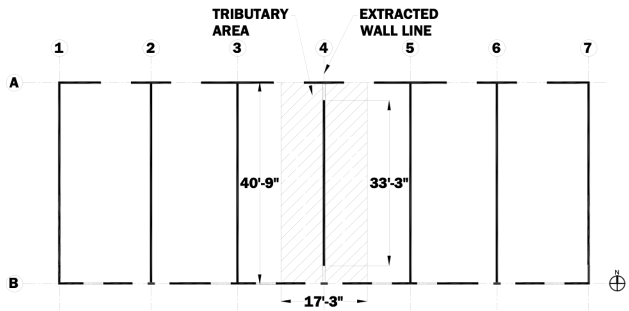


Figure 6-3. Typical Floor Plan (first story openings shown)

6.3 Cross-Laminated Timber Shear Wall Example Description

- A three-story, six-unit townhouse cross-laminated timber building of platform construction
- The CLT shear wall design in this example includes:
  - Check of CLT shear wall shear strength
  - Check of CLT shear wall hold-down size and compression zone length for overturning
  - Check of CLT shear wall deflection for conformance to seismic drift

6.3 Cross-Laminated Timber Shear Wall Example Description

Table 6-1: Weights of Roof/Ceiling, Floors, and Walls

Item	Description	Weight
Roof/Ceiling	Light-frame roof, gypsum board ceiling, roofing, insulation	25 psf
Floor	5-layer CLT (6.875 in. thick), gypsum board ceiling, flooring. Includes 8 psf of floor area for wall partitions	35 psf
Interior Walls	3-layer CLT (4.125 in. thick), light-frame wall, gypsum board finish, sound insulation	20 psf
Exterior Walls	3-layer CLT (4.125 in. thick), light-frame wall, gypsum board interior finish, stucco exterior, insulation	30 psf

6.3 Cross-Laminated Timber Shear Wall Example Description

Table 6-3: Design Coefficients and Factors for CLT Seismic Force-Resisting Systems (ASCE/SEI 7-22)

Seismic Force-Resisting System	Detailing Requirements, ASCE/SEI 7-22 Section	R	Ω_0	C_d	Structural Height, h_n, Limit Seismic Design Category B, C, D, E & F
Cross-laminated timber shear walls	14.5	3	3	3	65 feet
Cross-laminated timber shear walls with shear resistance provided by high aspect ratio panels only	14.5	4	3	4	65 feet

17

6.4 Seismic Forces

- Seismic base shear calculation assumptions:
  - S_{DS} = 1.0
  - I_e = 1.0
  - R = 3 (for *CLT shear walls)*
- Seismic base shear, V, per ASCE/SEI 7-22 Equation 12.8-2 (for short-period structures):

$$V = C_s W = \frac{S_{DS}}{(R/I)} W = \frac{1.0}{(3.0/1.0)} W = 0.333\ W\ kips$$

- The portion of base shear tributary to the CLT shear walls of interest is:

  $V_{(Line\ 4)}$ = 42.3 kips

18

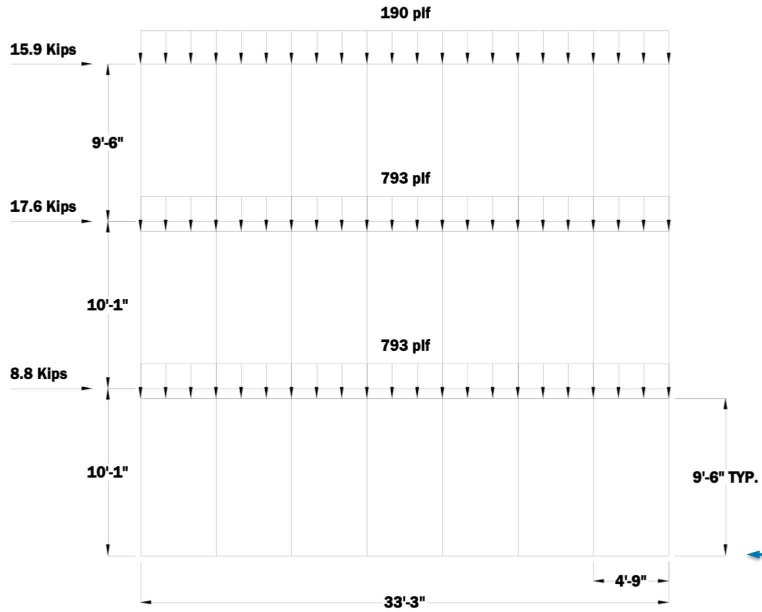


Figure 6-4. Vertical Distribution of Seismic Force and Dead Load Tributary to the CLT Shear Walls Located Along Line 4

6.4 Seismic Forces

Table 6-4: Summary of Cumulative Lateral Seismic Force and Unit Shear Force per Story (Along Line 4)

Story	Lateral force, V_x	Unit Shear Force per Foot of Shear Wall Length
	(kips)	(plf)
3	15.9	477
2	33.5	1,009
1	42.3	1,273

$V_{(\text{Line 4})}$ = 42.3 kips

6.5.1 Shear Capacity of Prescribed Connectors

- LRFD design unit shear capacity for seismic:

$$v_{s(\text{seismic})} = \phi(n)\left(\frac{2605}{b_s}\right)C_G \qquad \text{(SDPWS-21 Eq. B-2)}$$

where:

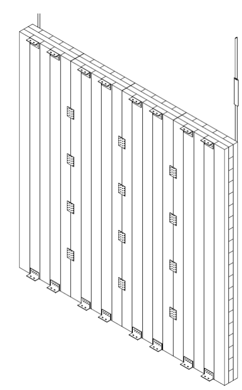
n = number of angle connectors along bottom of panel face

2,605 = connector nominal shear capacity (lb)

b_s = individual CLT panel length (ft)

C_G = CLT panel specific gravity factor which equals 1.0 for G≥0.42 specific gravity panels used in this example, and

ϕ = resistance factor equal to 0.5 for seismic design



From SDPWS Figure C-B.1

6.5.1 Shear Capacity of Prescribed Connectors

Table 6-5: CLT Shear Wall Connectors and LRFD Design Unit Shear Capacity

Story	Panel thick-ness	Panel length, b_s	Panel height, h	Number of connectors per panel at top and bottom panel edge	Number of connectors at each adjoining vertical panel edge	v_n, Nominal unit shear capacity, $(n \cdot 2605)/b_s$	$v_{s(seismic)}$, LRFD design unit shear capacity, (ϕ= 0.5)
	(in.)	(ft)	(ft)	(n)	(n x h/b_s)	(plf)	(plf)
3	4.125	4.75	9.5	2	4	1,096	548
2	4.125	4.75	9.5	4	8	2,193	1,097
1	4.125	4.75	9.5	5	10	2,742	1,371

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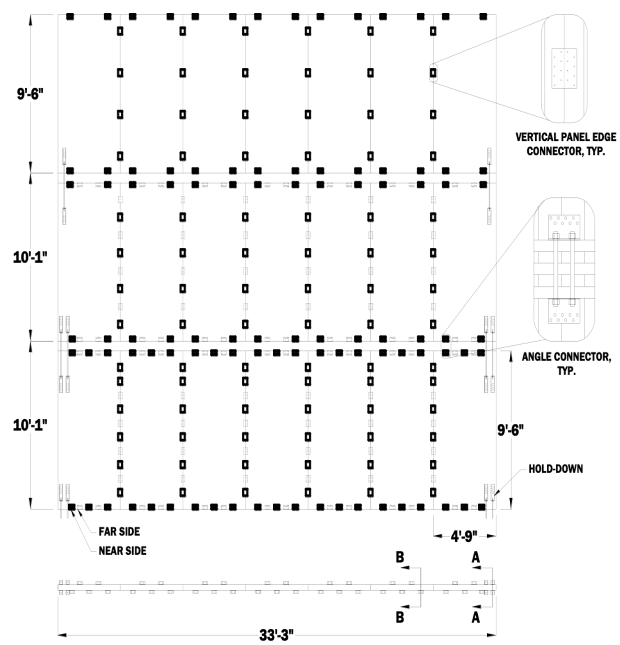


Figure 6-5. CLT Shear Walls at 1st, 2nd, and 3rd Story with Connector And Hold-down Location

6.5.1 Shear Capacity of Prescribed Connectors

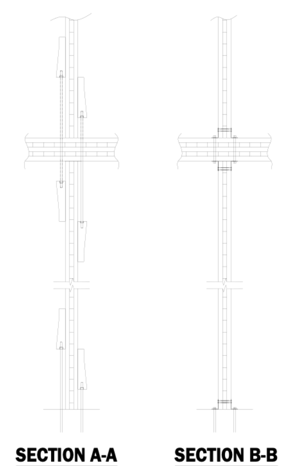


Figure 6-6. Wall-floor Intersections

6.5.2 Shear Capacity of CLT Panel

- For this 3-layer E1 grade CLT panel, the allowable stress design (ASD) in-plane shear unit shear capacity is converted to LRFD using NDS-2018 Table 10.3.1:

$$v_{\mathrm{r}}' = \phi\lambda K_F F_v(t_v) = 0.75(1.0)(2.88)(9{,}700) = 20{,}849 \text{ plf}$$

where:

$F_v(t_v)$= 9,700 plf (ASD value from CLT panel manufacturer's evaluation report)

- CLT panel in-plane unit shear capacity, v_{r}' = 20,849 plf is greater than the largest unit shear force story demand of 1,273 plf (from Table 6-4)

$$20{,}849\ plf \gg 1{,}273\ plf$$

- In-plane unit shear capacity value does not to account for holes, cuts or other modifications

6.6.1 CLT Shear Wall Hold-down Design

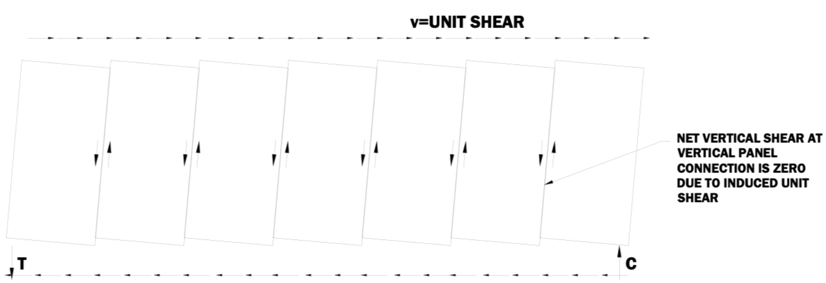


Figure 6-1. Illustration of Rocking Behavior of Seven Individual Panels in A Multi-panel CLT Shear Wall Designed in Accordance with SDPWS-21 Appendix B

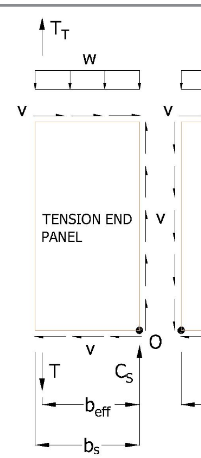


Figure 6-7. Free-body Diagram for the Tension End Panel of the CLT Multi-panel Shear Wall

6.6.1 CLT Shear Wall Hold-down Design

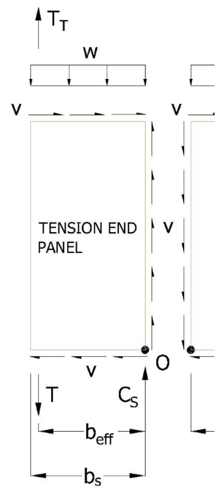
- $\sum M_o = 0$

$$T\,(b_{eff}) - vb_sh + wb_s\left(\frac{b_s}{2}\right) - T_T(b_{eff}) = 0$$ (SDPWS-21 Eq. C-B.1)

$$T = \frac{vb_sh - wb_s\left(\frac{b_s}{2}\right)}{b_{eff}} + T_T$$ (SDPWS-21 Eq. C-B.2)

Table 6-6: Solution for Tension Force, T, for Hold-down Strength Requirement

Story	Unit shear force per foot of shear wall length	$v_{s(seismic)}$, LRFD design unit shear capacity, (ϕ= 0.5)	2 x $v_{s(seismic)}$	T_T from story above	T for 2 x $v_{s(seismic)}$ requirement for load combination 1.0E - 0.7D
	(plf)	(plf)	(plf)	(lb)	(lb)
3	477	548	1,097	0	11,293
2	1,009	1,097	2,194	11,293	34,540
1	1,273	1,371	2,742	34,540	63,968



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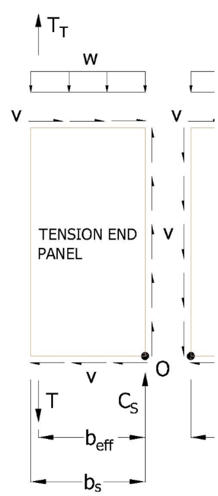
6.6.1 CLT Shear Wall Hold-down Design

- The same screw attached hold-down is used for all locations with each having an LRFD design tension capacity of 17,678 lb and associated deflection of 0.253 in.
  - 1st story walls to foundation, four hold-downs

    4 x 17,687 lb = 70,748 lb > 63,968 lbs
  - 2nd story to top of 1st story, four hold-downs

    4 x 17,687 lb = 70,748 lb > 34,540 lbs
  - 3rd story to top of 2nd story, two hold-downs

    2 x 17,687 lb = 37,374 lb > 11,293 lbs
- Check CLT panel for tension, row and group tear out



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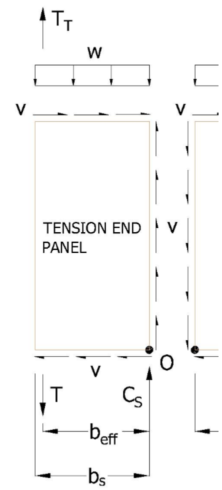
6.6.1 CLT Shear Wall Hold-down Design

- From SDPWS-21 Section B.3.4, hold-down device deformation for each story shall not exceed 0.185 in. for T forces from strength design load combinations (see Table 6-7)

Table 6-7: Solution for Tension Force, T, for Hold-down Deflection Requirement

Story	Unit shear force per foot of shear wall length	T for load combination 1.0E - 0.7D
	(plf)	(lb)
3	477	4,714
2	1,009	14,604
1	1,273	27,472



- Deflection of most highly loaded hold-down is less than 0.185 in. The SDPWS-21 deflection limit is satisfied

$$\Delta_{hold-down} = \frac{27{,}472\ lb}{4(17{,}678\ lb)}(0.253\ in.) = 0.098\ in. < 0.185\ in.$$

6.6.2 CLT Shear Wall Compression Zone

- Compression force, *C*, and length of compression zone, x, from compression end panel moment equilibrium
- $\sum M_o = 0$

$$C\left(b_s - \frac{x}{2}\right) - vb_sh - wb_s\left(\frac{b_s}{2}\right) - C_T\left(b_s - \frac{x_T}{2}\right) = 0 \quad \text{(SDPWS-21 Eq. C-B.3)}$$

$$C = F_{C\perp}'(t)(x)\left(\frac{12\text{in.}}{\text{ft}}\right) \quad \text{(SDPWS-21 Eq. C-B.4)}$$

$$C = Fc'(t_{parallel})(x)\left(\frac{12\text{in.}}{\text{ft}}\right) \quad \text{(SDPWS-21 Eq. C-B.5)}$$

- C and x summarized in Table 6-8

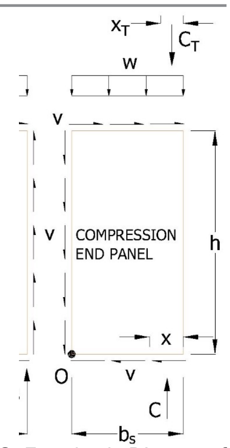
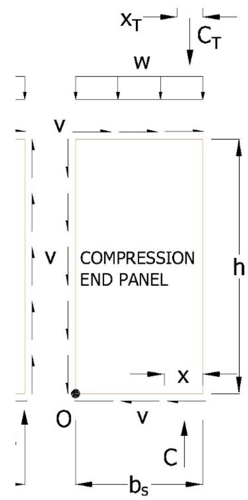


Figure 6-8. Free-body Diagram for the Compression End Panel of the CLT Multi-panel Shear Wall

6.6.2 CLT Shear Wall Compression Zone

Table 6-8: Solution for Compression Zone Length, x, and Force C

Story	Unit shear force per foot of shear wall length	Dead load, w_{DL}	Live load, w_{LL}	C_T, Compres-sion from top	Compres-sion zone length, x	C, for load combination 1.0E + 1.4D +0.5L
	(plf)	(plf)	(plf)	(lb)	(in.)	(lb)
3	477	190	0	0	2.00	5,257
2	1,009	793	690	5,257	7.64	20,144
1	1,273	793	690	20,144	4.56	36,545



- Check of CLT wall panel axial capacity is required

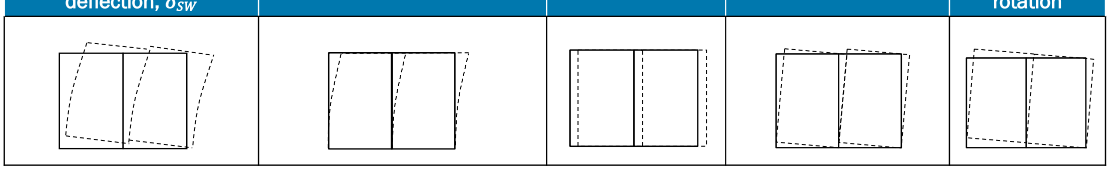
29

6.7 CLT Shear Wall Deflection

- $$\delta_{SW} = \frac{576 v b_s h^3}{EI_{eff(in-plane)}} + \frac{vh}{GA_{eff(in-plane)}} + 3\Delta_{nail\ slip,h} + 2\Delta_{nail\ slip,v}\left(\frac{h}{b_s}\right) + \Delta_a \frac{h}{\sum b_s}$$

(SDPWS-21 Eq. B-1)

Total shear wall = deflection, δ_{sw}	Panel bending and shear +	Sliding +	Panel rotation +	Rigid body rotation



30

6.7 CLT Shear Wall Deflection

Table 6-9: CLT Shear Wall Deflection Components and Total Shear Wall Deflection, δ_{SW}

Story	$\frac{576vb_sh^3}{EI_{eff(in-plane)}}$	$\frac{vh}{GA_{eff(in-plane)}}$	$3\Delta_{nail\ slip,h} + 2\Delta_{nail\ slip,v}\left(\frac{h}{b_s}\right)$	$\Delta_a \frac{h}{\sum b_s}$	δ_{SW}, shear wall deflection
	(in.)	(in.)	(in.)	(in.)	(in.)
3	0.02	0.04	0.15	0.04	0.24
2	0.04	0.09	0.16	0.04	0.33
1	0.05	0.11	0.16	0.03	0.35

- For allowable story drift limit is 2.5%*h* from ASCE/SEI 7-22 Table 12.12-1, corresponding allowable deflection calculated using, C_d, equal to 3 for cross-laminated timber shear walls:

$$\delta_e = \frac{0.025(h)}{C_d} = \frac{0.025(114 \text{ in.})}{3.0} = 0.95 \text{ in.} > \delta_{SW}$$

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31

6.8 References

- See the “Other Useful Design Aid Resources” in Section 6.1 for additional references.

- van de Lindt, J., Amini, M. O., Rammer, D., Line, P., Pei, S., and Popovski, M. (2022) “Determination of Seismic Performance Factors for Cross-Laminated Timber Shear Walls Based on the FEMA P695 Methodology.” General Technical Report FPL-GTR-281, Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory.
- FPInnovations (2013). US CLT Handbook, Special Publication SP-529E. Pointe-Claire, QC, Canada.

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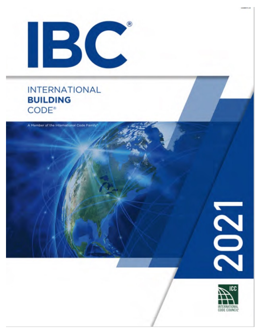
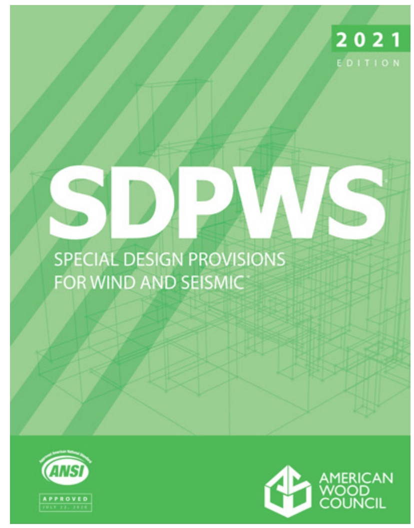
32

Building Code Reference of SDPWS Standard

2021 IBC

- References 2021 SDPWS in Section 2305 for lateral design and construction

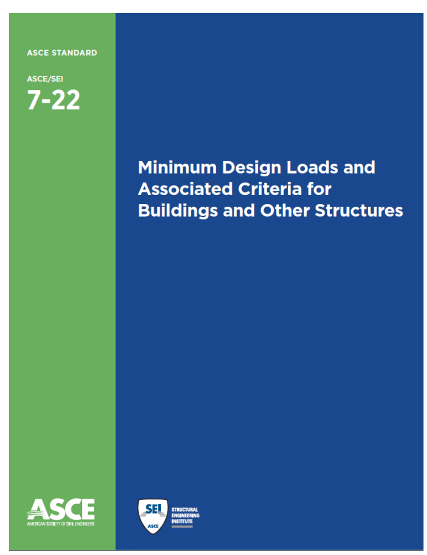




33

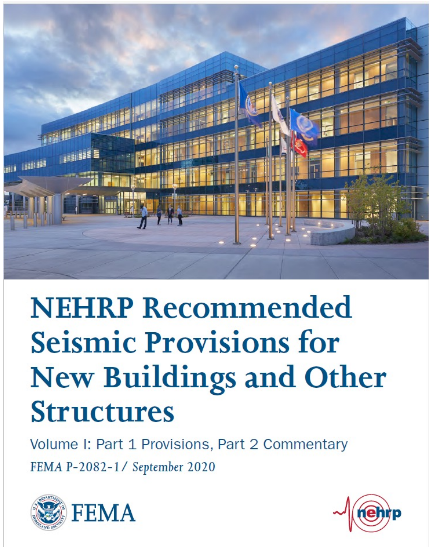
Building Code Reference of ASCE 7-22 Standard

Targeted for reference in 2024 IBC



34

NEHRP Provisions



- 2020 *NEHRP Recommended Seismic Provisions for New Buildings and Other Structures* (FEMA P-2082)

  https://www.fema.gov/sites/default/files/2020-10/fema_2020-nehrp-provisions_part-1-and-part-2.pdf

35

NEHRP Provisions Design Examples

- 2020 *NEHRP Recommended Seismic Provisions: Design Examples, Training Materials, and Design Flow Charts, FEMA P-2192*
- Volume 1: Design Examples

  https://www.fema.gov/sites/default/files/documents/fema_nehrp_design-examples-training-materials_volume-1.pdf

36

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Thank You

37

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38