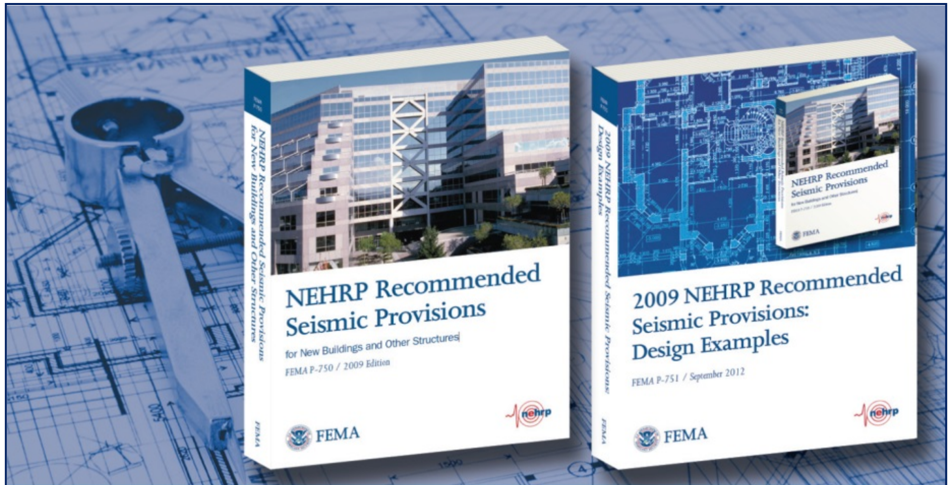


2009 NEHRP Recommended Seismic Provisions:

Training and Instructional Materials

FEMA P-752 CD / June 2013

FEMA

11

Wood Design

Peter W. Somers, P.E., S.E.

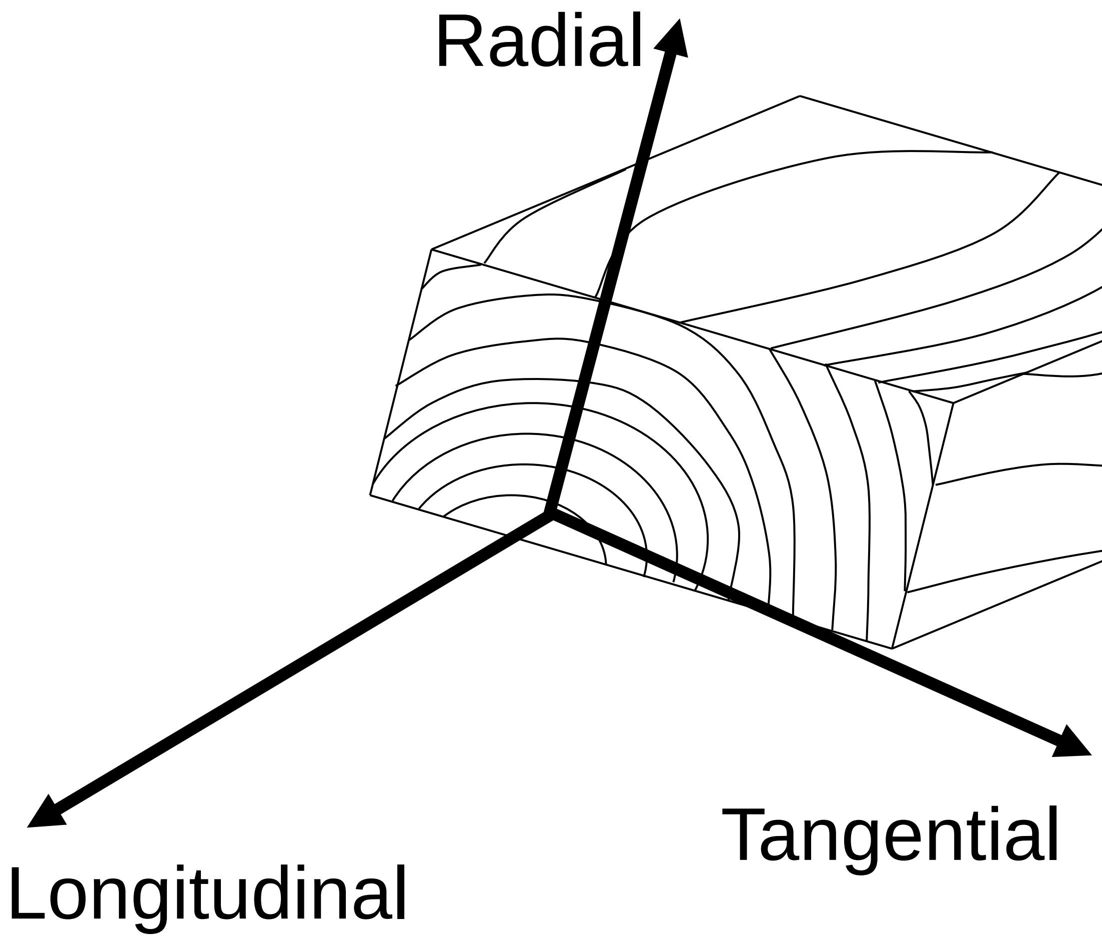
Includes materials developed by Steve Pryor, S.E.

WOOD STRUCTURES

NEHRP Recommended Provisions Wood Design Requirements

- Basic wood behavior
- Typical construction and framing methods
- Context in the *Provisions*
- Reference standards
- Analysis methods
- Lateral force resisting systems
- Shear walls and anchorage
- Diaphragms
- Concrete and masonry wall buildings

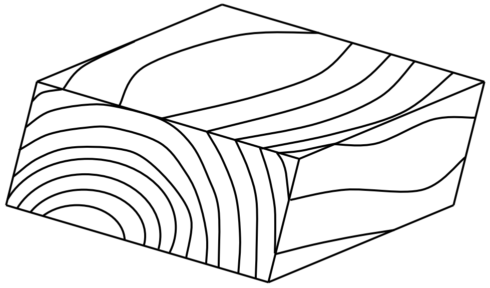
Basic Wood Material Properties



Wood is orthotropic

- Unique, independent, mechanical properties in 3 different directions
- Varies with moisture content
- Main strength axis is longitudinal - parallel to grain
- Radial and tangential are "perpendicular" to the grain - substantially weaker

Basic Wood Material Properties



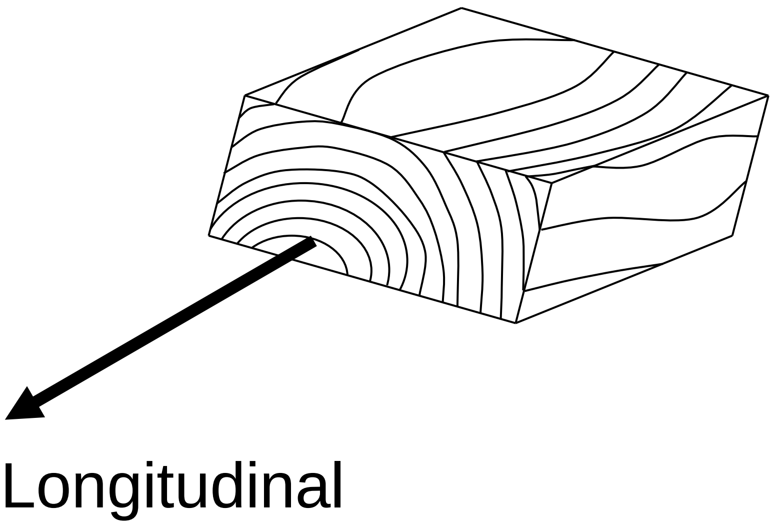
"Timber is as different from wood as concrete is from cement."

– Madsen, Structural Behaviour of Timber

Concept of "wood" as "clear wood": design properties used to be derived from clear wood with adjustments for a range of "strength reducing characteristics"

- Concept of "timber" as the useful engineering and construction material: "In-grade" testing (used now) determines engineering properties for a specific grade of timber based on full-scale tests of timber, a mixture of clear wood and strength reducing characteristics

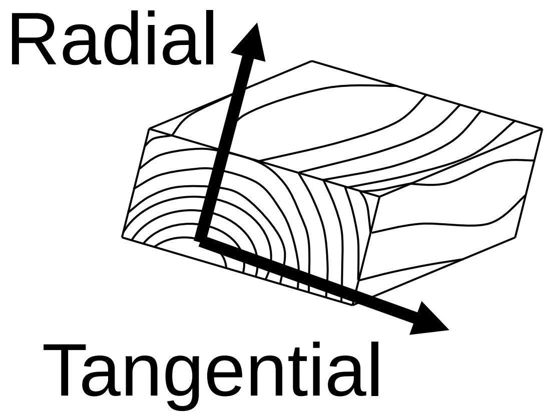
Basic Wood Material Properties



Sample DFL longitudinal design properties:

- Modulus of elasticity: 1,800,000 psi
- Tension (parallel to grain): 1,575 psi
- Bending: 2,100 psi
- Compression (parallel to grain): 1,875 psi

Basic Wood Material Properties



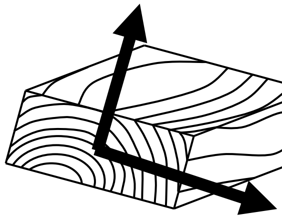
Sample DFL perpendicular to grain design properties:

- Modulus of elasticity: 45,000 psi (2.5 ~ 5 % of $E_{||}$!)
- Tension (perpendicular to grain): 180 to 350 psi FAILURE stresses

Timber is extremely weak for this stress condition. It should be avoided if at all possible, and mechanically reinforced if not avoidable.

- Compression (perpendicular to grain): 625 psi. Note that this is derived from a serviceability limit state of ~ 0.04” permanent deformation under stress in contact situations. This is the most "ductile" basic wood property.

Basic Wood Material Properties



<u>Shrinkage</u>

- Wood will shrink with changes in moisture content
- This is most pronounced in the radial and tangential directions (perpendicular to grain)
- May need to be addressed in the LFRS

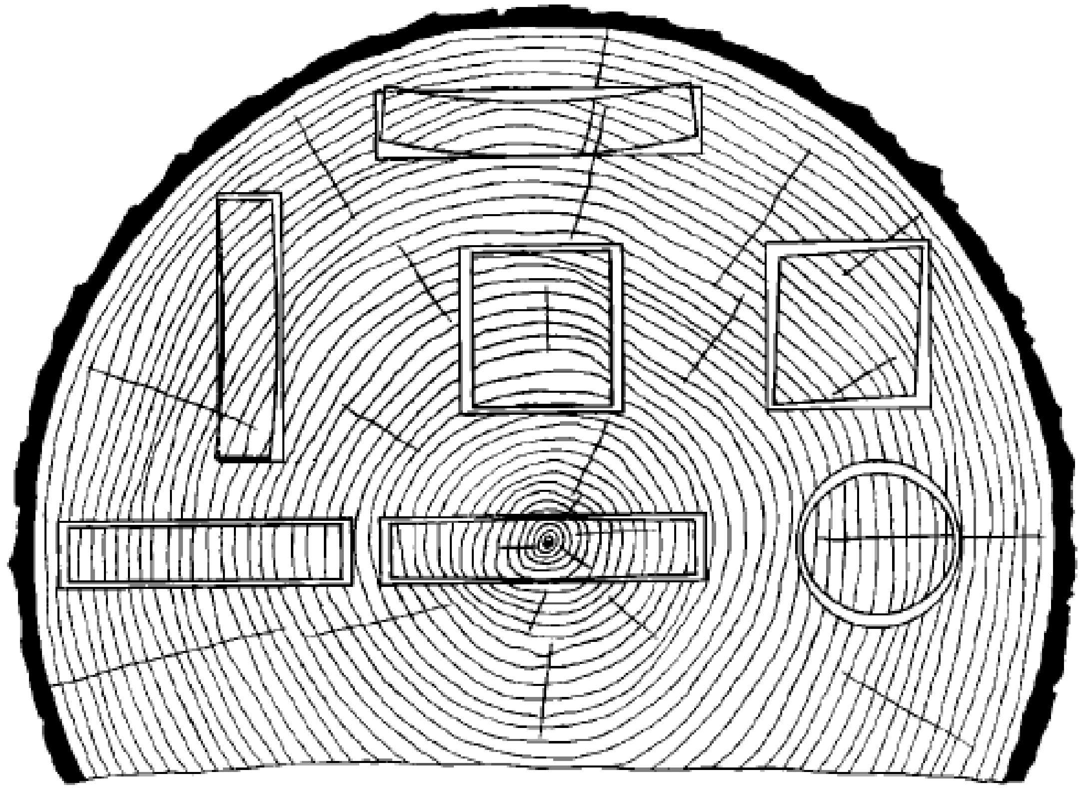


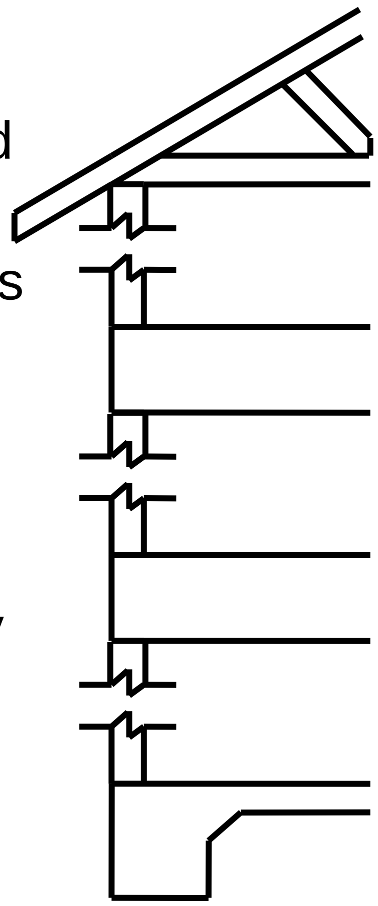
Figure 3–3. Characteristic shrinkage and distortion of flat, square, and round pieces as affected by direction of growth rings. Tangential shrinkage is about twice as great as radial.

(Wood Handbook, p. 58)

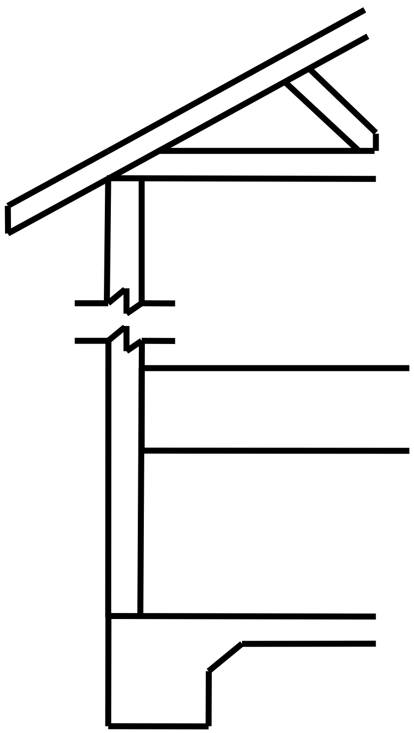
Wood Structure Construction Methods: Gravity

Platform

- Walls are interrupted by floor "platforms"
- Floors support walls
- Most common type of light-frame construction today
- Economical but creates discontinuity in the load path
- Metal connectors essential for complete load path



Balloon



- Walls feature foundation to roof framing members
- Floors supported by ledgers on walls or lapped with studs
- Not very common today

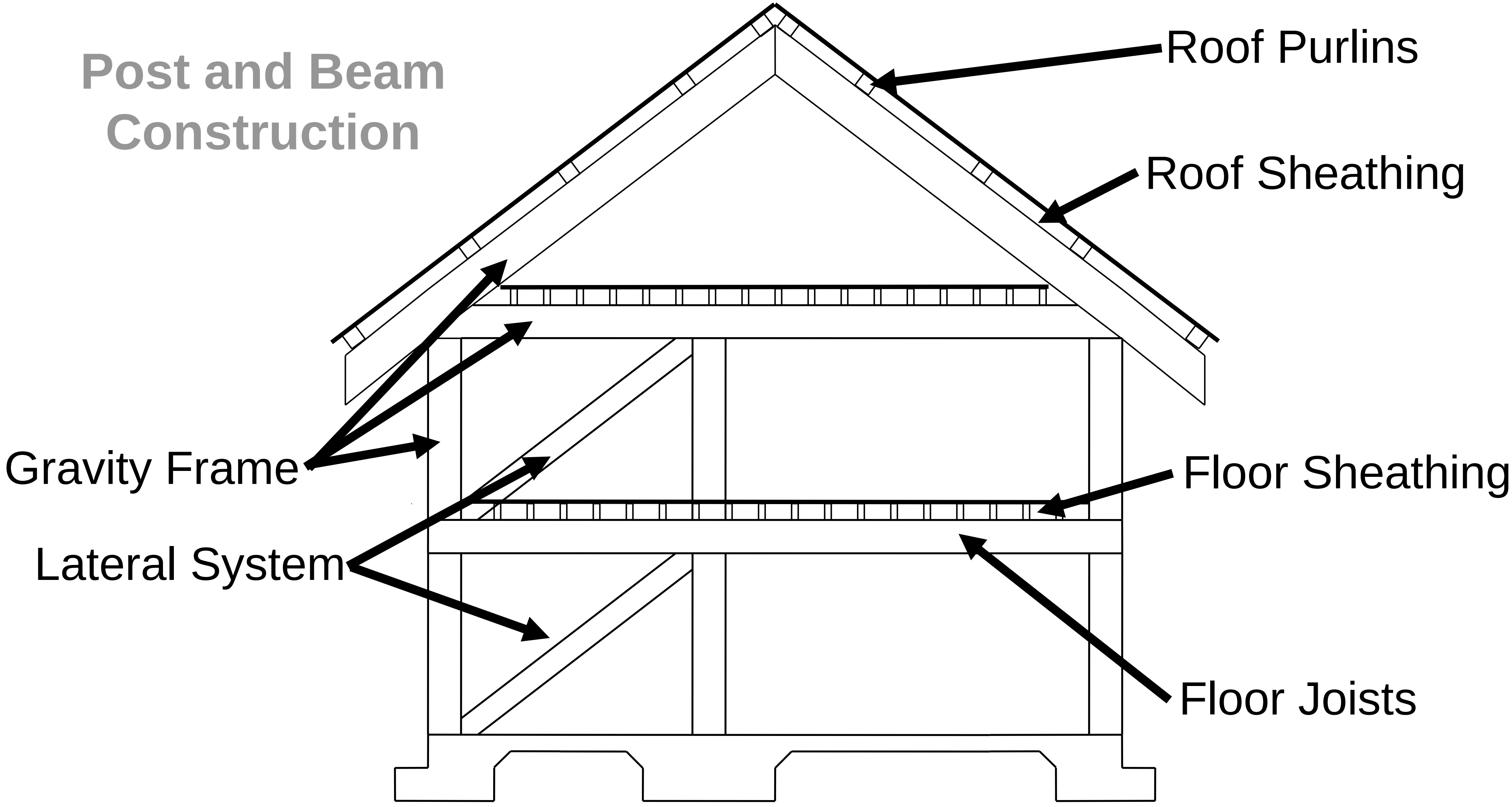
Wood Structure Construction Methods: Gravity

Post and Beam

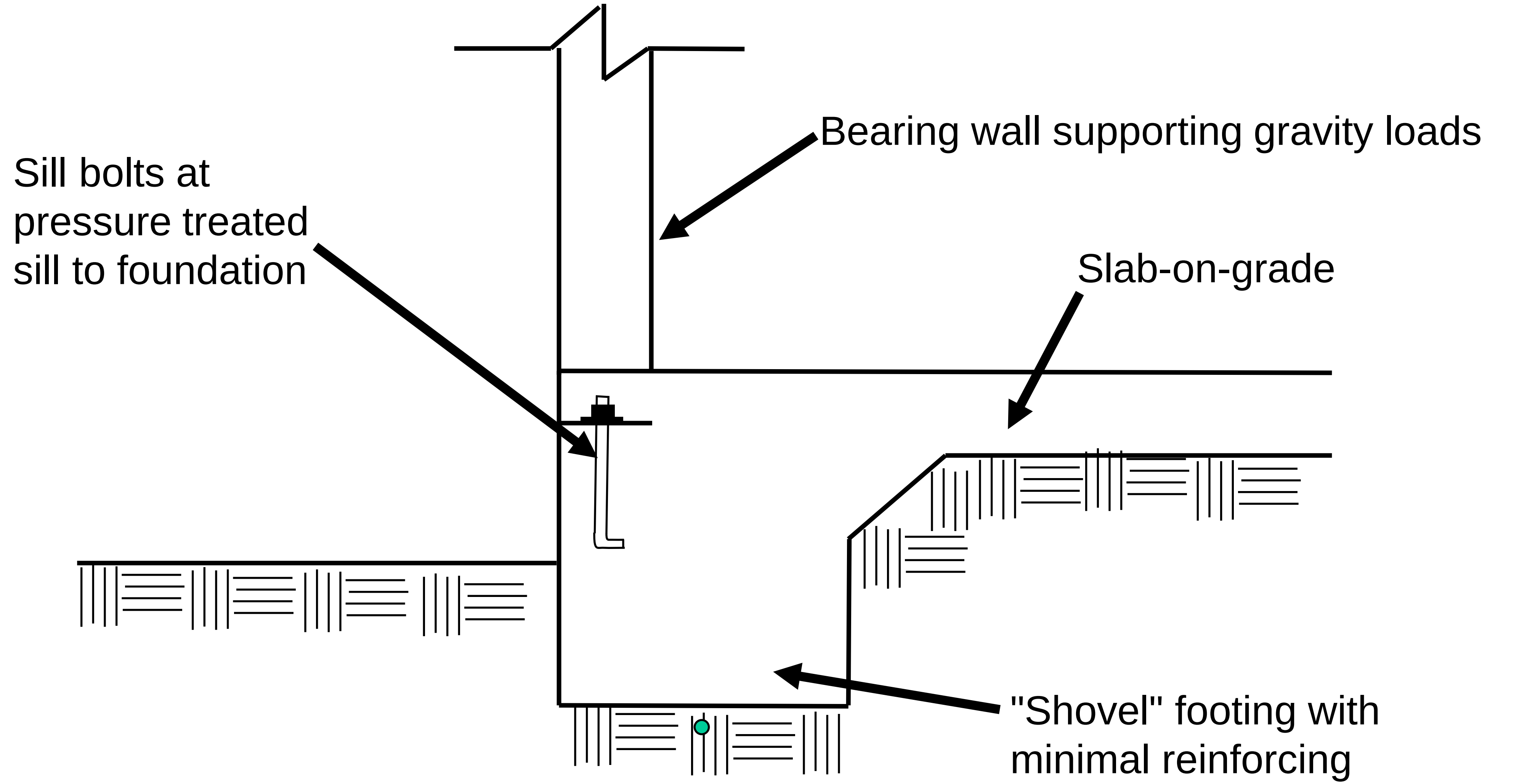
- Space frame for gravity loads
- Moment continuity at joint typically only if member is continuous through joint
- Lateral resistance through vertical diaphragms or braced frames
- Knee braces as seen here for lateral have no code design procedure for seismic

Six story main lobby Old Faithful Inn, Yellowstone, undergoing renovation work in 2005. Built in winter of 1903-1904, it withstood a major 7.5 earthquake in 1959.

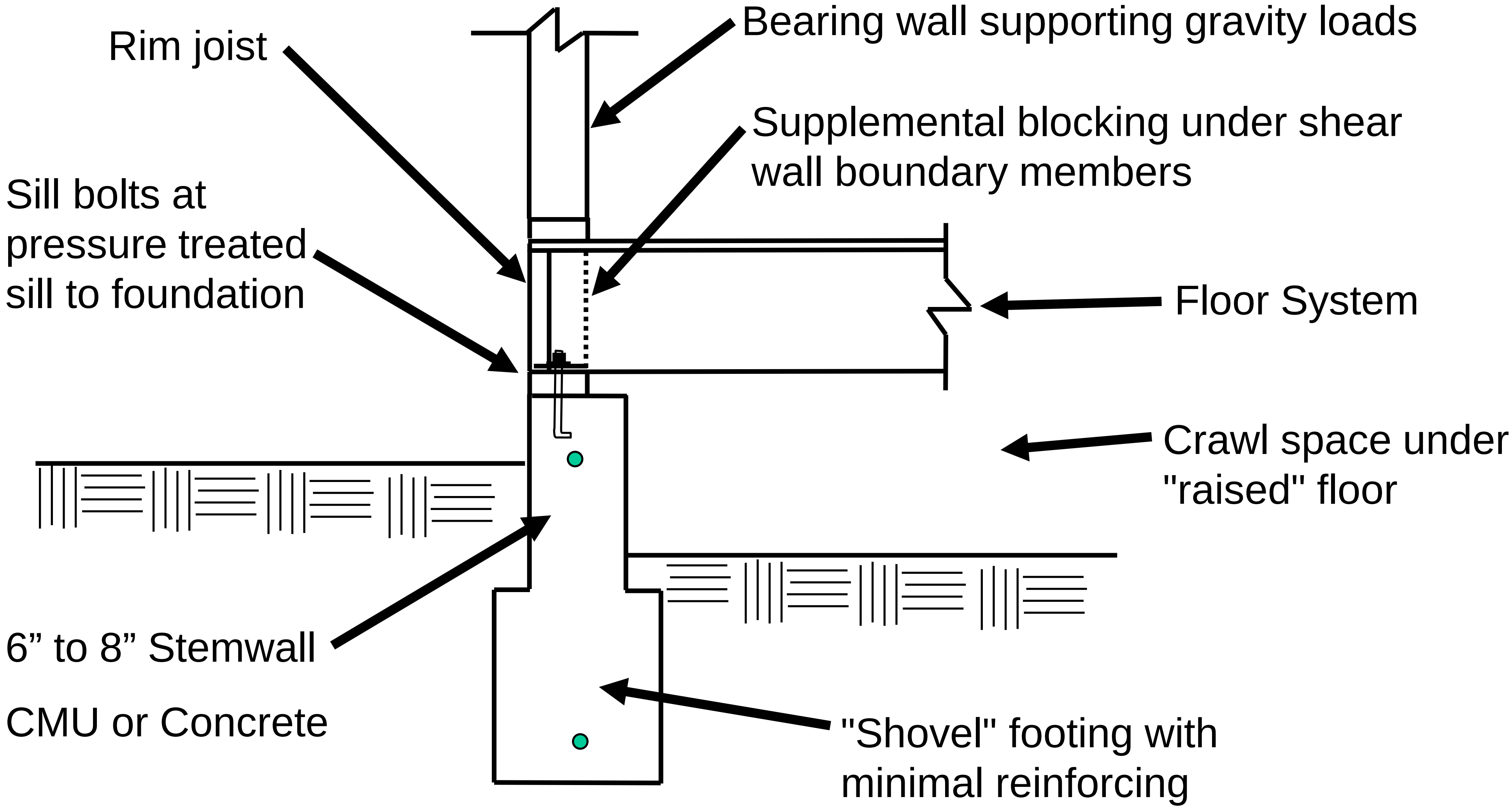
Wood Structure Construction Methods: Gravity



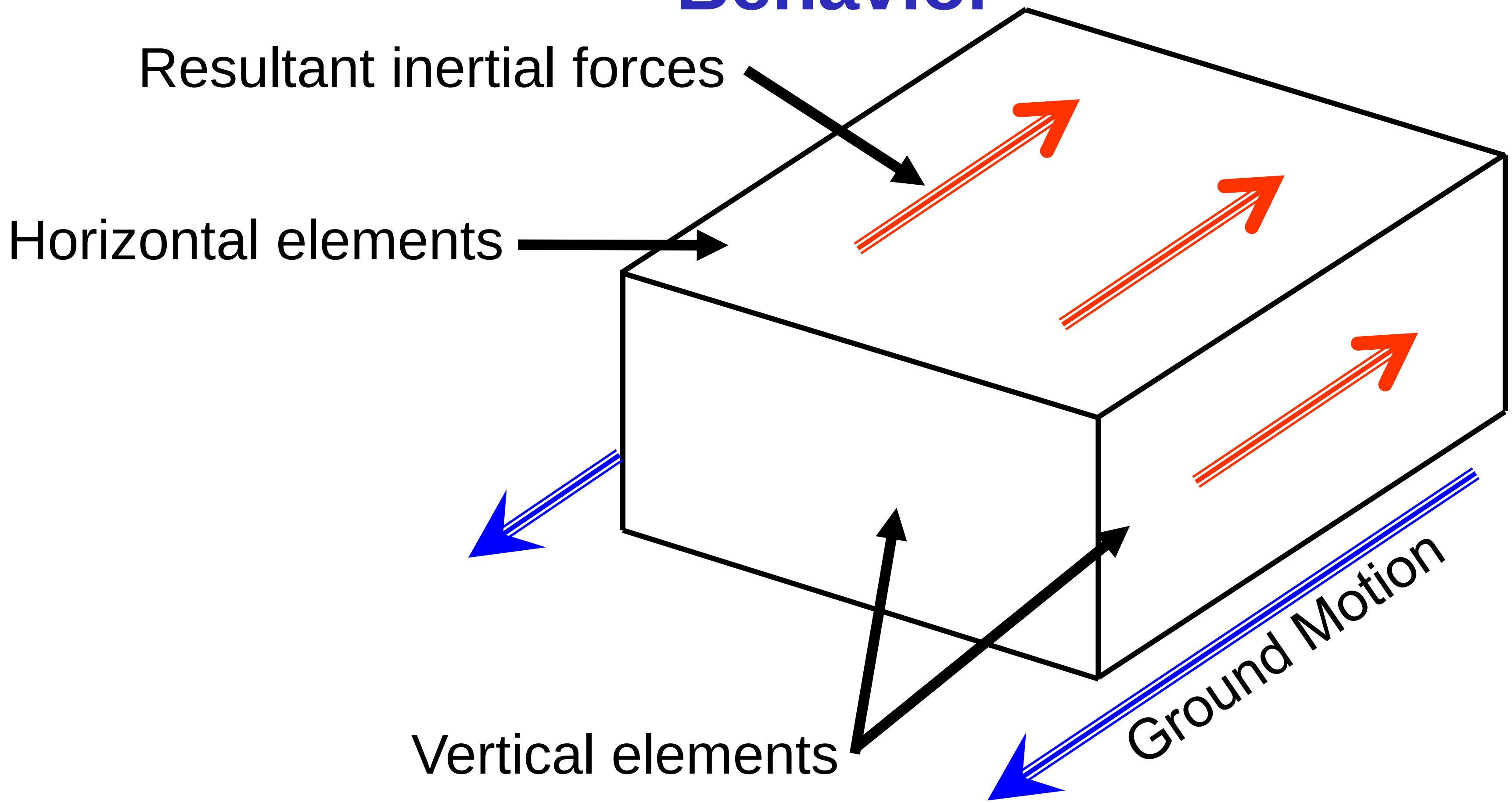
Typical Light-Frame Foundation: Slab-On-Grade



Typical Light-Frame Foundation: Raised Floor



Lateral Design Basics: Earthquake Behavior

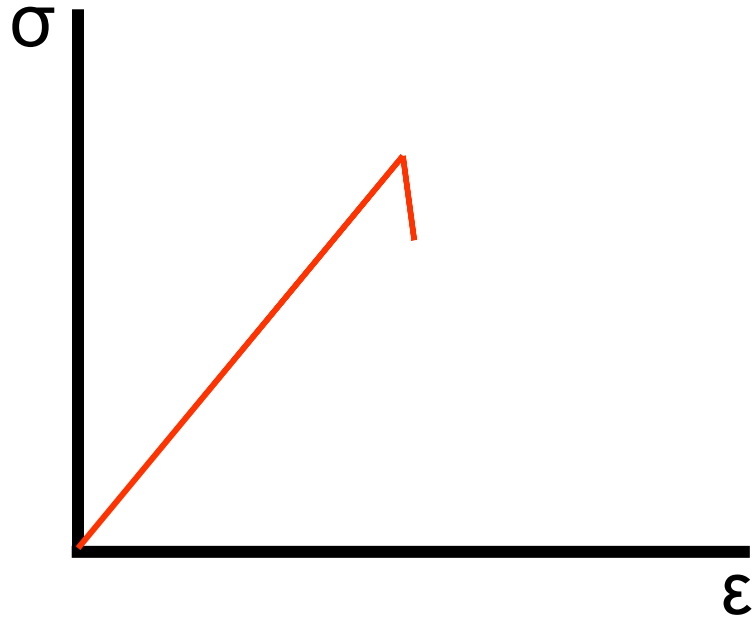


The basic approach to the lateral design of wood structures is the same as for other structures

Sources of Ductility and Energy Dissipation in Wood Structures

Stress in the wood

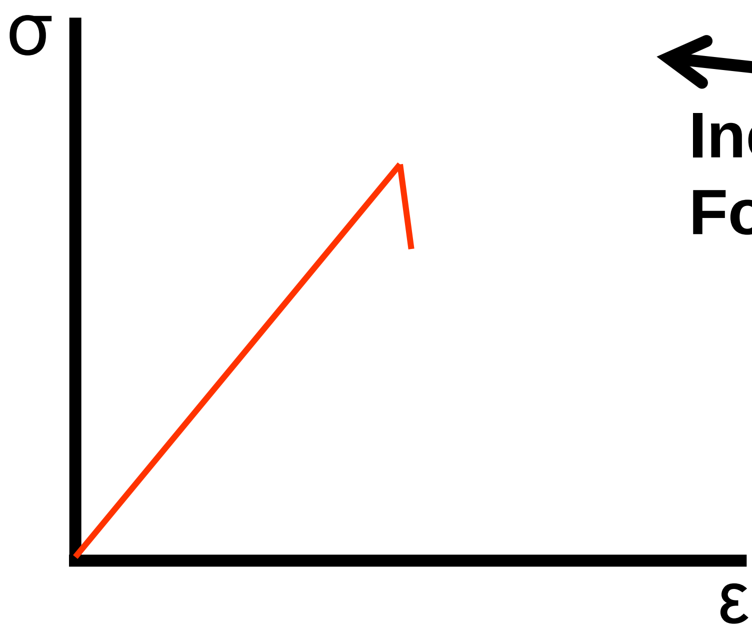
- Tension parallel to the grain: not ductile, low energy dissipation

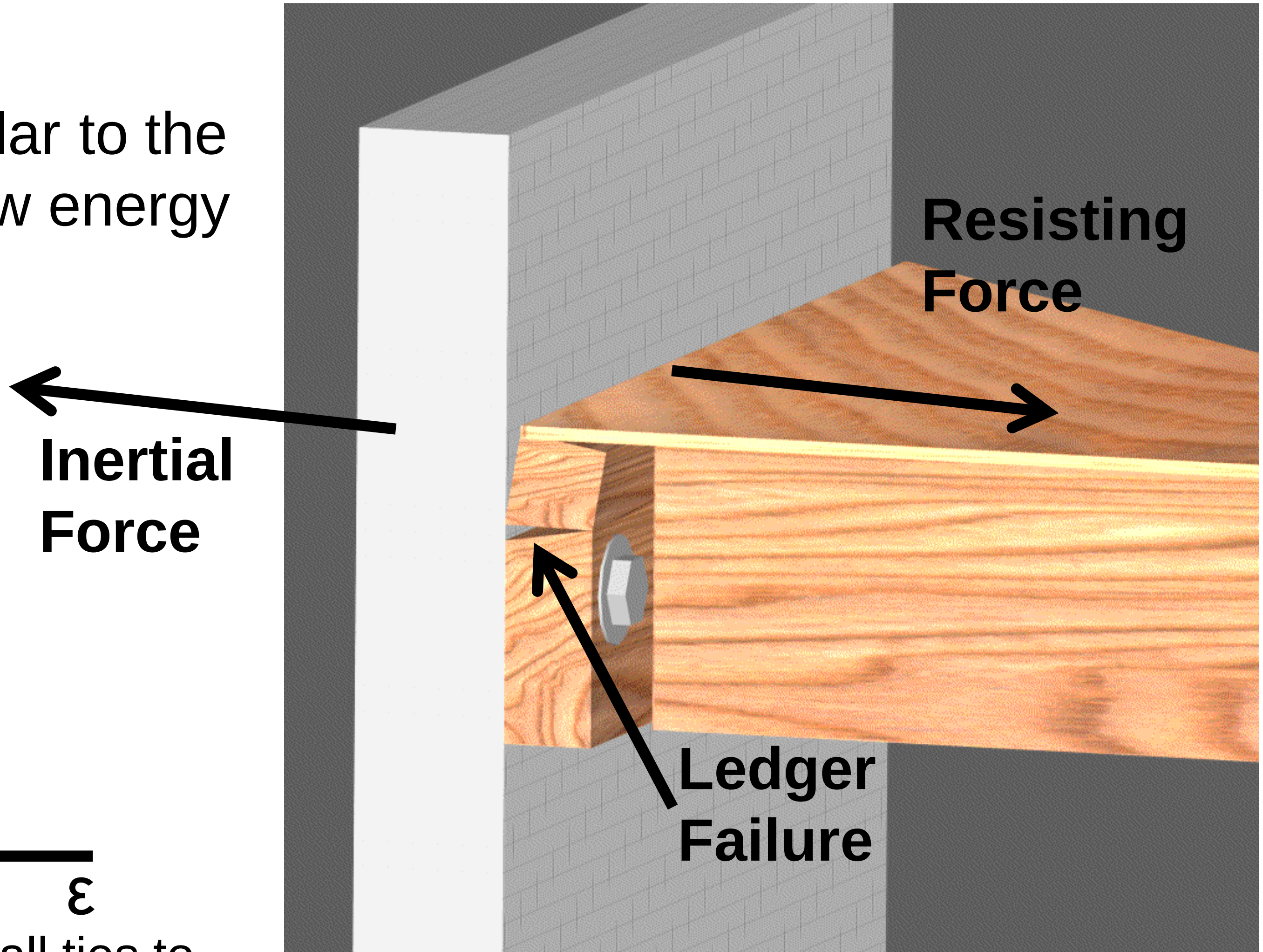


Sources of Ductility and Energy Dissipation in Wood Structures

Stress in the wood

- Tension perpendicular to the grain: not ductile, low energy dissipation

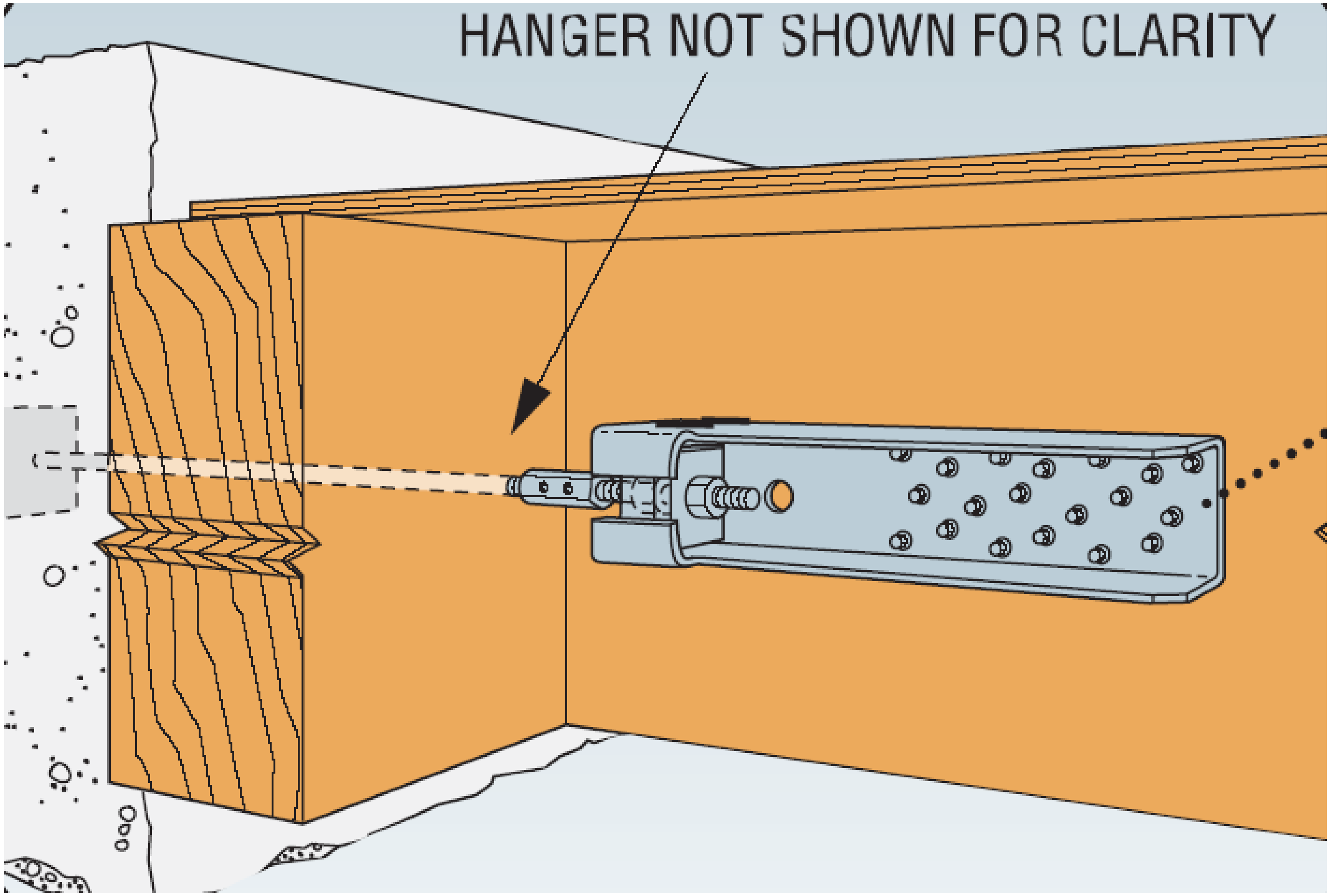




- Need to have positive wall ties to perpendicular framing

Sources of Ductility and Energy Dissipation in Wood Structures

Positive Wall Tie



Sources of Ductility and Energy Dissipation in Wood Structures

Stress in the wood

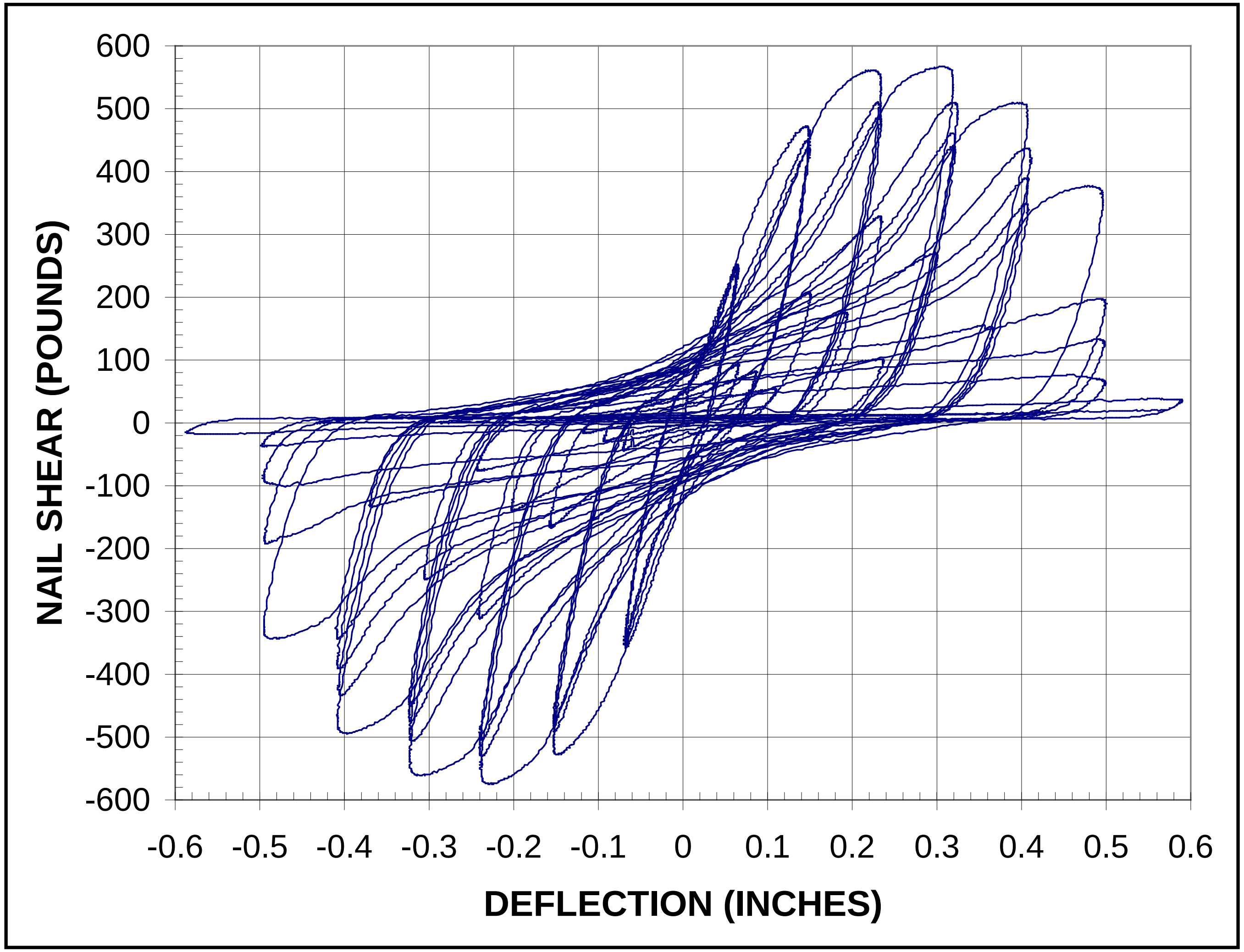
- Compression perpendicular to the grain: ductile, but not recoverable during an event – one way crushing similar to tension only braced frame behavior – ductile, but low energy dissipation
- Design allowable stress should produce ~0.04” permanent crushing

Sources of Ductility and Energy Dissipation in Wood Structures

Stress in the fastener

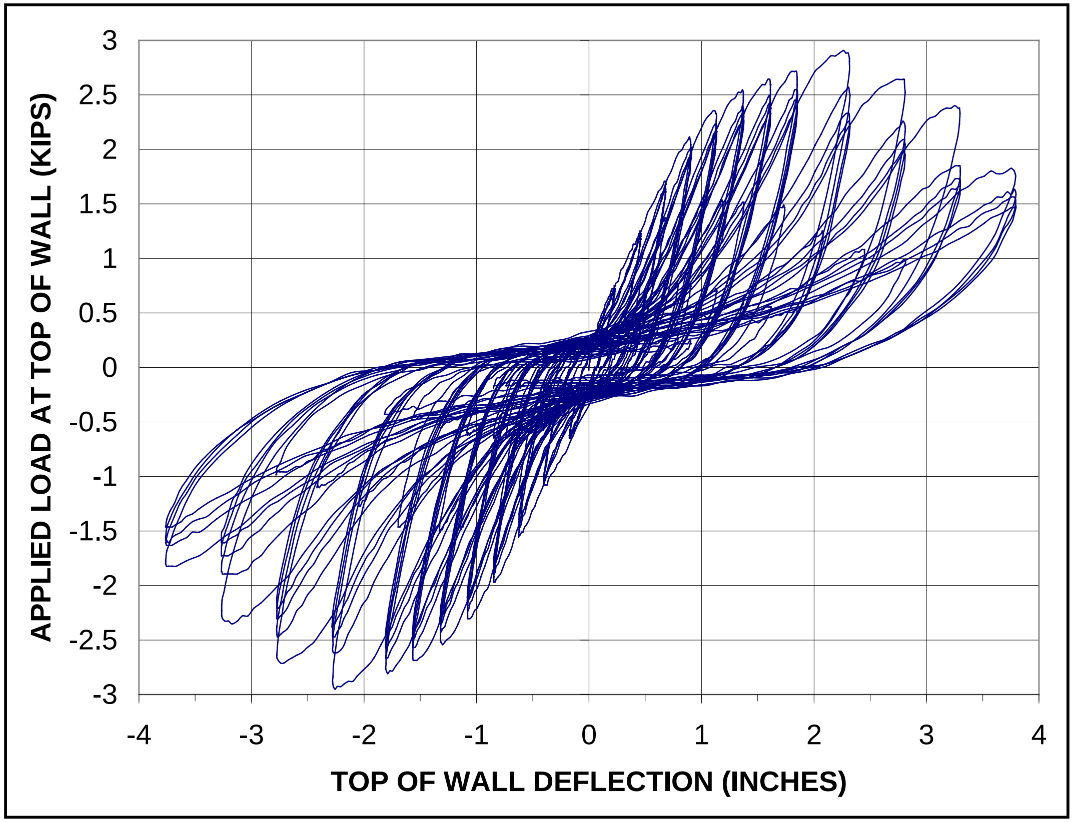
- Nailed joint between sheathing and framing is source of majority of ductility and energy dissipation for nailed wood structural panel shear walls
- The energy dissipation is a combination of yielding in the shank of the nail, and crushing in the wood fibers surrounding the nail
- Since wood crushing is nonrecoverable, this leads to a partial "pinching" effect in the hysteretic behavior of the joint.
- The pinching isn't 100% because of the strength of the nail shank undergoing reversed ductile bending yielding in the wood.
- As the joint cycles, joint resistance climbs above the pinching threshold when the nail "bottoms out" against the end of the previously crushed slot forming in the wood post

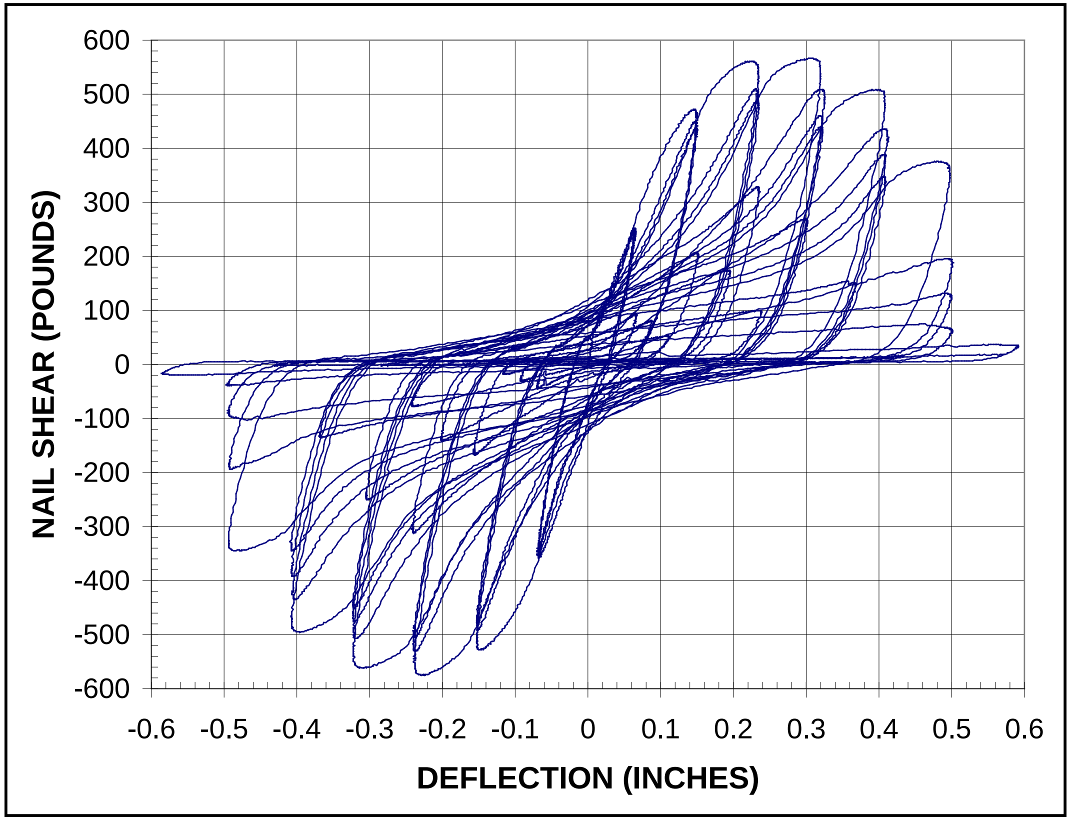
Sources of Ductility and Energy Dissipation in Wood Structures



Individual nail test

Sources of Ductility and Energy Dissipation in Wood Structures



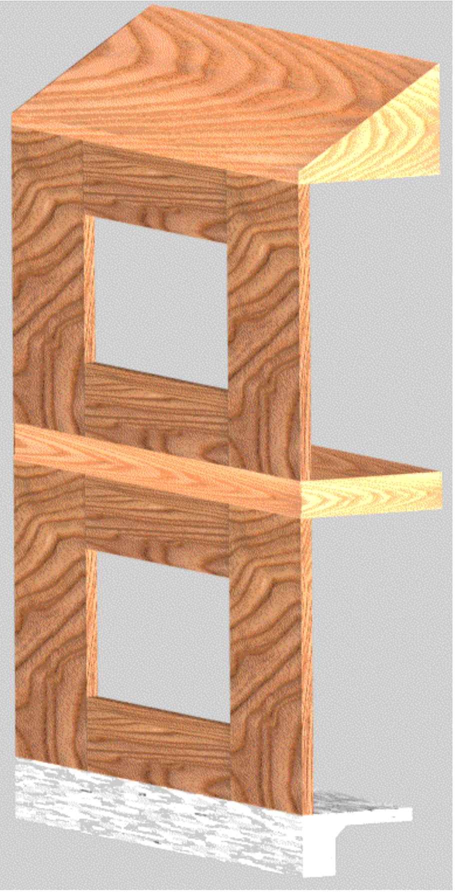


Full-scale shear wall test

Individual nail test

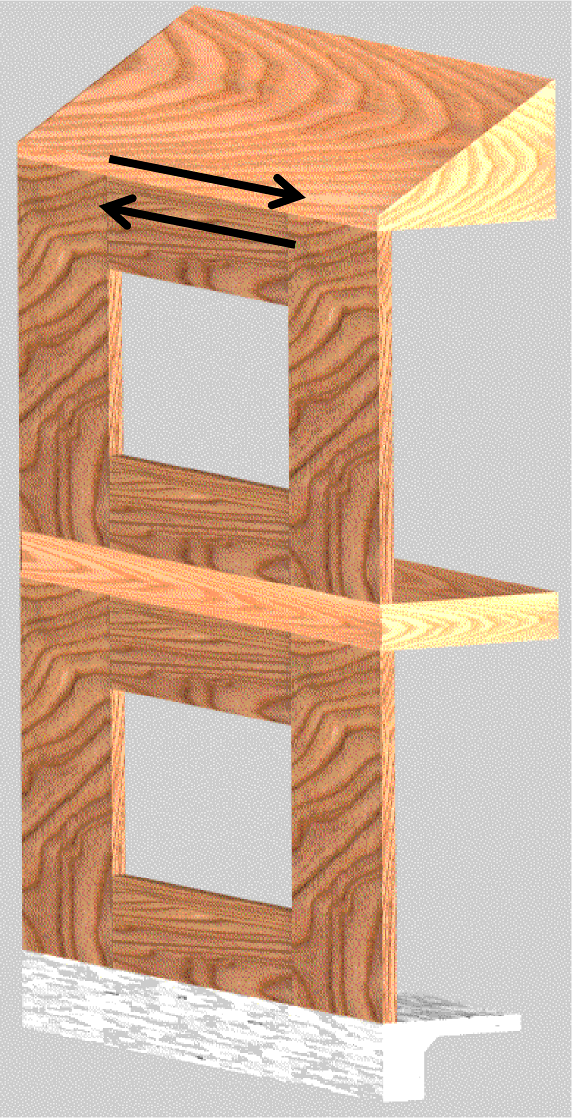
Lateral Design Basics: Complete Load Path

- Earthquakes move the foundations of a structure
- If the structure doesn't keep up with the movements of the foundations, failure will occur
- Keeping a structure on its foundations requires a complete load path from the foundation to all mass in a structure
- Load path issues in wood structures can be complex
- For practical engineering, the load path is somewhat simplified for a "good enough for design" philosophy



Lateral Design Basics: Complete Load Path

- Shear wall overturning
- Diaphragm to shear wall
- Overturning tension/ compression through floor
- Shear transfer through floor
- Shear transfer to foundation



Wood Structure LFRS Design Methods: Engineered

- If a structures does not meet the code requirements for "prescriptive" or "conventional" construction, it must be "engineered"
- As in other engineered structures, wood structures are only limited by the application of good design practices applied through principles of mechanics (and story height limitations in the code)
- A dedicated system of horizontal and vertical elements, along with complete connectivity, must be designed and detailed.

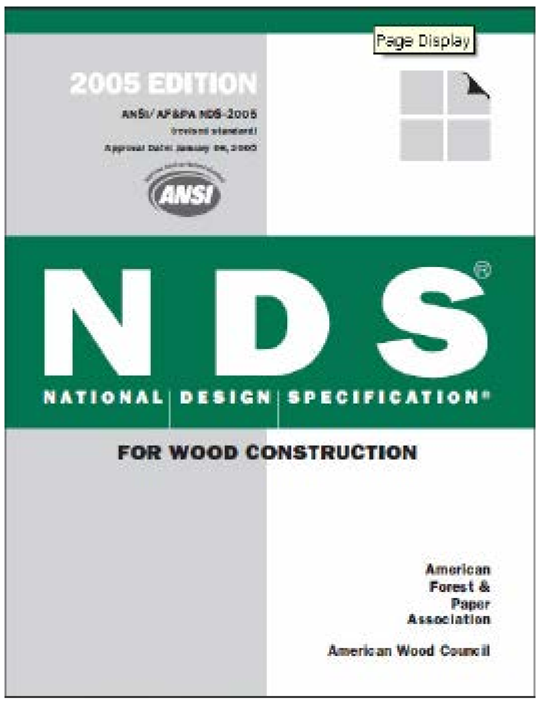
Wood Structure LFRS Design Methods: Prescriptive

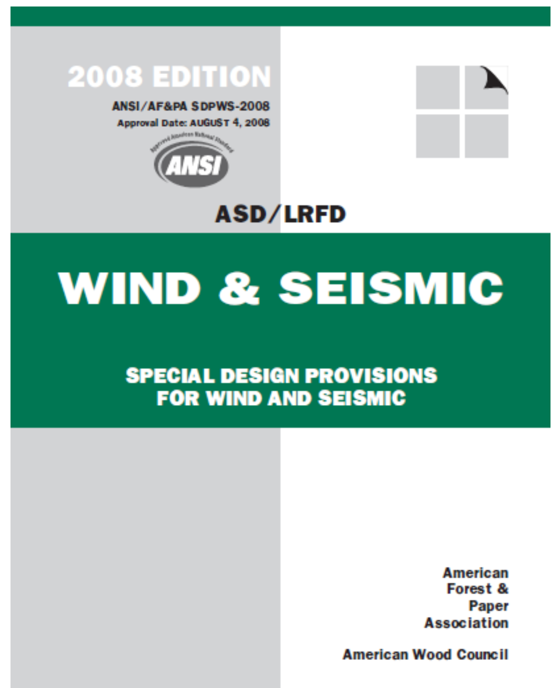
Also referred to as "*Conventional Construction*"

- Traditionally, many simple wood structures have been designed without "engineering"
- Over time, rules of how to build have been developed, most recently in the 2009 International Residential Code (IRC)
- For the lateral system, the "dedicated" vertical element is referred to as a *braced wall panel*, which is part of a *braced wall line*
- Based on SDC and number of stories, rules dictate the permissible spacing between braced wall lines, and the spacing of braced wall panels within braced wall lines

Context in the Provisions

- ASCE 7-05 Sec. 12.2 Structural Systems
- ASCE 7-05 Sec. 14.5 Wood Structures
- AF&PA NDS – wood framing and connections
- AF&PA SDPWS – shears, diaphragms, and anchorage





2005 NDS / SDPWS

- Supports ASD and LRFD
- Framing and connections
  - ASD: $F'_x = F_x C_D C_y C_z$ etc
  - LRFD: $F'_x = F_x K_D \phi_x \lambda C_y C_z$ etc
- Shear walls and diaphragms
  - $v_{ASD} = v_s / 2$
  - $v_{LRFD} = \phi_D v_s = 0.8 v_s$

Lateral Systems (Bearing Walls)

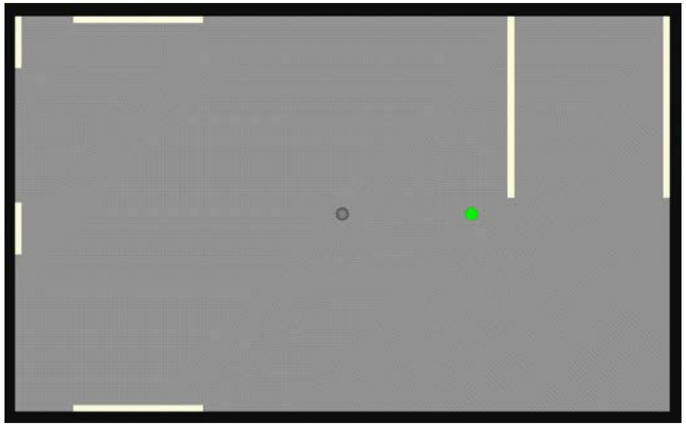
Seismic Force Resisting System	Response Modification Coefficient, R	Seismic Design Category
Shear walls with wood structural panels	6 ½	B & C: NL D – F: 65 ft max
Shear walls with other materials	2	B & C: NL D: 35 ft max E & F: NP
Walls with flat strap bracing	4	B & C: NL D – F: 65 ft max

Lateral Systems (Building Frame)

Seismic Force Resisting System	Response Modification Coefficient, R	Seismic Design Category
Shear walls with wood structural panels	7	B & C: NL D – F: 65 ft max
Shear walls with other materials	2 1/2	B & C: NL D: 35 ft max E & F: NP

Typical Wood Structure Analysis Methods

Flexible vs Rigid Diaphragm



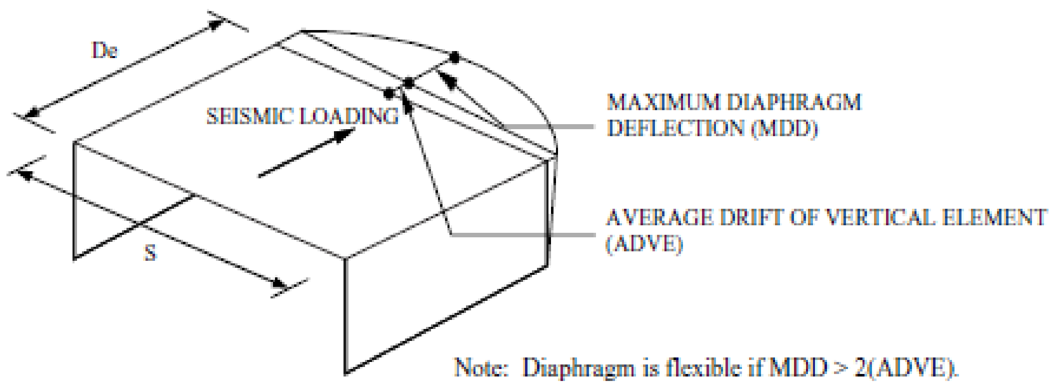
- Neither the rigid nor flexible diaphragm methods really represent the distribution of lateral resistance in a typical structure
- Both methods (typically) ignore the stiffness distribution of interior and exterior wall finishes
- Wood structural diaphragms are neither "flexible" or "rigid" – they are somewhere in between. "Glued and screwed" floor sheathing makes floors more rigid than flexible. The nailing of interior wall sill plates across sheathing joints has the same effect. Exterior walls can act as "flanges", further stiffening the diaphragm.
- However, encouraging rigid diaphragm analysis is also encouraging the design of structures with torsional response – may not be a good thing!

Diaphragm Flexibility

- ASCE 7-05 Sec. 12.3.1.3:

  "Diaphragms … are permitted to be idealized as flexible where the computed maximum in-plane deflection of the diaphragm under lateral load is more than two times the average story drift of adjoining vertical elements of the lateral force-resisting system of the associated story under equivalent tributary lateral load."
- SDPWS Sec. 2.2 (Terminology): Same as above.
- ASCE 7-05 Simplified Procedure (Sec. 12.14.5):

"Diaphragms constructed of ... wood structural panels … are permitted to be considered flexible."



Wood Structure LFRS – Shear Walls

Per AF&PA Sec. 4.3, design provisions include

- Deflection determination
- Unit shear capacities (shear wall tables)
- Aspect ratios
- Anchorage
- Construction requirements

Wood Structure LFRS: Shear Walls

- Unit shear capacities (shear wall tables)
- Tables are for DFL or SP – need to adjust values if framing with wood species with lower specific gravities

Major divisions:

- Structural 1 vs. rated sheathing Panels applied directly to framing vs. panels applied over gypsum wallboard
- Unblocked edges allowed in some conditions

Wood-based Panels[4]

Sheathing Material	Minimum Nominal Panel Thickness (in.)	Minimum Fastener Penetration in Framing Member or Blocking (in.)	Fastener Type & Size	A SEISMIC — Panel Edge Fastener Spacing (in.): 6 — v_s (plf)	6 — G_a (kips/in.)		4 — v_s (plf)	4 — G_a (kips/in.)		3 — v_s (plf)	3 — G_a (kips/in.)		2 — v_s (plf)	2 — G_a (kips/in.)	
			Nail (common or galvanized box)		OSB	PLY		OSB	PLY		OSB	PLY		OSB	PLY
Wood Structural Panels - Structural I[4,5]	5/16	1-1/4	6d	400	13	10	600	18	13	780	23	16	1020	35	22
	3/8[7]	1-3/8	8d	460	19	14	720	24	17	920	30	20	1220	43	24
	7/16[7]			510	16	13	790	21	16	1010	27	19	1340	40	24
	15/32			560	14	11	860	18	14	1100	24	17	1460	37	23
	15/32	1-1/2	10d	680	22	16	1020	29	20	1330	36	22	1740	51	28
Wood Structural Panels – Sheathing[4,5]	5/16	1-1/4	6d	360	13	9.5	540	18	12	700	24	14	900	37	18
	3/8			400	11	8.5	600	15	11	780	20	13	1020	32	17
	3/8[7]	1-3/8	8d	440	17	12	640	25	15	820	31	17	1060	45	20
	7/16[7]			480	15	11	700	22	14	900	28	17	1170	42	21
	15/32			520	13	10	760	19	13	980	25	15	1280	39	20
	15/32	1-1/2	10d	620	22	14	920	30	17	1200	37	19	1540	52	23
	19/32			680	19	13	1020	26	16	1330	33	18	1740	48	22
Plywood Siding			Nail (galvanized casing)												
	5/16	1-1/4	6d	280	13		420	16		550	17		720	21	
	3/8	1-3/8	8d	320	16		480	18		620	20		820	22	
Particleboard Sheathing - (M-S "Exterior Glue" and M-2 "Exterior Glue")			Nail (common or galvanized box)												
	3/8		6d	240	15		360	17		460	19		600	22	
	3/8		8d	260	18		380	20		480	21		630	23	
	1/2			280	18		420	20		540	22		700	24	
	1/2		10d	370	21		550	23		720	24		920	25	
	5/8			400	21		610	23		790	24		1040	26	
Structural Fiberboard Sheathing	1/2		Nail (galvanized roofing) 11 ga. galv. roofing nail (0.120" x 1-1/2" long x 7/16" head)				340	4.0		460	5.0		520	5.5	
	25/32		11 ga. galv. roofing nail (0.120" x 1-3/4" long x 3/8" head)				340	4.0		460	5.0		520	5.5	

Wood Structure LFRS: Shear Walls

Aspect ratios

- Individual full-height segments
- Force transfer around openings
- Perforated shear walls

Figure 4E **Typical Individual Full-Height Wall Segments Height-to-Width Ratio**

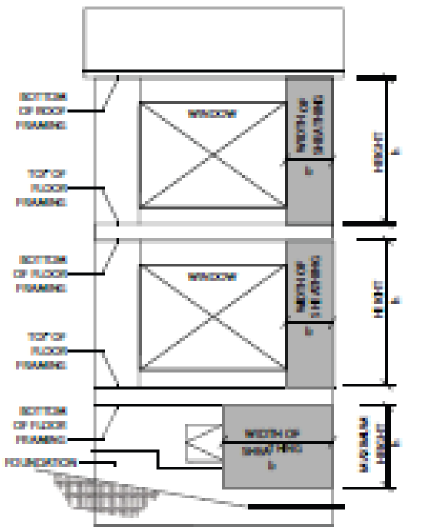


Figure 4F **Typical Shear Wall Height-to-Width Ratio for Shear Walls Designed for Force Transfer Around Openings**

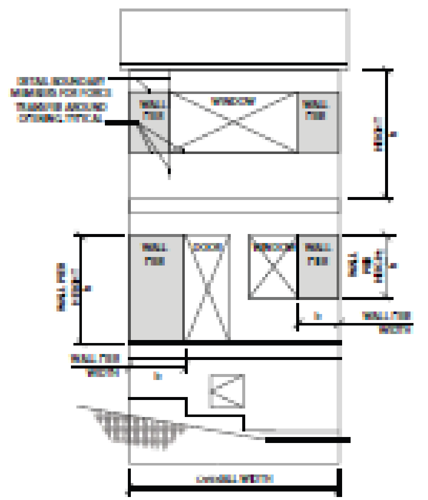
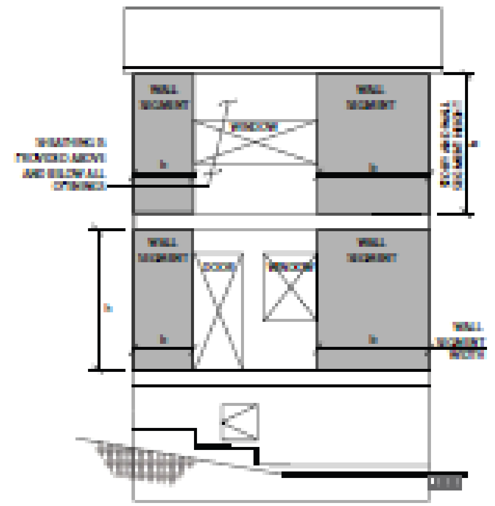
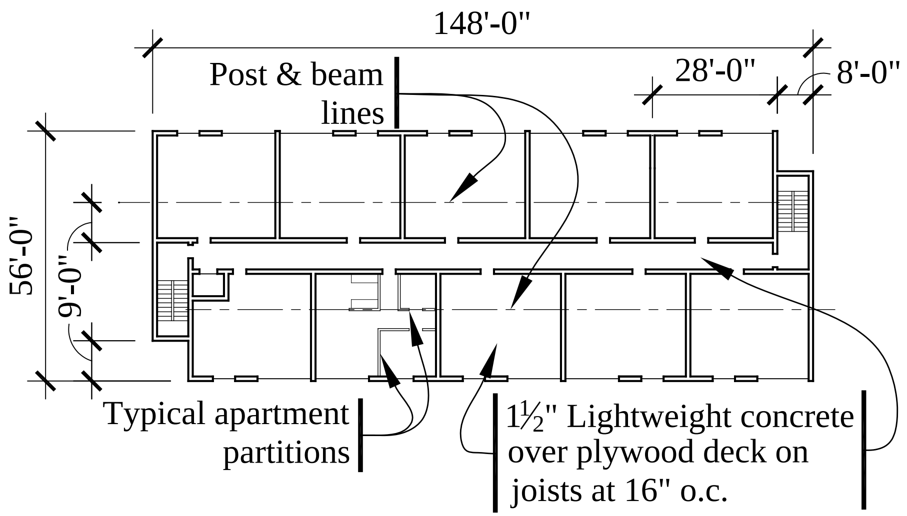


Figure 4D **Typical Shear Wall Height-to-Width Ratio for Perforated Shear Walls**

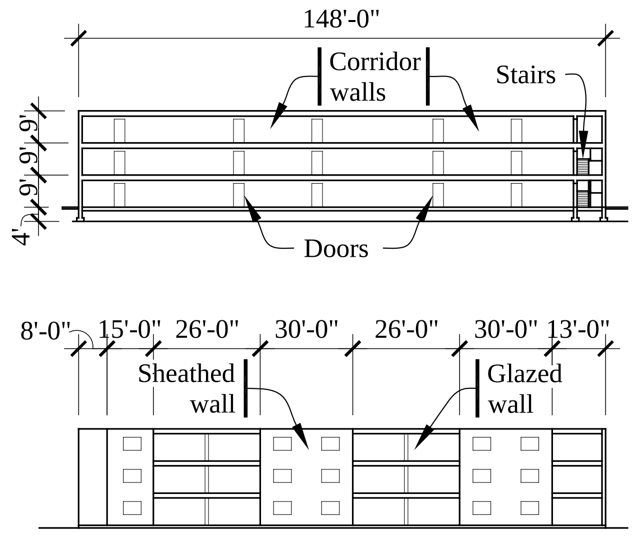


Design Example

- 3-story apartment building
- Stick framed with plywood shear walls and diaphragms
- Seismic Design Category D
- ASCE 7-05 Simplified Procedure



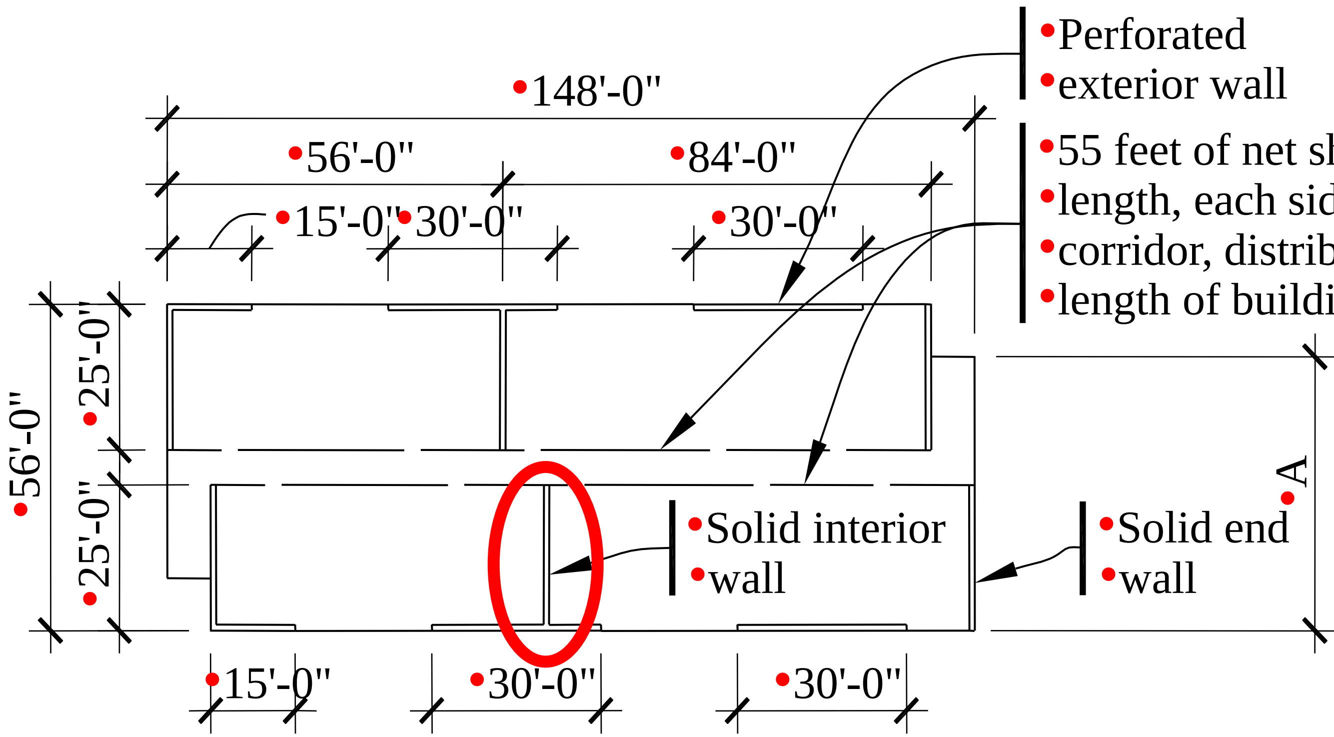
Plan



Section & Elevation

Example – Shear Wall Design

- Interior shear wall, 25 feet long, solid



Shear Wall Design – Shear

First floor wall

V_1 = 30.9 kips

v = 30.9/25 = 1.24 klf

5/8” rated sheathing on 2x framing with 10d at 2” o.c.

Nominal unit shear (SDPWS Table 4.3A), v_s = 1.74 klf

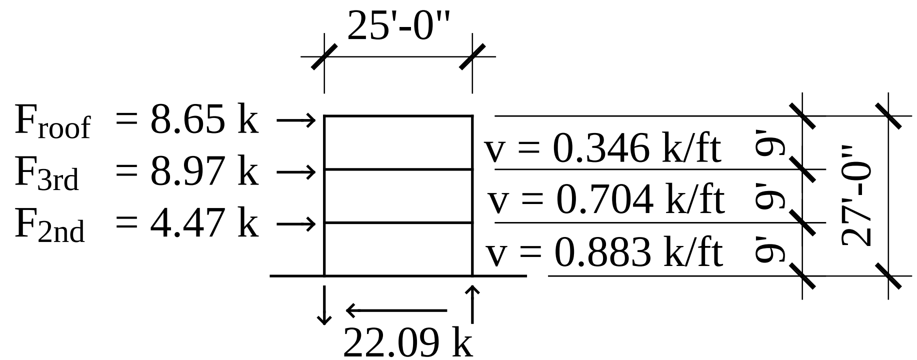
Reduction factor, φ = 0.80

Adjust for Hem-Fir (SG = 0.43)

1-(0.5-0.43) = 0.93

$0.93\varphi_D v_s$ = 0.93(0.8)(1.74)

= 1.29 klf OK

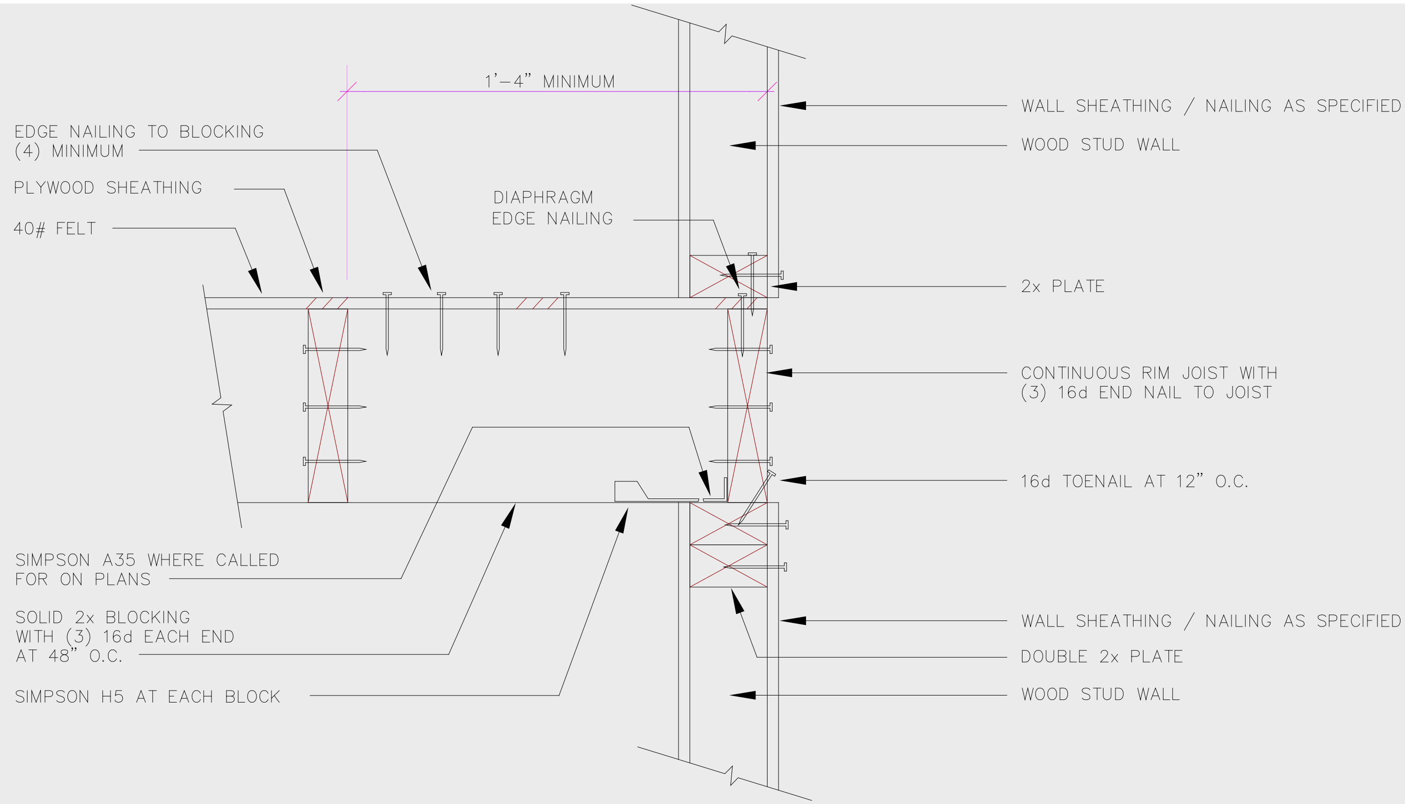


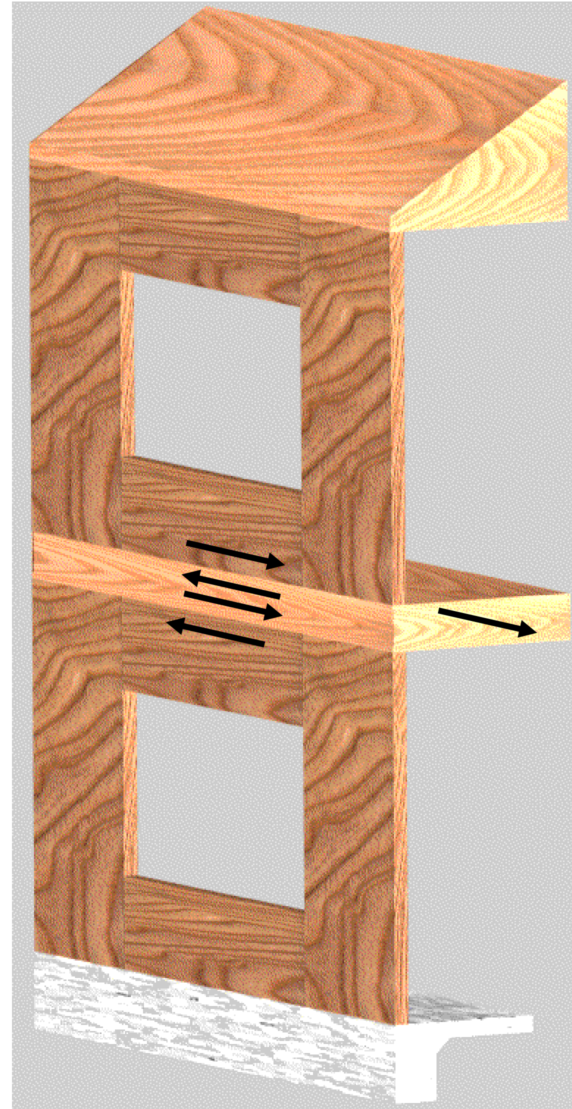
Wood-based Panels[4]

Sheathing Material	Minimum Nominal Panel Thickness (in.)	Minimun Fastener Penetration in Framing Member or Blocking (in.)	Fastener Type & Size	A SEISMIC: Panel Edge Fastener Spacing (in.): 6			4			3			2		
				v_s (plf)	G_a (kips/in.)		v_s (plf)	G_a (kips/in.)		v_s (plf)	G_a (kips/in.)		v_s (plf)	G_a (kips/in.)	
			Nail (common or galvanized box)		OSB	PLY		OSB	PLY		OSB	PLY		OSB	PLY
Wood Structural Panels - Structural I[4,5]	5/16	1-1/4	6d	400	13	10	600	18	13	780	23	16	1020	35	22
	3/8[2]	1-3/8	8d	460	19	14	720	24	17	920	30	20	1220	43	24
	7/16[2]			510	16	13	790	21	16	1010	27	19	1340	40	24
	15/32			560	14	11	860	18	14	1100	24	17	1460	37	23
	15/32	1-1/2	10d	680	22	16	1020	29	20	1330	36	22	1740	51	28
Wood Structural Panels – Sheathing[4,5]	5/16	1-1/4	6d	360	13	9.5	540	18	12	700	24	14	900	37	18
	3/8			400	11	8.5	600	15	11	780	20	13	1020	32	17
	3/8[2]	1-3/8	8d	440	17	12	640	25	15	820	31	17	1060	45	20
	7/16[2]			480	15	11	700	22	14	900	28	17	1170	42	21
	15/32			520	13	10	760	19	13	980	25	15	1280	39	20
	15/32	1-1/2	10d	620	22	14	920	30	17	1200	37	19	1540	52	23
	19/32			680	19	13	1020	26	16	1330	33	18	1740	48	22

Shear Wall Anchorage and Load Path

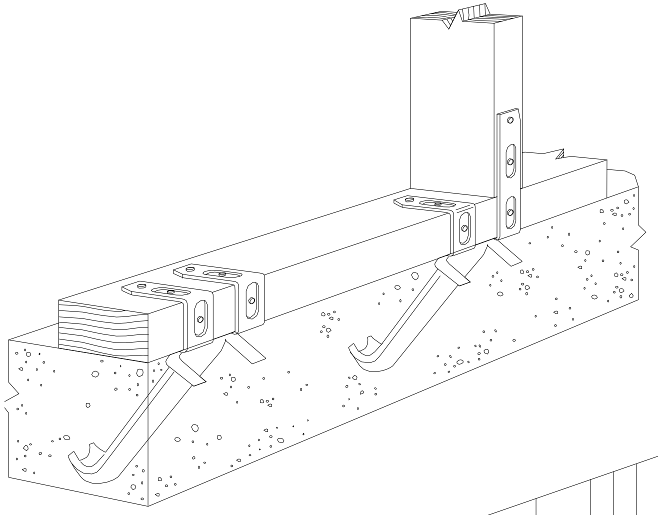
Diaphragm to shear wall / shear transfer through floor

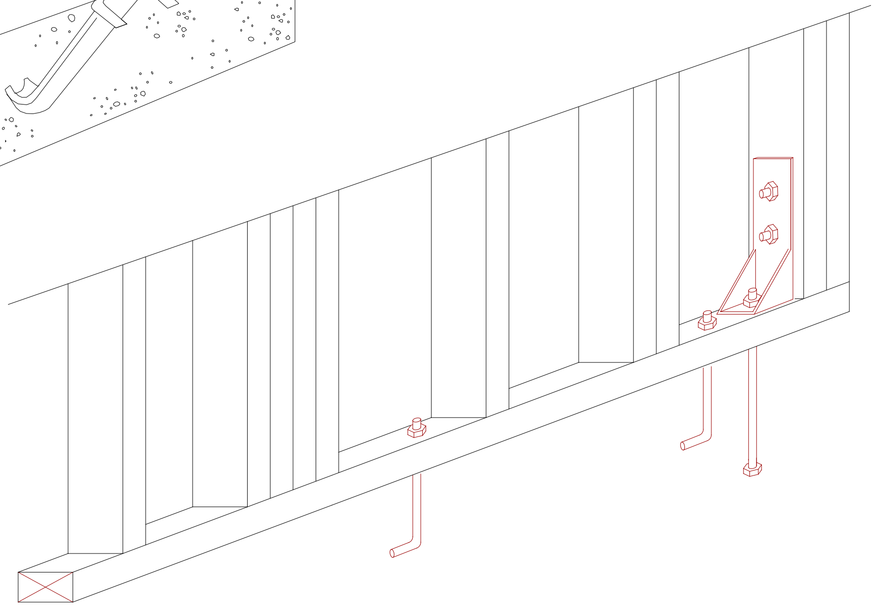


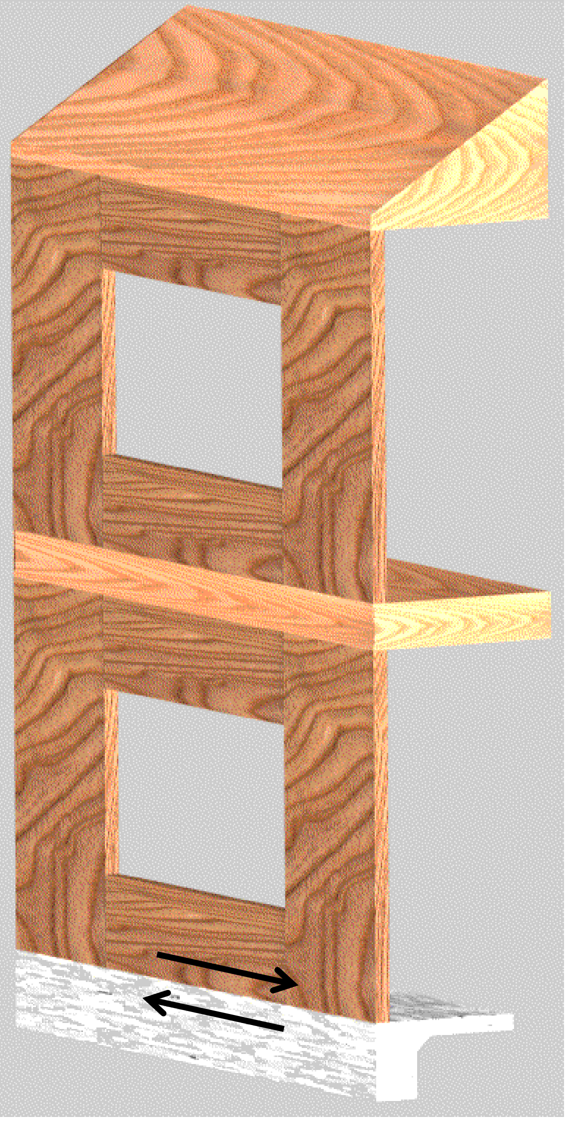


Shear Wall Anchorage and Load Path

Shear transfer to foundation







Shear Wall Design – Foundation Anchorage

- Provide in-plane anchorage for induced shear force
- Anchor bolt in wood, 2005 AF&PA NDS
- Anchor bolt in concrete, ACI 318-08 Appendix D
- Plate washer (1/4 x 3 x 3 minimum)

First floor interior wall

v = 1.24 klf

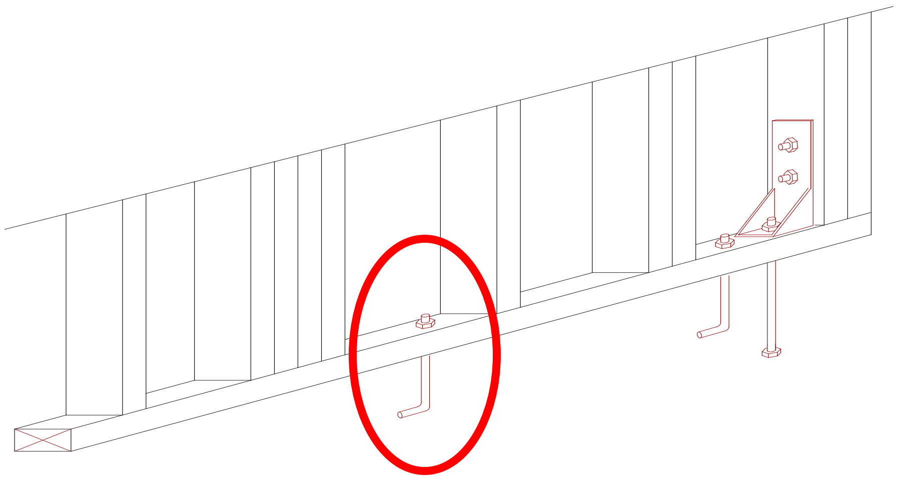
5/8-in. bolts in a 3× DFL sill plate

AF&PA NDS:

$$ZK_F\phi\lambda = (1.11)(2.16/0.65)(0.65)(1.0)$$
$$= 2.40 \text{ kips per bolt}$$

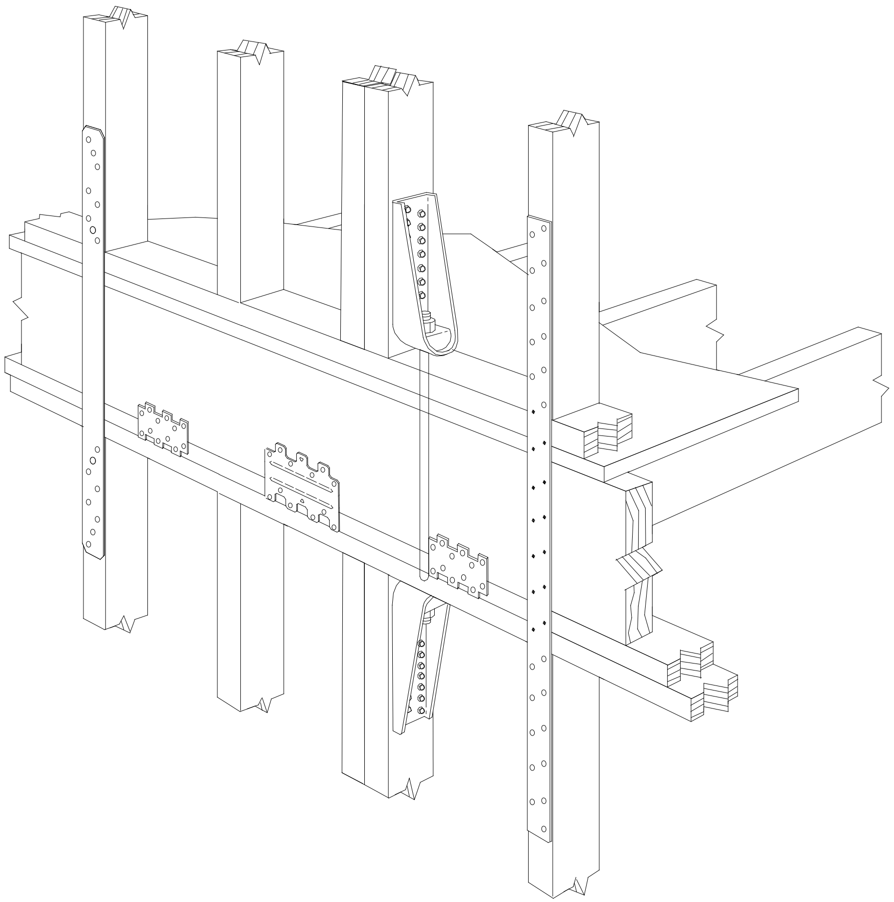
Max spacing is 2.4/[(1.24)/(12)] = 23.3 in.

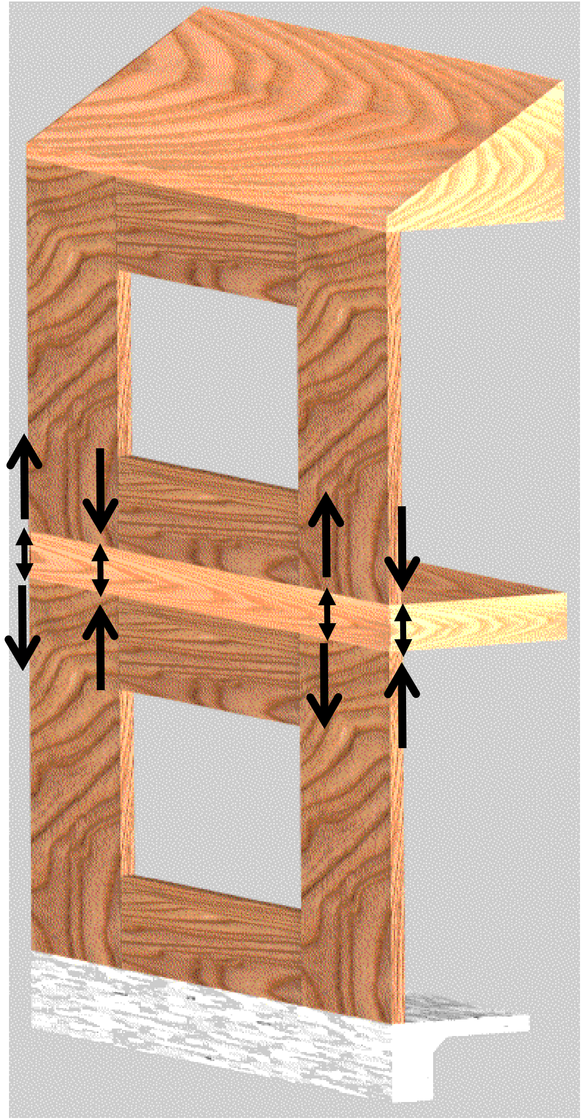
Use 5/8 in. bolts at 16 in. on center



Shear Wall Anchorage and Load Path

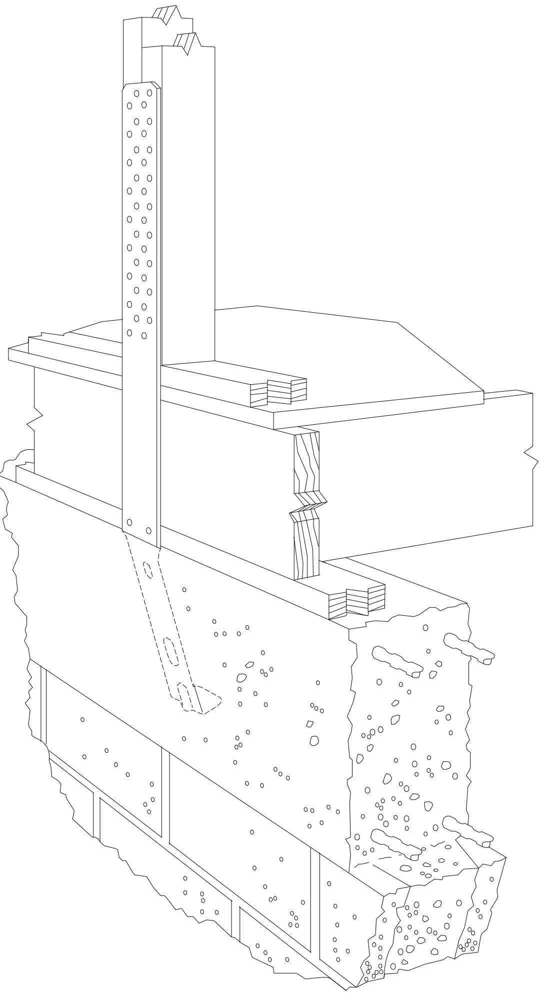
Shear wall overturning / transfer of vertical forces through floor

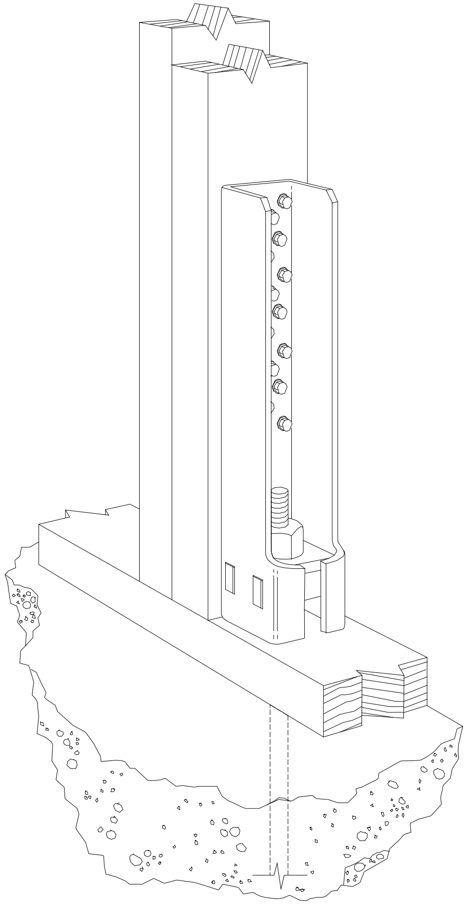


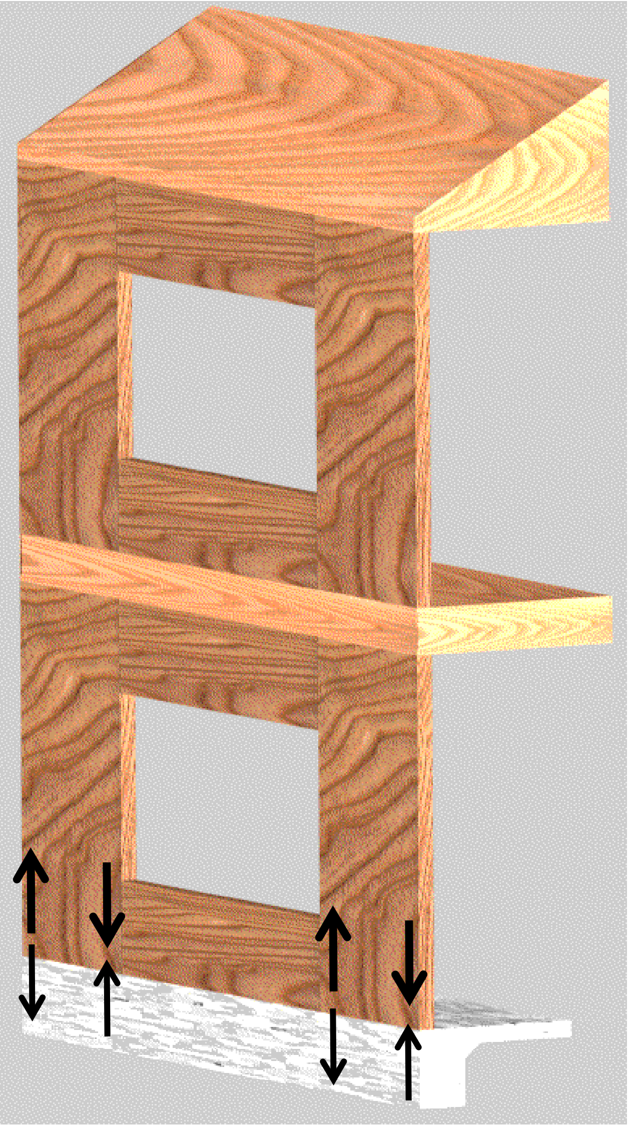


Shear Wall Anchorage and Load Path

Overturning tension/compression to foundation







Shear Wall Design – Chords & Anchorage

- Provide tension and compression chords for $T = C = vh$
  where, v = induced unit shear and h = shear wall height
- Where net tension is induced, provide anchorage for net tension force

First floor interior wall

Overturning, $M_{OT} = 517$ k-ft

Stabilizing, $M_{ST} = (0.9 - 0.2Sds)M_D = 222$ k-ft

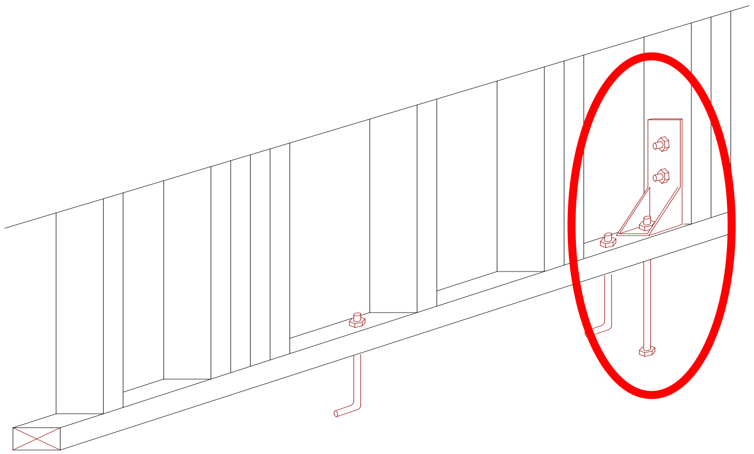
Therefore, net tension so uplift anchorage is req'd

Uplift anchorage = Σvh (all 3 stories)

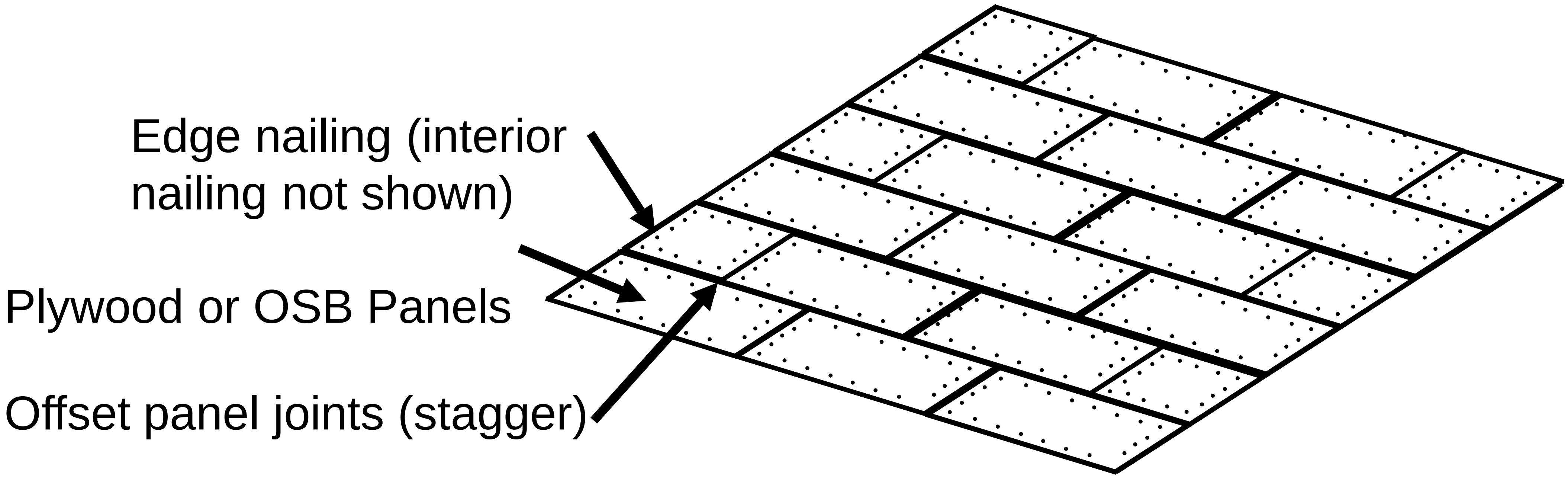
T= 16.0 kips

Use pre-engineered hold down with manufacturer's capacities converted to LFRD

Check for eccentricity and net section at end post

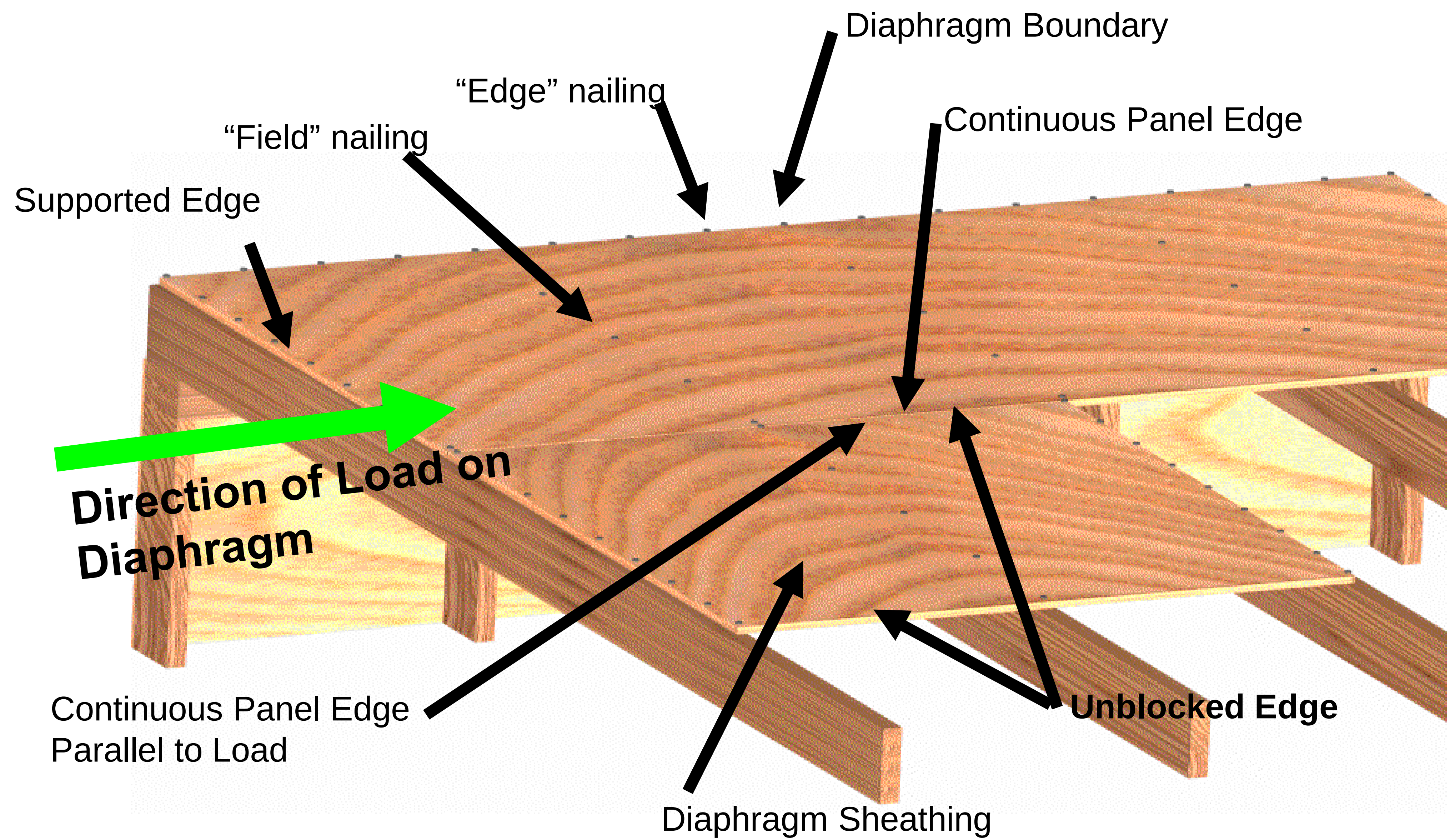


Wood Structure LRFS – Diaphragms



- Most structures rely on some form of nailed wood structural panels to act as diaphragms for the horizontal elements of the LFRS (plywood or oriented strand board – OSB)
- Capacity of diaphragm varies with sheathing grade and thickness, nail type and size, framing member size and species, geometric layout of the sheathing (stagger), direction of load relative to the stagger, and whether or not there is blocking behind every joint to ensure shear continuity across panel edges

Diaphragm Terminology

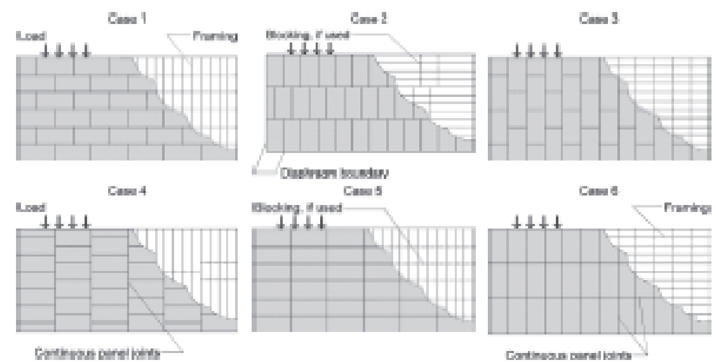


Wood Structure LFRS: Diaphragms

- SDPWS Sec. 4.2
- Deflection determination
- Aspect ratio limitations
- Unit shear capacities (diaphragm tables)
- ASD & LRFD
- Tables are for DFL or SP – need to adjust values if framing with wood species with lower specific gravities
- Major divisions:
  - Structural 1 vs. rated sheathing
  - blocked vs. unblocked panel edges
  - high load diaphragms

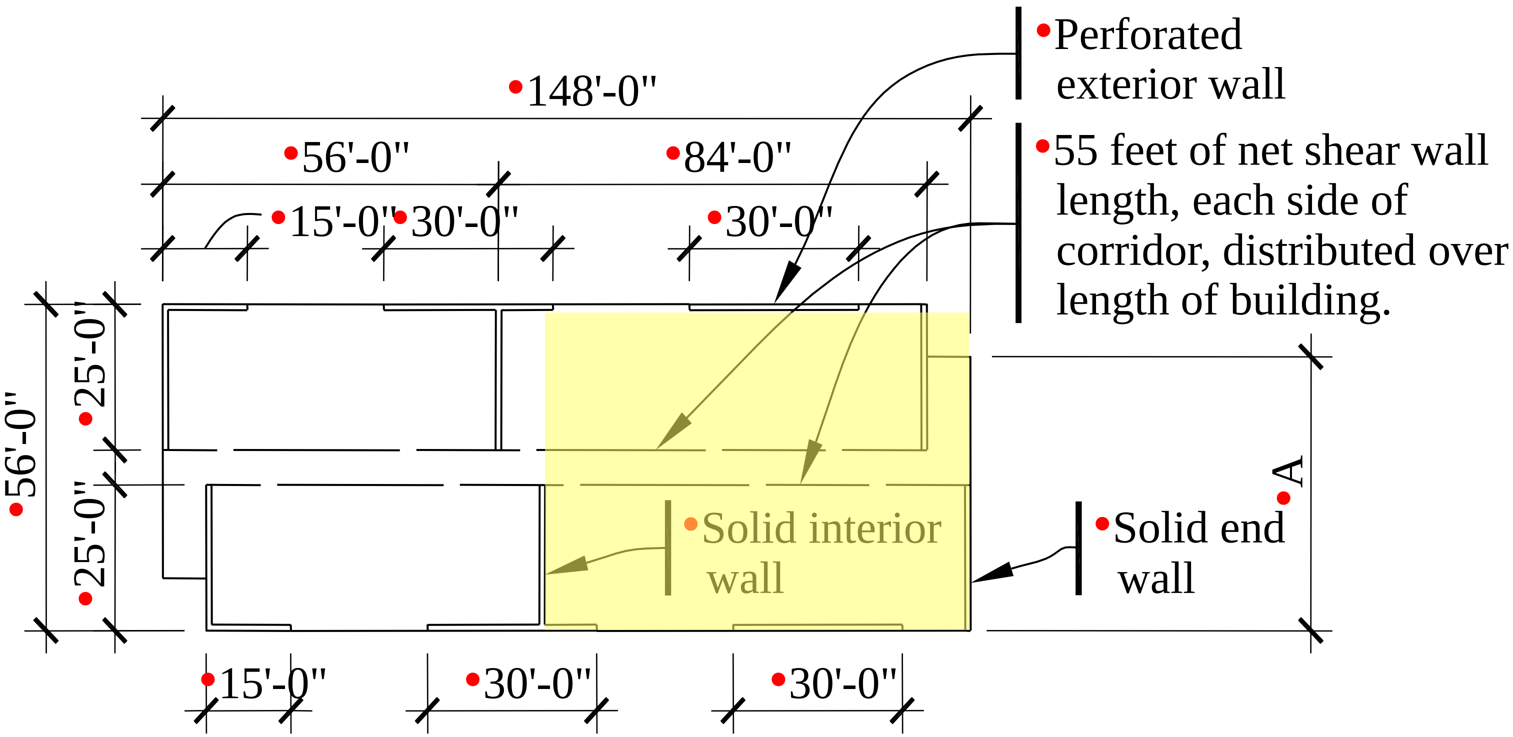
Blocked Wood Structural Panel Diaphragms[1,2,3,4]

Sheathing Grade	Common Nail Size	Minimum Fastener Penetration in Framing Member or Blocking (in.)	Minimum Nominal Panel Thickness (in.)	Minimum Nominal Width of Nailed Face at Adjoining Panel Edges and Boundaries (in.)	A SEISMIC											
					Nail Spacing (in.) at diaphragm boundaries (all cases), at continuous panel edges parallel to load (Cases 3 & 4), and at all panel edges (Cases 5 & 6)											
					6			4			2-1/2			2		
					Nail Spacing (in.) at other panel edges (Cases 1, 2, 3, & 4)											
					6			6			4			3		
					v_s (plf)	G_a (kips/in.)		v_s (plf)	G_a (kips/in.)		v_s (plf)	G_a (kips/in.)		v_s (plf)	G_a (kips/in.)	
						OSB	PLY		OSB	PLY		OSB	PLY		OSB	PLY
Structural I	6d	1-1/4	5/16	2	370	15	12	500	8.5	7.5	750	12	10	840	20	15
				3	420	12	9.5	560	7.0	6.0	840	9.5	8.5	950	17	13
	8d	1-3/8	3/8	2	540	14	11	720	9.0	7.5	1060	13	10	1200	21	15
				3	600	12	10	800	7.5	6.5	1200	10	9.0	1350	18	13
	10d	1-1/2	15/32	2	640	24	17	850	15	12	1280	20	15	1460	31	21
				3	720	20	15	960	12	9.5	1440	16	13	1640	26	18
Sheathing and Single-Floor	6d	1-1/4	5/16	2	340	15	10	450	9.0	7.0	670	13	9.5	760	21	13
				3	380	12	9.0	500	7.0	6.0	760	10	8.0	860	17	12
			3/8	2	370	13	9.5	500	7.0	6.0	750	10	8.0	840	18	12
				3	420	10	8.0	560	5.5	5.0	840	8.5	7.0	950	14	10
	8d	1-3/8	3/8	2	480	15	11	640	9.5	7.5	960	13	9.5	1090	21	13
				3	540	12	9.5	720	7.5	6.0	1080	11	8.5	1220	18	12
			7/16	2	510	14	10	680	8.5	7.0	1010	12	9.5	1150	20	13
				3	570	11	9.0	760	7.0	6.0	1140	10	8.0	1290	17	12
			15/32	2	540	13	9.5	720	7.5	6.5	1060	11	8.5	1200	19	13
				3	600	10	8.5	800	6.0	5.5	1200	9.0	7.5	1350	15	11
	10d	1-1/2	15/32	2	580	25	15	770	15	11	1150	21	14	1310	33	18
				3	650	21	14	860	12	9.5	1300	17	12	1470	28	16
			19/32	2	640	21	14	850	13	9.5	1280	18	12	1460	28	17
				3	720	17	12	960	10	8.0	1440	14	11	1640	24	15



Example – Diaphragm Design

- 3^{rd} floor diaphragm, 84 foot span (idealized)



Diaphragm Design – Shear

3rd floor diaphragm

V_{max} = 13.9 kips

v = 13.9/56 = 0.25 klf

1/2" rated sheathing on 2x DFL framing with 8d at 6" o.c.

Nominal unit shear (SDPWS Table 4.2A),

v_s = 0.54 klf

Reduction factor,

ϕ = 0.80

$\phi_D v_s$ = 0.8(0.54)

= 0.43 klf OK

Blocked Wood Structural Panel Diaphragms[1,2,3,4]

A — SEISMIC

Sheathing Grade	Common Nail Size	Minimum Fastener Penetration in Framing Member or Blocking (in.)	Minimum Nominal Panel Thickness (in.)	Minimum Nominal Width of Nailed Face at Adjoining Panel Edges and Boundaries (in.)	Nail Spacing (in.) at diaphragm boundaries (all cases), at continuous panel edges parallel to load (Cases 3 & 4), and at all panel edges (Cases 5 & 6): 6			4			2-1/2			2		
					Nail Spacing (in.) at other panel edges (Cases 1, 2, 3, & 4): 6			6			4			3		
					v_s (plf)	G_a (kips/in.) OSB	G_a (kips/in.) PLY	v_s (plf)	G_a (kips/in.) OSB	G_a (kips/in.) PLY	v_s (plf)	G_a (kips/in.) OSB	G_a (kips/in.) PLY	v_s (plf)	G_a (kips/in.) OSB	G_a (kips/in.) PLY
Structural I	6d	1-1/4	5/16	2	370	15	12	500	8.5	7.5	750	12	10	840	20	15
				3	420	12	9.5	560	7.0	6.0	840	9.5	8.5	950	17	13
	8d	1-3/8	3/8	2	540	14	11	720	9.0	7.5	1060	13	10	1200	21	15
				3	600	12	10	800	7.5	6.5	1200	10	9.0	1350	18	13
	10d	1-1/2	15/32	2	640	24	17	850	15	12	1280	20	15	1460	31	21
				3	720	20	15	960	12	9.5	1440	16	13	1640	26	18
Sheathing and Single-Floor	6d	1-1/4	5/16	2	340	15	10	450	9.0	7.0	670	13	9.5	760	21	13
				3	380	12	9.0	500	7.0	6.0	760	10	8.0	860	17	12
			3/8	2	370	13	9.5	500	7.0	6.0	750	10	8.0	840	18	12
				3	420	10	8.0	560	5.5	5.0	840	8.5	7.0	950	14	10
	8d	1-3/8	3/8	2	480	15	11	640	9.5	7.5	960	13	9.5	1090	21	13
				3	540	12	9.5	720	7.5	6.0	1080	11	8.5	1220	18	12
			7/16	2	510	14	10	680	8.5	7.0	1010	12	9.5	1150	20	13
				3	570	11	9.0	760	7.0	6.0	1140	10	8.0	1290	17	12
			15/32	2	540	13	9.5	720	7.5	6.5	1060	11	8.5	1200	19	13
				3	[illegible]	10	8.5	800	6.0	5.5	1200	9.0	7.5	1350	15	11
	10d	1-1/2	15/32	2	[illegible]	25	15	770	15	11	1150	21	14	1310	33	18
				3	[illegible]	21	14	860	12	9.5	1300	17	12	1470	28	16
			19/32	2	[illegible]	21	14	850	13	9.5	1280	18	12	1460	28	17
				3	[illegible]	17	12	960	10	8.0	1440	14	11	1640	24	15

Diaphragm Design – Chords

3rd floor diaphragm

V = 46.7 kips

w = 46.7/148 ft = 0.315 klf

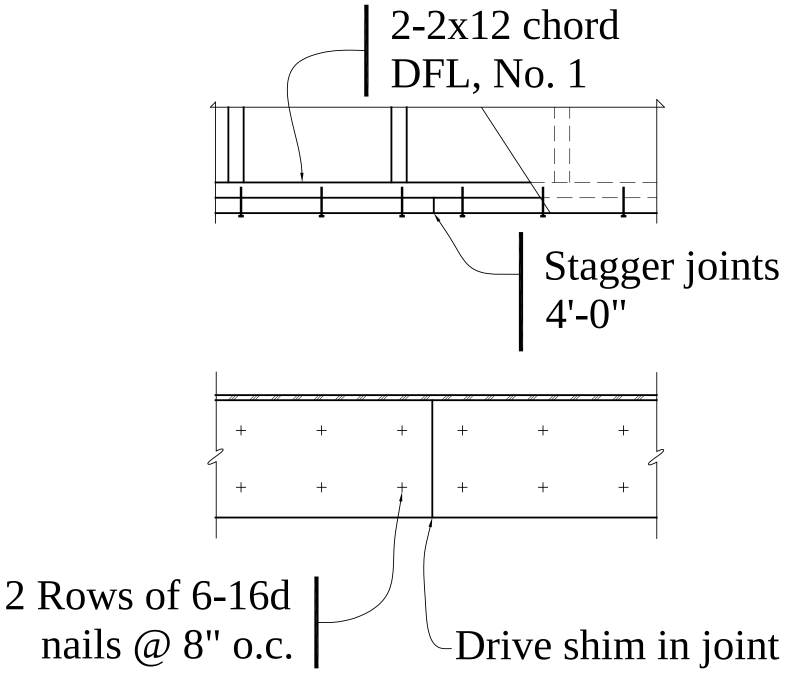
$M_{max} = wL^2/8 = 0.315(84)^2/8$

= 278 k-ft

$T = C$ = 278/56 = 4.96 kips

Chord: 2x12 DFL

Splice: 12 16d nails



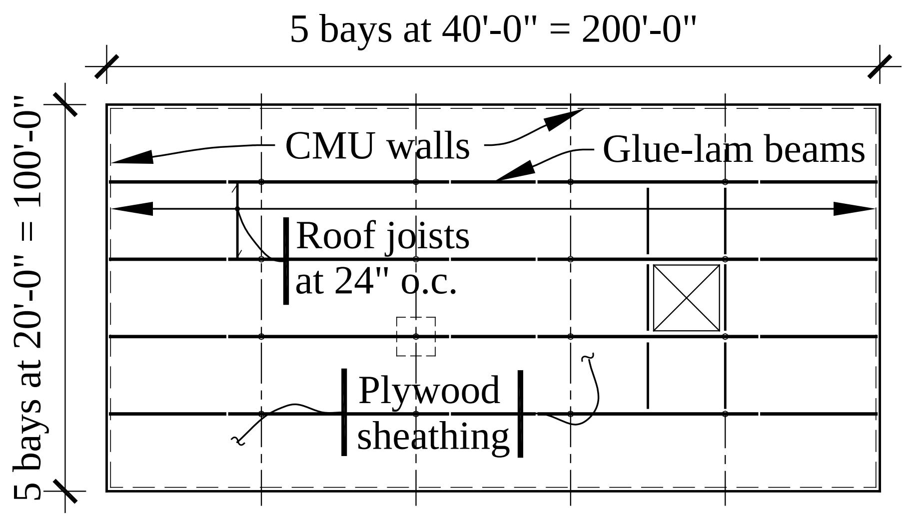
Wood Diaphragms in Concrete and Masonry Buildings

Key wood components:

- Diaphragm strength and stiffness
- Chords and collectors
- Wall anchorage
- Sub-diaphragms and cross ties

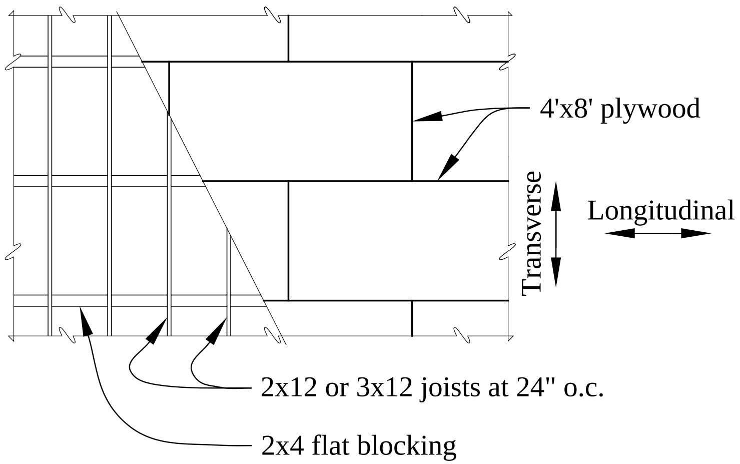
Example – Masonry Wall Building

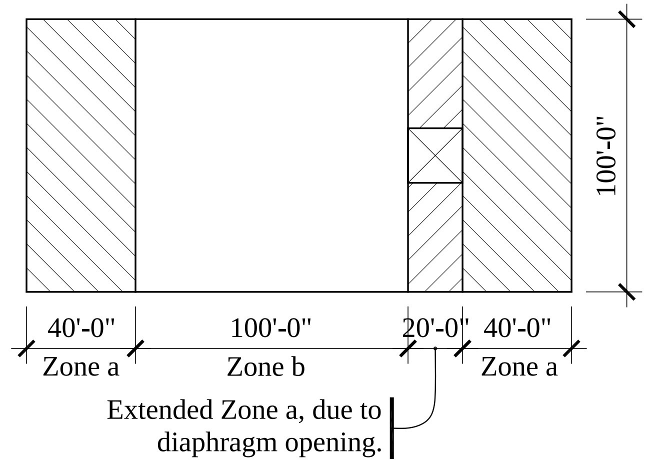
- 1-story warehouse building
- CMU walls with panelized wood roof system
- Seismic Design Category D



Example – Roof Diaphragm

- Construction and design generally similar to wood-framed buildings
- Due to large size of diaphragms, typically use different zones of nailing depending on magnitude of shear
- Chords and collectors similar to wood-framed buildings except that collector design requires consideration of Ω_0 for SDC C and above





Example – Wall Anchorage

For walls anchored to flexible diaphragms, wall anchorage force per ASCE 7-05 Sec. 12.11.2.1 and Eq. 12.11-1 is:

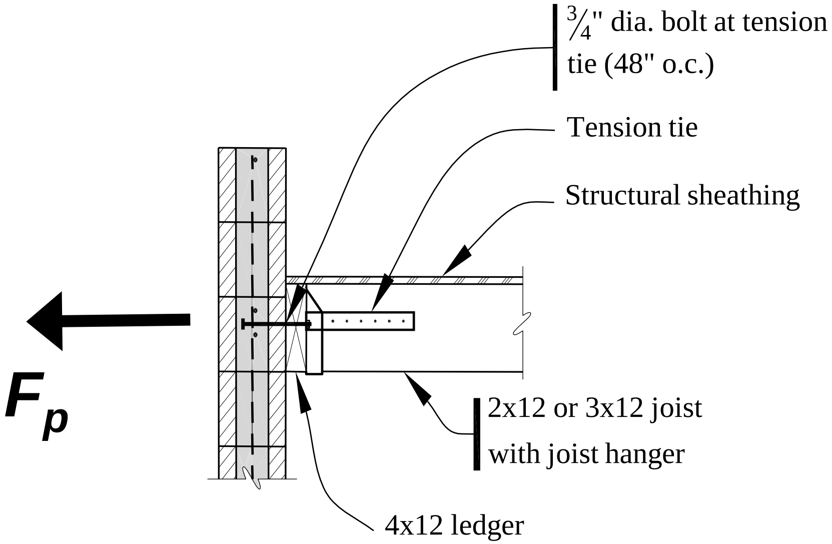
$F_p = 0.8S_{DS}IW_p$

where

$S_{DS} = 1.0$, $I = 1.0$
$W_p = 1.04$ klf (tributary CMU wall wt)

Therefore, $F_p = 0.83$ klf

Joists perpendicular to wall
If anchor ever other joist,
then $F_p = (0.83)(4) = 3.32$ kip / joist



Wall Anchorage

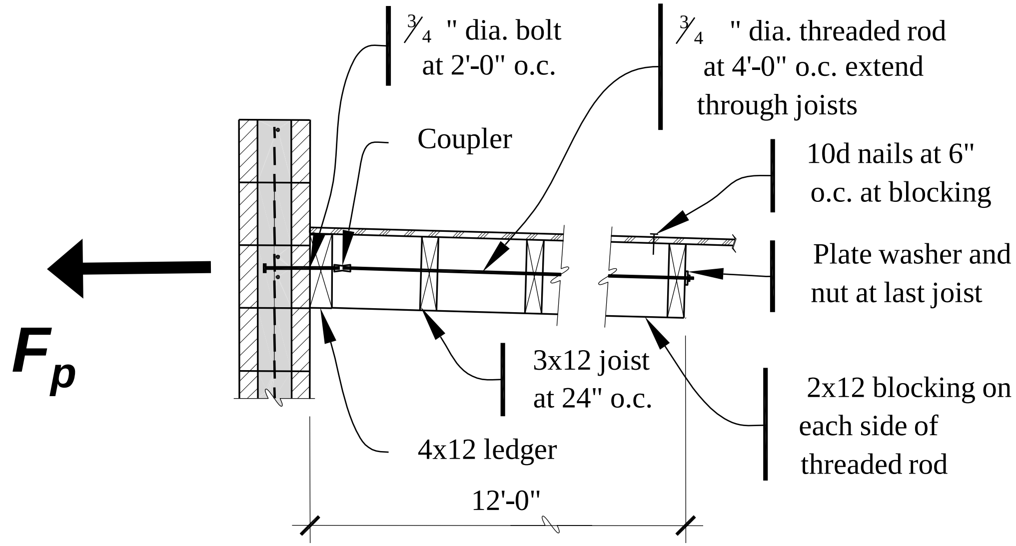
Wall anchorage design elements

- Anchor bolt (ACI 530)
- Anchorage devise (manufacturer data or evaluation report)
- Joist tension (NDS)
- Joist nailing to diaphragm (NDS)

Wall Anchorage

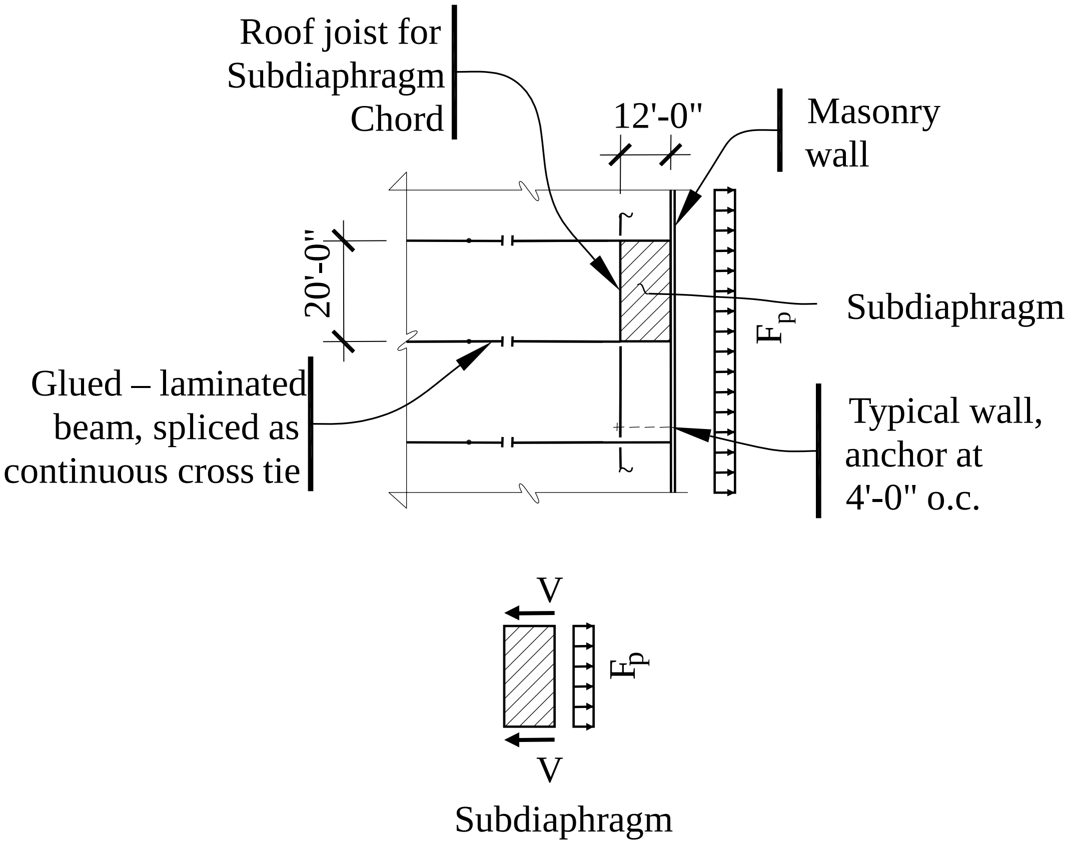
Anchorage at joists parallel to wall

- Develop wall anchorage force into diaphragm across multiple joists
- Many acceptable details for this

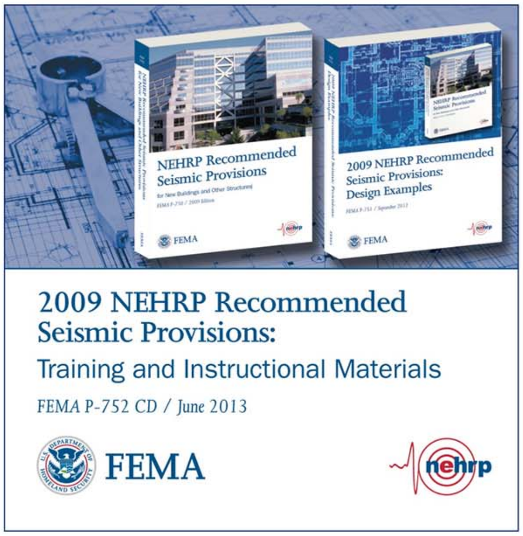


Sub-diaphragms

- Use to develop wall anchorage force into diaphragms
- Design for anchorage force between cross ties
- Maximum aspect ratio is 2.5 to 1



Questions?



11

Wood Design

Peter W. Somers, P.E., S.E.

Includes materials developed by Steve Pryor, S.E.

Title slide for Wood Design.

WOOD STRUCTURES

FEMA nehrp Instructional Material Complementing FEMA P-751, Design Examples Wood Structures - 2

Interior of the Old Faithful Inn, Yellowstone National Park, taken by previous author S. Pryor. Note heavy post and beam construction.

Design Example 11 is the **seismic design of wood structures**. During this presentation you will learn the basics of seismic design of wood buildings and wood elements within other types of buildings.

The examples in this topic draw heavily on the examples in the FEMA P-751 Design Examples CD. Please see Chapter 11 of that CD for additional details regarding these examples.

NEHRP Recommended Provisions
Wood Design Requirements

- Basic wood behavior
- Typical construction and framing methods
- Context in the *Provisions*
- Reference standards
- Analysis methods
- Lateral force resisting systems
- Shear walls and anchorage
- Diaphragms
- Concrete and masonry wall buildings

FEMA nehrp Instructional Material Complementing FEMA P-751, Design Examples Wood Structures - 3

This slide provides the outline of this presentation.

The first two parts address general behavior of wood elements (both individual members and systems) and typical wood construction methods, respectively. These section do not directly relate to the *Provisions* and can be shortened or eliminated based on the length or focus of the presentation.

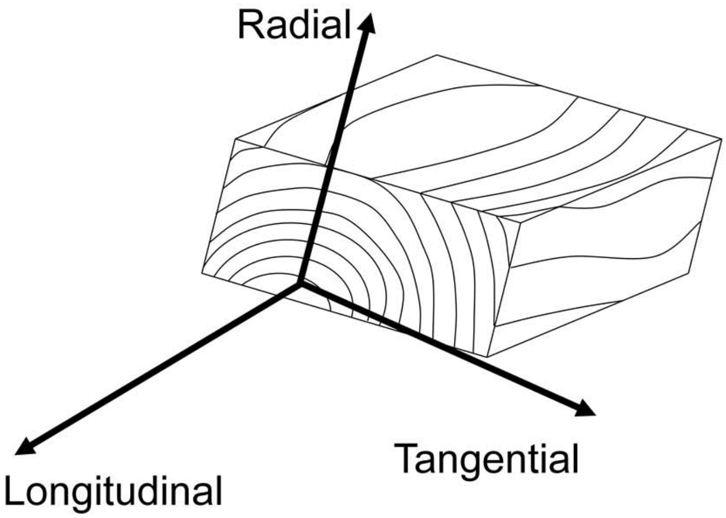
The third and fourth parts cover the requirements for wood structures based on the *Provisions*, ASCE 7, the 2005 AF&PA National Design Specification (NDS), and the 2008 AF&PA Special Design Provisions for Wind and Seismic (SDPWS).

The fifth part covers the some basics of analysis methods for wood buildings, in particular regarding rigid and flexible diaphragms.

The sixth part addresses the general requirements for lateral force-resisting systems, followed by descriptions of the two main wood systems: shear walls and diaphragms.

The final part covers specific requirements for wood diaphragms that are in concrete and masonry wall buildings.

Basic Wood Material Properties



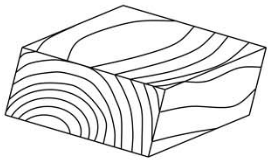
Wood is orthotropic

- Unique, independent, mechanical properties in 3 different directions
- Varies with moisture content
- Main strength axis is longitudinal - parallel to grain
- Radial and tangential are "perpendicular" to the grain - substantially weaker

Wood is a very complex organic building material. Nevertheless, it has been used successfully throughout the history of mankind for everything from structures to ships to planes to weaponry.

Mention that naturally occurring “strength reducing characteristics” such as knots, shakes, and splits will contribute the actual strength of lumber.

Basic Wood Material Properties



"Timber is as different from wood as concrete is from cement."

– Madsen, Structural Behaviour of Timber

Concept of "wood" as "clear wood": design properties used to be derived from clear wood with adjustments for a range of "strength reducing characteristics"

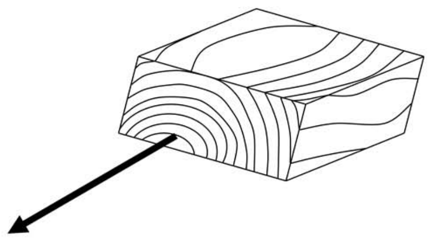
- Concept of "timber" as the useful engineering and construction material: "In-grade" testing (used now) determines engineering properties for a specific grade of timber based on full-scale tests of timber, a mixture of clear wood and strength reducing characteristics

FEMA nehrp Instructional Material Complementing FEMA P-751, Design Examples Wood Structures - 5

Borg Madsen's distinction is a good one. The understanding of how timber behaves must address the natural occurrence of strength reducing characteristics.

Although that distinction is meaningful, this unit (and the corresponding chapter of Design Examples) follows the practice in using the term "wood" where Madsen would use "timber."

Basic Wood Material Properties



Sample DFL longitudinal design properties:

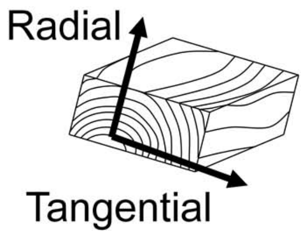
- Modulus of elasticity: 1,800,000 psi
- Tension (parallel to grain): 1,575 psi
- Bending: 2,100 psi
- Compression (parallel to grain): 1,875 psi

DFL: Douglas Fir-Larch

This slide and the next are intended to provide a feel for general level of design allowable stresses (ASD) unless where noted otherwise. LRFD could be used, but ASD is still predominant in the design community.

Discuss how bending > tension because for tension entire cross section is stressed, which means tension strength reducing characteristics will be found/encountered, whereas for bending, max stresses are at the outer edges of the board and grading rules take into account the size and location of strength reducing characteristics and how they would affect bending.

Basic Wood Material Properties



Sample DFL perpendicular to grain design properties:

- Modulus of elasticity: 45,000 psi (2.5 ~ 5 % of $E_{||}$!)
- Tension (perpendicular to grain): 180 to 350 psi FAILURE stresses

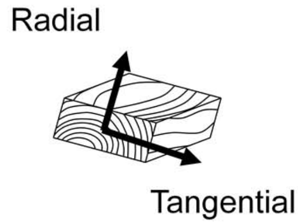
Timber is extremely weak for this stress condition. It should be avoided if at all possible, and mechanically reinforced if not avoidable.

- Compression (perpendicular to grain): 625 psi. Note that this is derived from a serviceability limit state of ~ 0.04” permanent deformation under stress in contact situations. This is the most "ductile" basic wood property.

Intended to provide a feel for general level of design allowable stresses and to emphasize the weakness of wood stressed perpendicular to grain. In commercial lumber, tension perpendicular is very low and designs must not rely on this type of action.

Note how miners have long taken advantage of the ductile nature of compression perpendicular to grain in shoring up mine shafts.

Basic Wood Material Properties



<u>Shrinkage</u>

- Wood will shrink with changes in moisture content
- This is most pronounced in the radial and tangential directions (perpendicular to grain)
- May need to be addressed in the LFRS

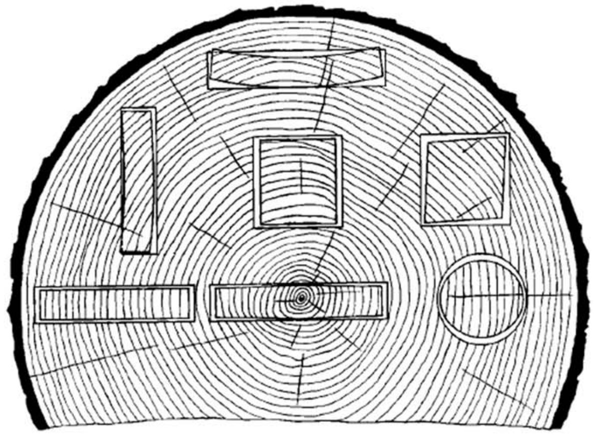


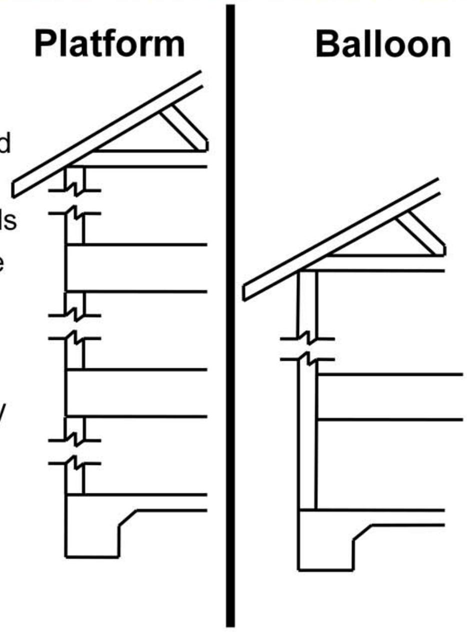
Figure 3–3. Characteristic shrinkage and distortion of flat, square, and round pieces as affected by direction of growth rings. Tangential shrinkage is about twice as great as radial.

(Wood Handbook, p. 58)

For most designs shrinkage in the longitudinal direction can be ignored. However, that may not be the case for perpendicular to grain shrinkage. Accumulated effects in the boundary chords of shear walls can degrade the performance of the shear wall system and may need to be addressed with shrinkage compensating devices. While tangential ~ 2x radial, for design purposes. this is ignored as one won't know that the orientation will be in service.

Figure is 3-3 from the *Wood Handbook*.

Wood Structure Construction Methods: Gravity



Platform

- Walls are interrupted by floor "platforms"
- Floors support walls
- Most common type of light-frame construction today
- Economical but creates discontinuity in the load path
- Metal connectors essential for complete load path

Balloon

- Walls feature foundation to roof framing members
- Floors supported by ledgers on walls or lapped with studs
- Not very common today

FEMA nehrp Instructional Material Complementing FEMA P-751, Design Examples Wood Structures - 9

Self explanatory. Note the accumulation potential of shrinkage perpendicular to grain in each floor over the height of the structure.

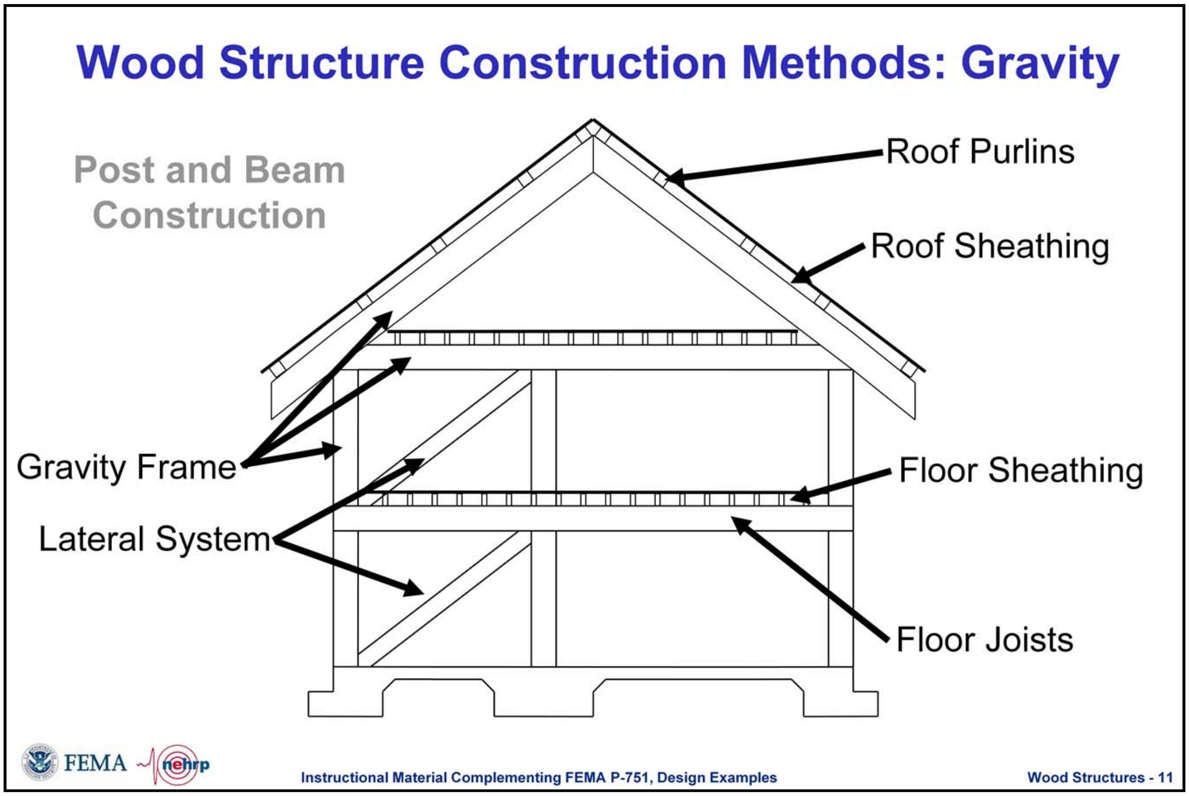
Wood Structure Construction Methods: Gravity

Post and Beam

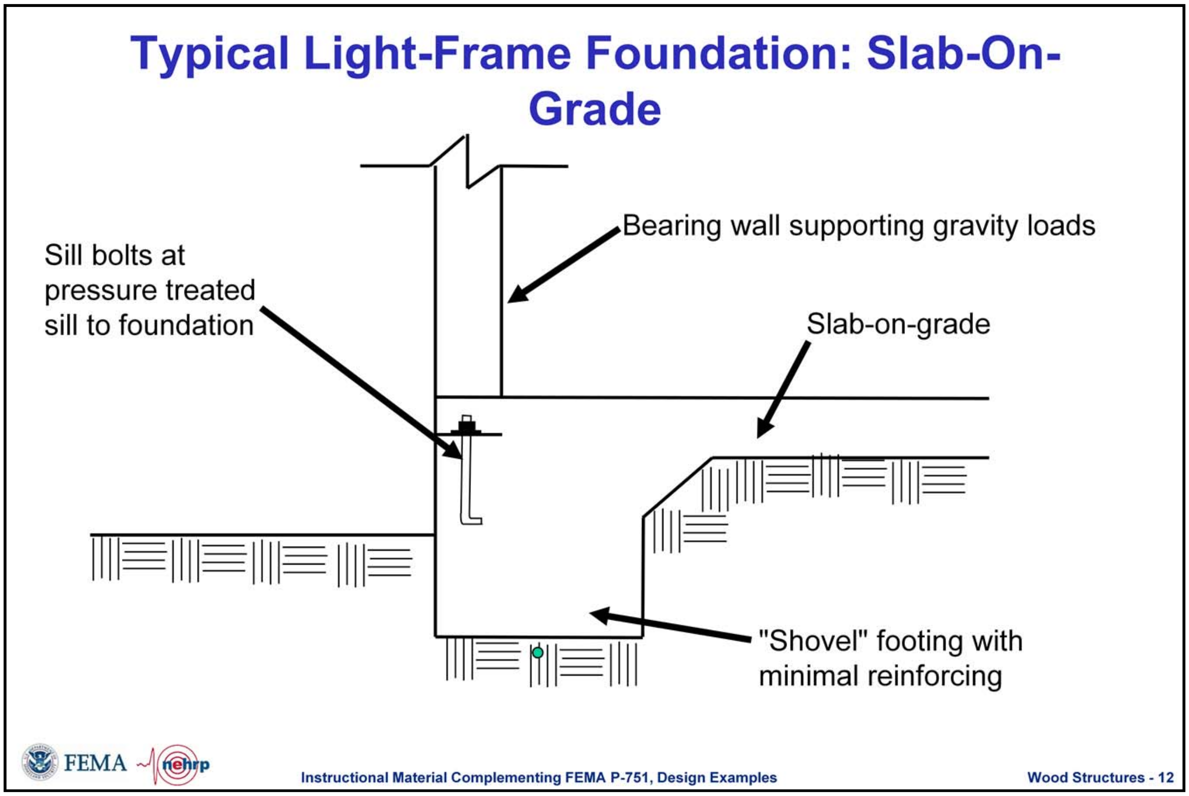
- Space frame for gravity loads
- Moment continuity at joint typically only if member is continuous through joint
- Lateral resistance through vertical diaphragms or braced frames
- Knee braces as seen here for lateral have no code design procedure for seismic

Six story main lobby Old Faithful Inn, Yellowstone, undergoing renovation work in 2005. Built in winter of 1903-1904, it withstood a major 7.5 earthquake in 1959.

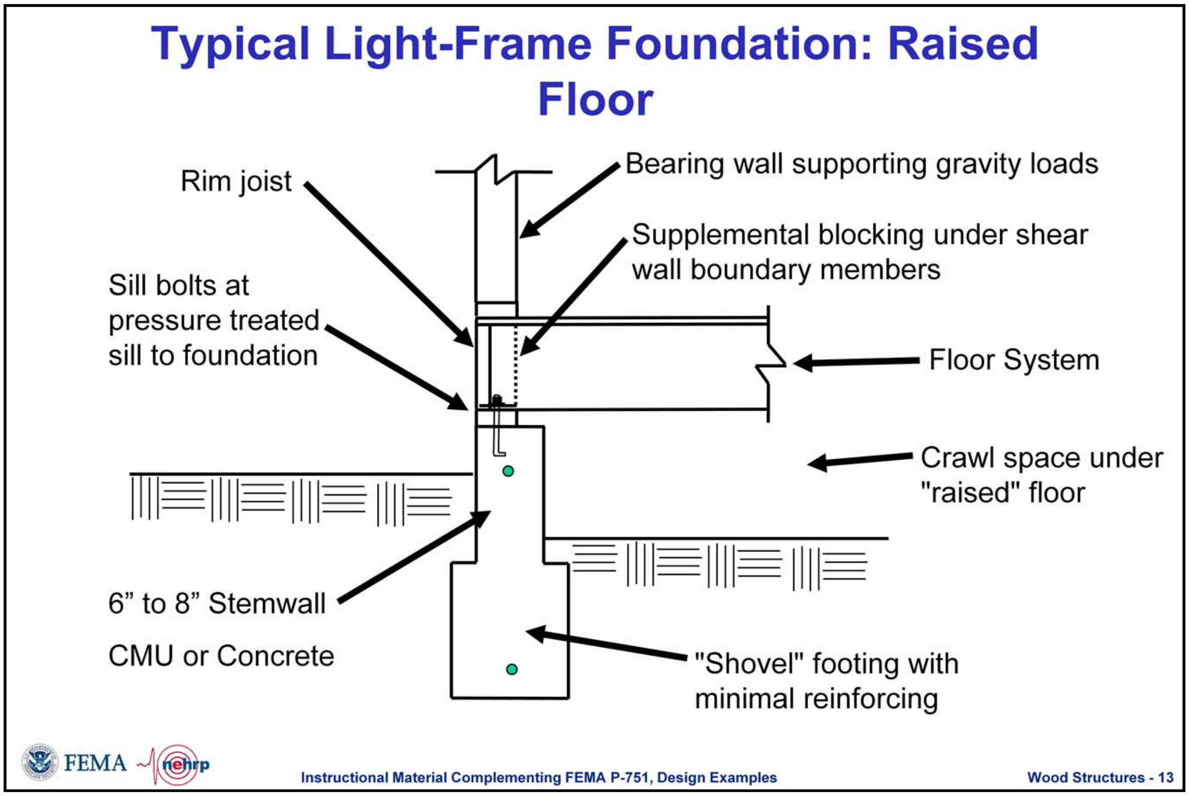
The Old Faithful Inn wasn't "designed" for seismic, but the designers and builders provided a structure that suffered only minor damage in the 1959 earthquake. Lateral resistance of this structure is a combination of wood moment frame action due to the knee braces at the post/beam connection (note eccentricity in the braces under axial forces due to architectural curvature of the braces, in every brace) and diaphragm action in the roof/walls. Some beam/column connections in the very top of the lobby, which supported a "crows nest" platform where a small orchestra would play and entertain guests, were damaged and so that practice was stopped. Here it is being repaired and strengthened (summer 2005).



For the most part. this slide is self explanatory. Emphasize that the lateral system typically will not support gravity load, and while braced frame action is shown here, it could also be wood shear walls (stud walls with nailed wood structural panel sheathing). Because the LFRS doesn’t support gravity loads, it is in a different category when it comes to the R factor used to determine lateral demand. Also, spread footings are more likely to support the concentrated loads from the columns as compared to platform style construction.

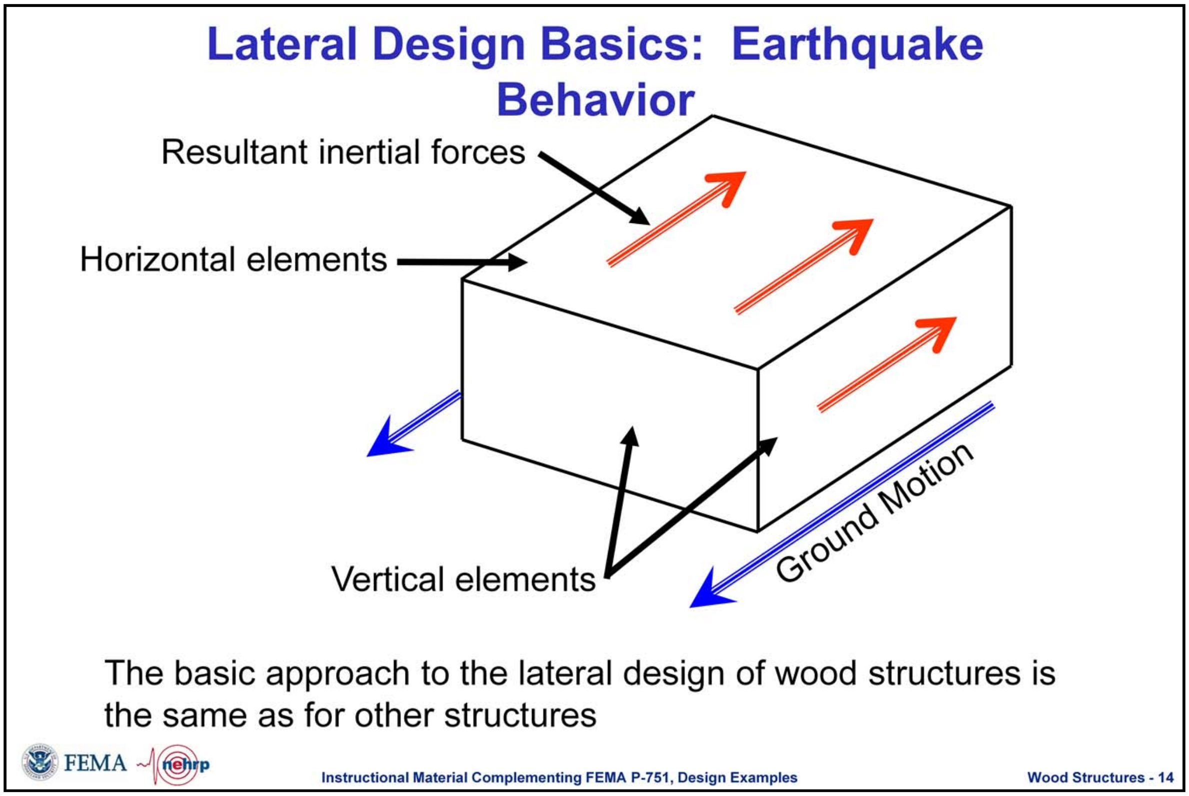


Self explanatory. Note that relatively little engineering goes into the footings for the most part.

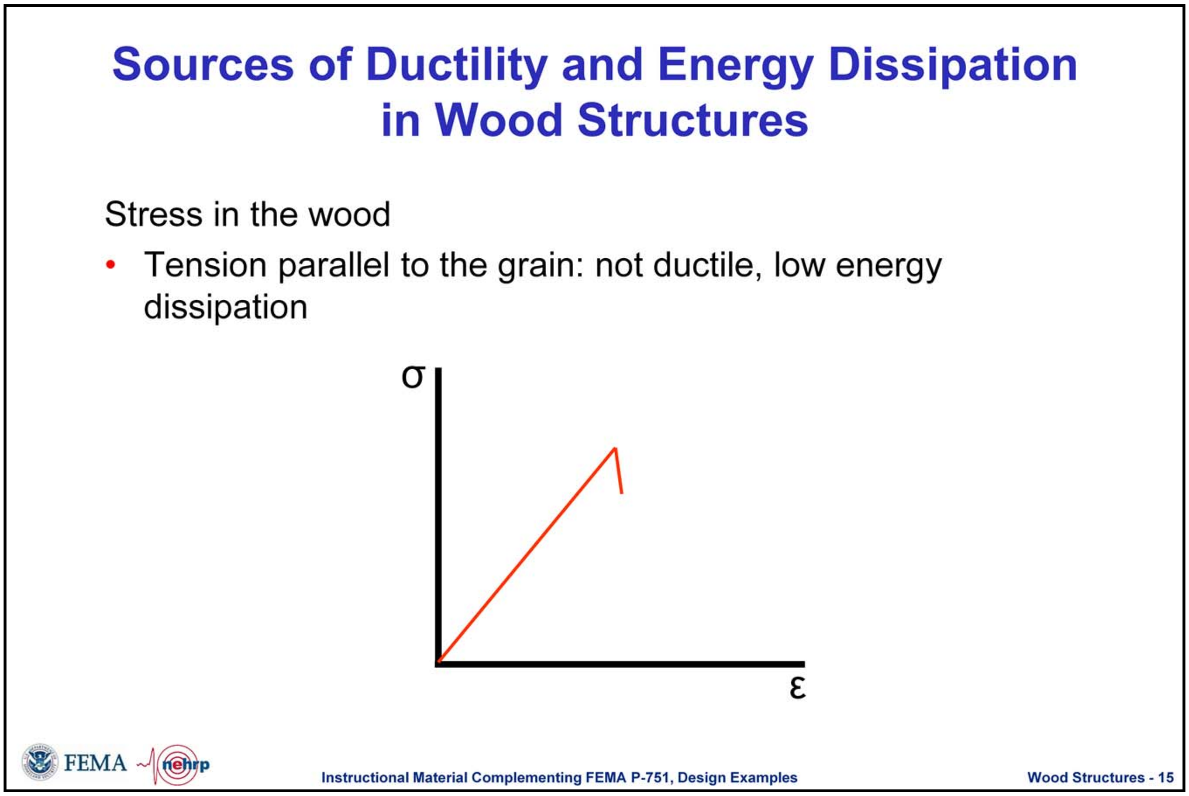


As before, not much attention beyond code reinforcing minimums for the foundation. Shear wall boundary members can create large overturning compression forces that require supplemental blocking to prevent excess deformations through elastic compression of the floors (recall that the MOE of wood perpendicular to grain is 2.5% to 5% of the MOE of wood parallel to the grain. These same issues need to be considered at upper level floors in platform style construction.

Again, note that for uplift forces coming through the walls, careful attention needs to be placed on the load path and ensuring that it is continuous. More on this later.



Slide emphasizes that basic design principles apply to wood structures. Horizontal and vertical elements of resistance need to be identified and designed. In the case of prescriptive or nonengineered light-frame structures, this is accomplished through required construction and detailing provisions of the building code.

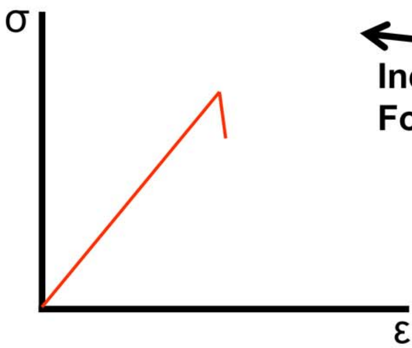


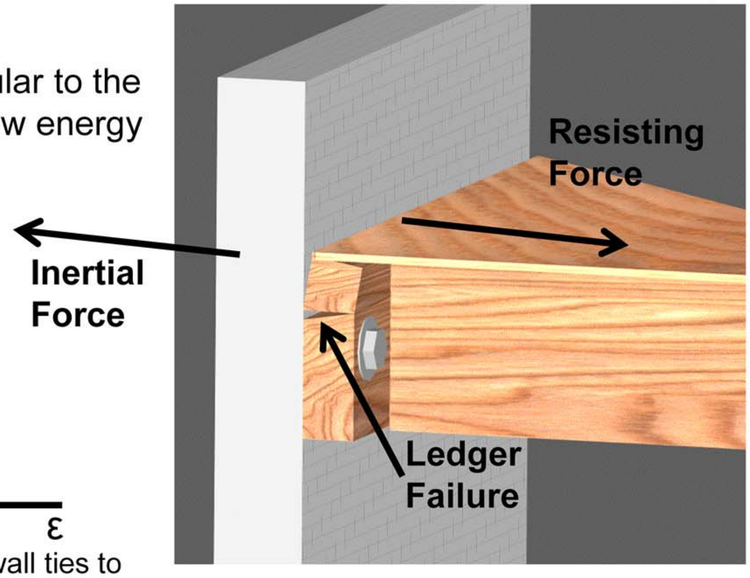
Slide shows a stress strain curve for wood that is essentially liner elastic, with a brittle failure. There is virtually no ductility, and no energy dissipation capacity.

Sources of Ductility and Energy Dissipation in Wood Structures

Stress in the wood

- Tension perpendicular to the grain: not ductile, low energy dissipation



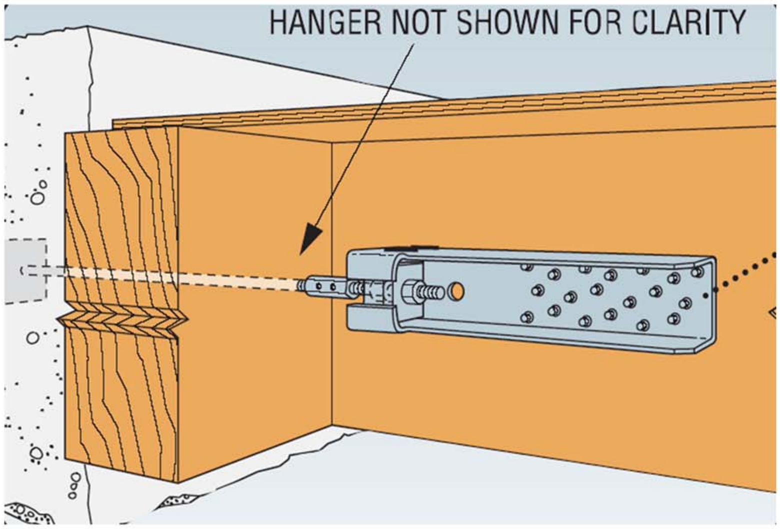


- Need to have positive wall ties to perpendicular framing

Comment on how inertial force of wall will pull away from roof. Also note that if there are no ties between the framing members perpendicular to the wall and the wall, the sheathing attachment to the ledger will fail the ledger in cross grain bending/tension, causing collapse of the roof and wall.

Sources of Ductility and Energy Dissipation in Wood Structures

Positive Wall Tie



FEMA nehrp Instructional Material Complementing FEMA P-751, Design Examples Wood Structures - 17

One of the most important design aspects of wood structures is to tie the building together. The connections are extremely important in achieving adequate seismic behavior.

Sources of Ductility and Energy Dissipation in Wood Structures

Stress in the wood

- Compression perpendicular to the grain: ductile, but not recoverable during an event – one way crushing similar to tension only braced frame behavior – ductile, but low energy dissipation
- Design allowable stress should produce ~0.04” permanent crushing

FEMA nehrp

For single excursions, wood perpendicular to grain nonlinear behavior can be a good one-time energy dissipater. However, for cyclic loading, such as seismic, it becomes a poor energy dissipater because the wood won’t recover from the crushing, leading to slack behavior in the system connected to it.

Sources of Ductility and Energy Dissipation in Wood Structures

Stress in the fastener

- Nailed joint between sheathing and framing is source of majority of ductility and energy dissipation for nailed wood structural panel shear walls
- The energy dissipation is a combination of yielding in the shank of the nail, and crushing in the wood fibers surrounding the nail
- Since wood crushing is nonrecoverable, this leads to a partial "pinching" effect in the hysteretic behavior of the joint.
- The pinching isn't 100% because of the strength of the nail shank undergoing reversed ductile bending yielding in the wood.
- As the joint cycles, joint resistance climbs above the pinching threshold when the nail "bottoms out" against the end of the previously crushed slot forming in the wood post

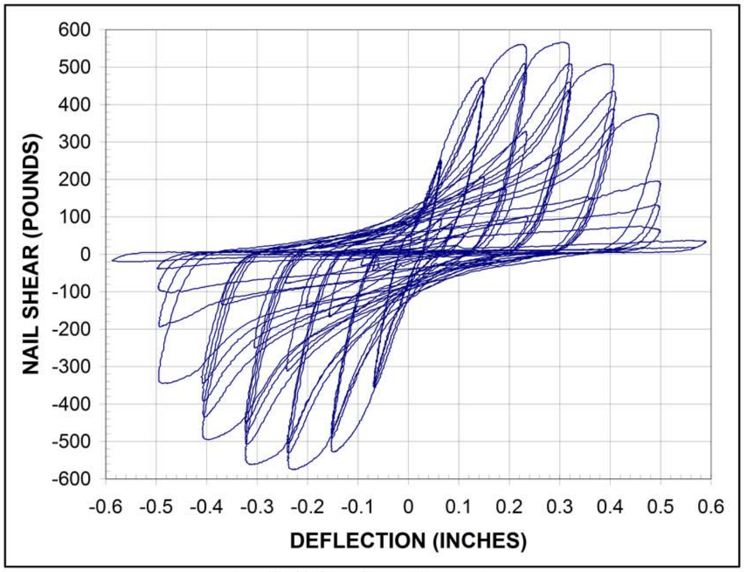
FEMA nehrp

Instructional Material Complementing FEMA P-751, Design Examples

Wood Structures - 19

Self explanatory: List of sources of energy dissipation in wood structures.

Sources of Ductility and Energy Dissipation in Wood Structures



Individual nail test

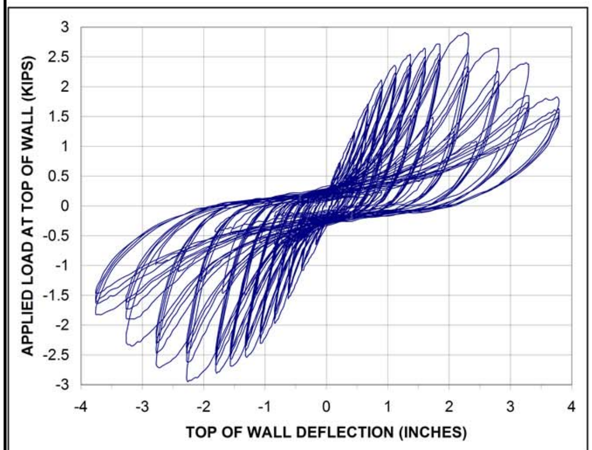
FEMA nehrp

Instructional Material Complementing FEMA P-751, Design Examples

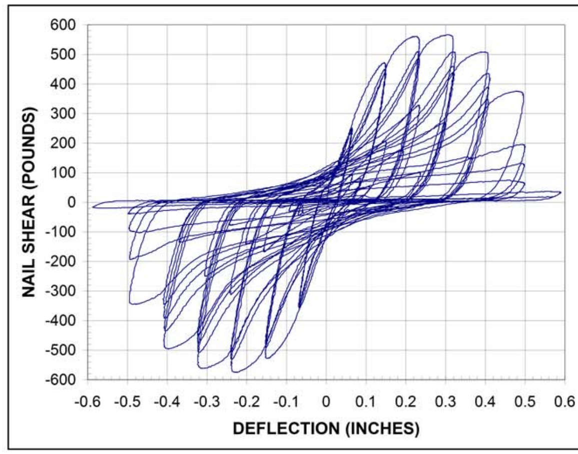
Wood Structures - 20

Comment on how permanent crushing of wood around shank of nail leads to pinched nature of nail hysteresis.

Sources of Ductility and Energy Dissipation in Wood Structures



Full-scale shear wall test



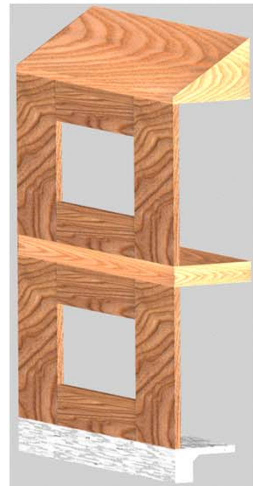
Individual nail test

FEMA nehrp Instructional Material Complementing FEMA P-751, Design Examples Wood Structures - 21

Note similarities between single nail hysteresis and global shear wall hysteresis. Comment on how shear wall behavior, globally, is a product of local fastener hysteresis.

Lateral Design Basics: Complete Load Path

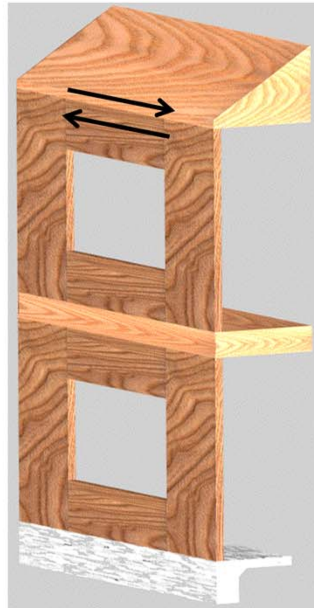
- Earthquakes move the foundations of a structure
- If the structure doesn't keep up with the movements of the foundations, failure will occur
- Keeping a structure on its foundations requires a complete load path from the foundation to all mass in a structure
- Load path issues in wood structures can be complex
- For practical engineering, the load path is somewhat simplified for a "good enough for design" philosophy



Self explanatory. Slide discusses the need for a complete load path.

Lateral Design Basics: Complete Load Path

- Shear wall overturning
- Diaphragm to shear wall
- Overturning tension/ compression through floor
- Shear transfer through floor
- Shear transfer to foundation



FEMA nehrp Instructional Material Complementing FEMA P-751, Design Examples Wood Structures - 23

Self explanatory. Continuation of previous slide discussing need for complete load path.

Wood Structure LFRS Design Methods: Engineered

- If a structures does not meet the code requirements for "prescriptive" or "conventional" construction, it must be "engineered"
- As in other engineered structures, wood structures are only limited by the application of good design practices applied through principles of mechanics (and story height limitations in the code)
- A dedicated system of horizontal and vertical elements, along with complete connectivity, must be designed and detailed.

FEMA nehrp Instructional Material Complementing FEMA P-751, Design Examples Wood Structures - 24

Emphasize the importance of engineering in "engineered" wood structures, developing the "complete load path". The structural load path for lateral forces is complex in wood structures. A system of diaphragms and shear walls, connected through drag struts and shear transfer details, is designed. However, the "nonstructural" sheathing on the inside and outside of the structure significantly contributes to the performance during an earthquake. While largely ignored, this extra contribution is thought to be inherent in the code R factors used for design.

Wood Structure LFRS Design Methods: Prescriptive

Also referred to as "*Conventional Construction*"

- Traditionally, many simple wood structures have been designed without "engineering"
- Over time, rules of how to build have been developed, most recently in the 2009 International Residential Code (IRC)
- For the lateral system, the "dedicated" vertical element is referred to as a *braced wall panel*, which is part of a *braced wall line*
- Based on SDC and number of stories, rules dictate the permissible spacing between braced wall lines, and the spacing of braced wall panels within braced wall lines

FEMA nehrp

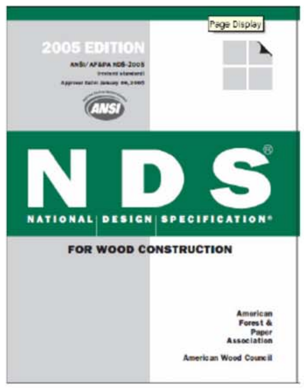
Instructional Material Complementing FEMA P-751, Design Examples

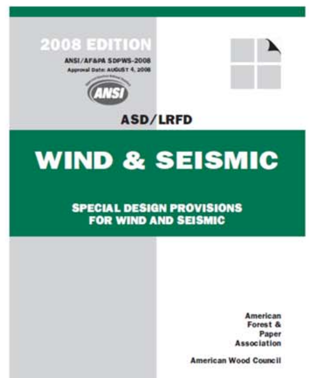
Wood Structures - 25

The prescriptive, or conventional construction" design method is shown here but is not covered in this presentation.

Context in the Provisions

- ASCE 7-05 Sec. 12.2 Structural Systems
- ASCE 7-05 Sec. 14.5 Wood Structures
- AF&PA NDS – wood framing and connections
- AF&PA SDPWS – shears, diaphragms, and anchorage





The 2009 *NEHRP Recommended Provisions* uses ASCE 7-05 as it's primary reference standard for seismic loads and design criteria. ASCE 7-05 in turn references the NDS and SDPWS for wood structures. Required strength (demand) is determined from ASCE 7 Chapter 12, and provided strength (capacity) is calculated using the AF&PA documents.

Neither ASCE 7 nor the *Provisions* makes significant modifications to the AF&PA standards.

2005 NDS / SDPWS

- Supports ASD and LRFD
- Framing and connections
  - ASD: $F'_x = F_x C_D C_y C_z$ etc
  - LRFD: $F'_x = F_x K_D \phi_x \lambda C_y C_z$ etc
- Shear walls and diaphragms
  - $v_{ASD} = v_s / 2$
  - $v_{LRFD} = \phi_D v_s = 0.8 v_s$

FEMA nehrp Instructional Material Complementing FEMA P-751, Design Examples Wood Structures - 27

The NDS and SDPWS are both formatted for both the ASD & LRFD methods. The basic capacity parameters are adjusted differently to suite the design method. The various c-factors common to wood design are generally the same for both methods.

This slide illustrates the procedures for framing and connections in the NDS and for shear walls and diaphragms using the SDPWS. Note the differences between the two standards.

For framing and connections, "F_x" can be flexure, compression, bolt shear, etc. For ASD there is a load duration factor C_D. For LRFD, there is a format conversion factor, K_D, a strength reduction factor, ϕ, and a time effect factor, λ. For earthquake effects, λ is 1.0.

The shear wall and diaphragm conversions are relatively straightforward.

Lateral Systems (Bearing Walls)

Seismic Force Resisting System	Response Modification Coefficient, R	Seismic Design Category
Shear walls with wood structural panels	6 ½	B & C: NL D – F: 65 ft max
Shear walls with other materials	2	B & C: NL D: 35 ft max E & F: NP
Walls with flat strap bracing	4	B & C: NL D – F: 65 ft max

This slide presents the coefficients and limitations for shear walls that are part of a bearing wall system.

Lateral Systems (Building Frame)

Seismic Force Resisting System	Response Modification Coefficient, R	Seismic Design Category
Shear walls with wood structural panels	7	B & C: NL D – F: 65 ft max
Shear walls with other materials	2 1/2	B & C: NL D: 35 ft max E & F: NP

FEMA nehrp

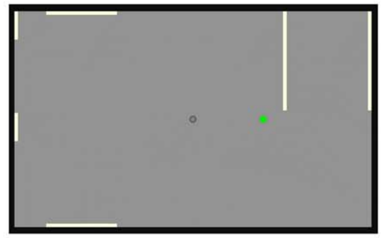
Instructional Material Complementing FEMA P-751, Design Examples

Wood Structures - 29

This slide presents the coefficients and limitations for shear walls that are part of a bearing wall system.

Typical Wood Structure Analysis Methods

Flexible vs Rigid Diaphragm



- Neither the rigid nor flexible diaphragm methods really represent the distribution of lateral resistance in a typical structure
- Both methods (typically) ignore the stiffness distribution of interior and exterior wall finishes
- Wood structural diaphragms are neither "flexible" or "rigid" – they are somewhere in between. "Glued and screwed" floor sheathing makes floors more rigid than flexible. The nailing of interior wall sill plates across sheathing joints has the same effect. Exterior walls can act as "flanges", further stiffening the diaphragm.
- However, encouraging rigid diaphragm analysis is also encouraging the design of structures with torsional response – may not be a good thing!

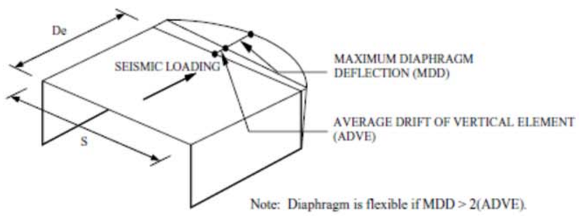
Comment on how designers must have techniques that are "good enough" for design. While neither the flexible nor rigid methods are perfect, the flexible method, used more often by far than the rigid method, has a good track record in properly designed structures.

Diaphragm Flexibility

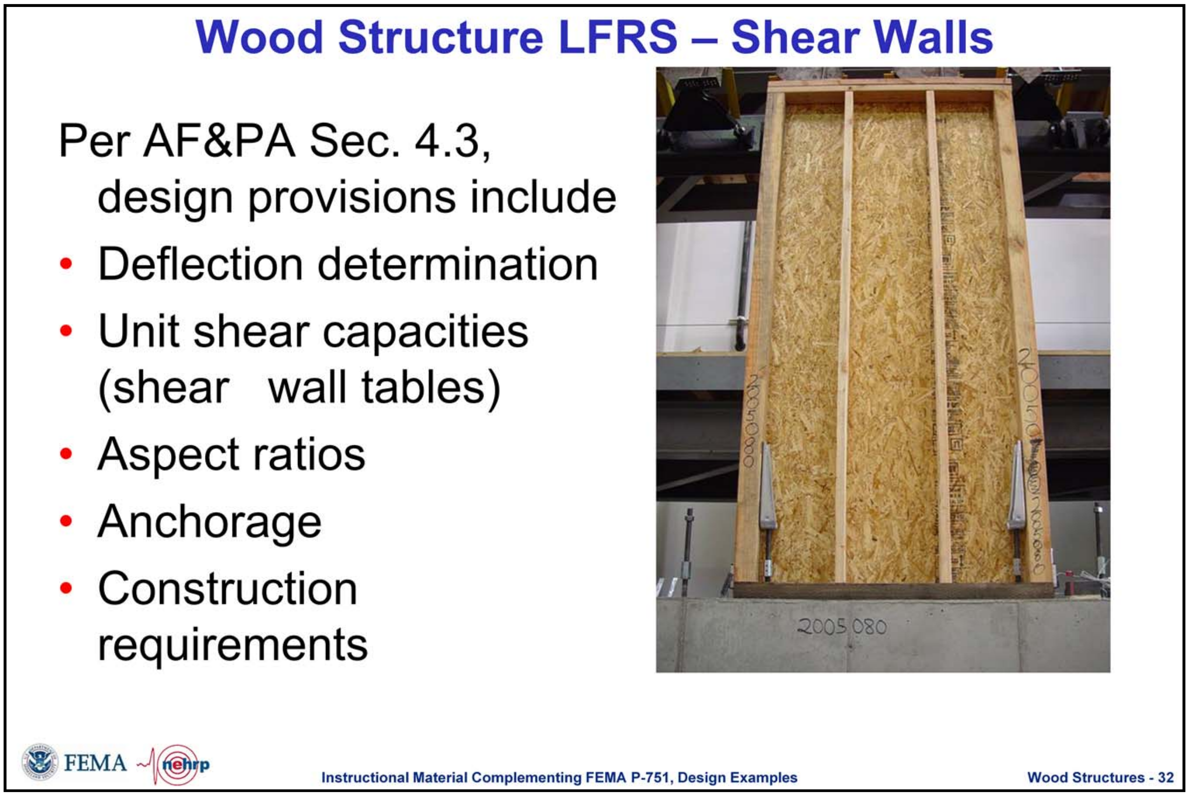
- ASCE 7-05 Sec. 12.3.1.3:

  "Diaphragms … are permitted to be idealized as flexible where the computed maximum in-plane deflection of the diaphragm under lateral load is more than two times the average story drift of adjoining vertical elements of the lateral force-resisting system of the associated story under equivalent tributary lateral load."
- SDPWS Sec. 2.2 (Terminology): Same as above.
- ASCE 7-05 Simplified Procedure (Sec. 12.14.5):

  "Diaphragms constructed of ... wood structural panels … are permitted to be considered flexible."



Note the differences between the ASCE 7-05 general procedure and the simplified procedure of Sec. 12.14.



Most vertical elements in wood structures really are vertical diaphragms. Vertical trusses, in the form of heavy timber braced frames as shown on the slide of post and beam construction, are also allowed but seldom used.

Note the hold-downs in the wall corners providing overturning restraint.

Note that prescriptive construction will rely heavily on the strength of gypsum

Wood Structure LFRS: Shear Walls

- Unit shear capacities (shear wall tables)
- Tables are for DFL or SP – need to adjust values if framing with wood species with lower specific gravities

Major divisions:

- Structural 1 vs. rated sheathing Panels applied directly to framing vs. panels applied over gypsum wallboard
- Unblocked edges allowed in some conditions

Wood-based Panels[4]

Sheathing Material	Minimum Nominal Panel Thickness (in.)	Minimum Fastener Penetration in Framing Member or Blocking (in.)	Fastener Type & Size	A SEISMIC – Panel Edge Fastener Spacing (in.) 6: v_s (plf)	6: G_a (kips/in.) OSB	6: G_a (kips/in.) PLY	4: v_s (plf)	4: G_a OSB	4: G_a PLY	3: v_s (plf)	3: G_a OSB	3: G_a PLY	2: v_s (plf)	2: G_a OSB	2: G_a PLY
Wood Structural Panels - Structural I[3,4]	5/16	1-1/4	Nail (common or galvanized box) 6d	400	13	10	600	18	13	780	23	16	1020	35	22
	3/8[2]	1-3/8	8d	460	19	14	720	24	17	920	30	20	1220	43	24
	7/16[2]			510	16	13	790	21	16	1010	27	19	1340	40	24
	15/32			560	14	11	860	18	14	1100	24	17	1460	37	23
	15/32	1-1/2	10d	680	22	16	1020	29	20	1330	36	22	1740	51	28
Wood Structural Panels – Sheathing[3,4]	5/16	1-1/4	6d	360	13	9.5	540	18	12	700	24	14	900	37	18
	3/8			400	11	8.5	600	15	11	780	20	13	1020	32	17
	3/8[2]	1-3/8	8d	440	17	12	640	25	15	820	31	17	1060	45	20
	7/16[2]			480	15	11	700	22	14	900	28	17	1170	42	21
	15/32			520	13	10	760	19	13	980	25	15	1280	39	20
	15/32	1-1/2	10d	620	22	14	920	30	17	1200	37	19	1540	52	23
	19/32			680	19	13	1020	26	16	1330	33	18	1740	48	22
Plywood Siding	5/16	1-1/4	Nail (galvanized casing) 6d	280	13		420	16		550	17		720	21	
	3/8	1-3/8	8d	320	16		480	18		620	20		820	22	
Particleboard Sheathing - (M-S "Exterior Glue" and M-2 "Exterior Glue")	3/8		Nail (common or galvanized box) 6d	240	15		360	17		460	19		600	22	
	3/8		8d	260	18		380	20		480	21		630	23	
	1/2			280	18		420	20		540	22		700	24	
	1/2		10d	370	21		550	23		720	24		920	25	
	5/8			400	21		610	23		790	24		1040	26	
Structural Fiberboard Sheathing	1/2		Nail (galvanized roofing) 11 ga. galv. roofing nail (0.120" x 1-1/2" long x 7/16" head)				340	4.0		460	5.0		520	5.5	
	25/32		11 ga. galv. roofing nail (0.120" x 1-3/4" long x 3/8" head)				340	4.0		460	5.0		520	5.5	

FEMA nehrp

Instructional Material Complementing FEMA P-751, Design Examples

Wood Structures - 33

This slide provides a summary of the design aspects of shear walls. The table is taken from the SDPWS and can't necessarily be read on the slide but is useful for illustration purposes.

Emphasize the reductions (footnotes) for non DFL/SP framing members. Point out that it is not uncommon to have pressure treated sill plate material of a softer species of lumber than the framing members, in which case the reductions are needed even if using DFL or SP studs.

Wood Structure LFRS: Shear Walls

Aspect ratios

- Individual full-height segments
- Force transfer around openings
- Perforated shear walls

Figure 4E Typical Individual Full-Height Wall Segments Height-to-Width Ratio

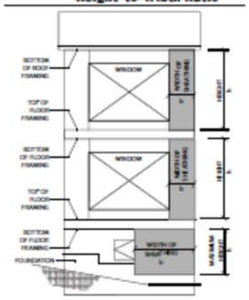


Figure 4F Typical Shear Wall Height-to-Width Ratio for Shear Walls Designed for Force Transfer Around Openings

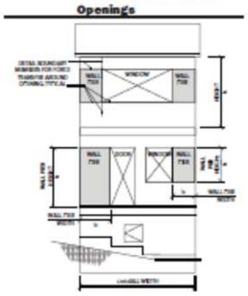
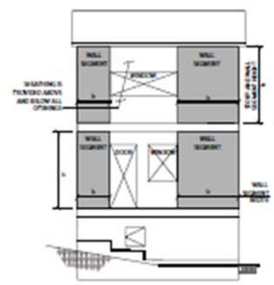


Figure 4D Typical Shear Wall Height-to-Width Ratio for Perforated Shear Walls

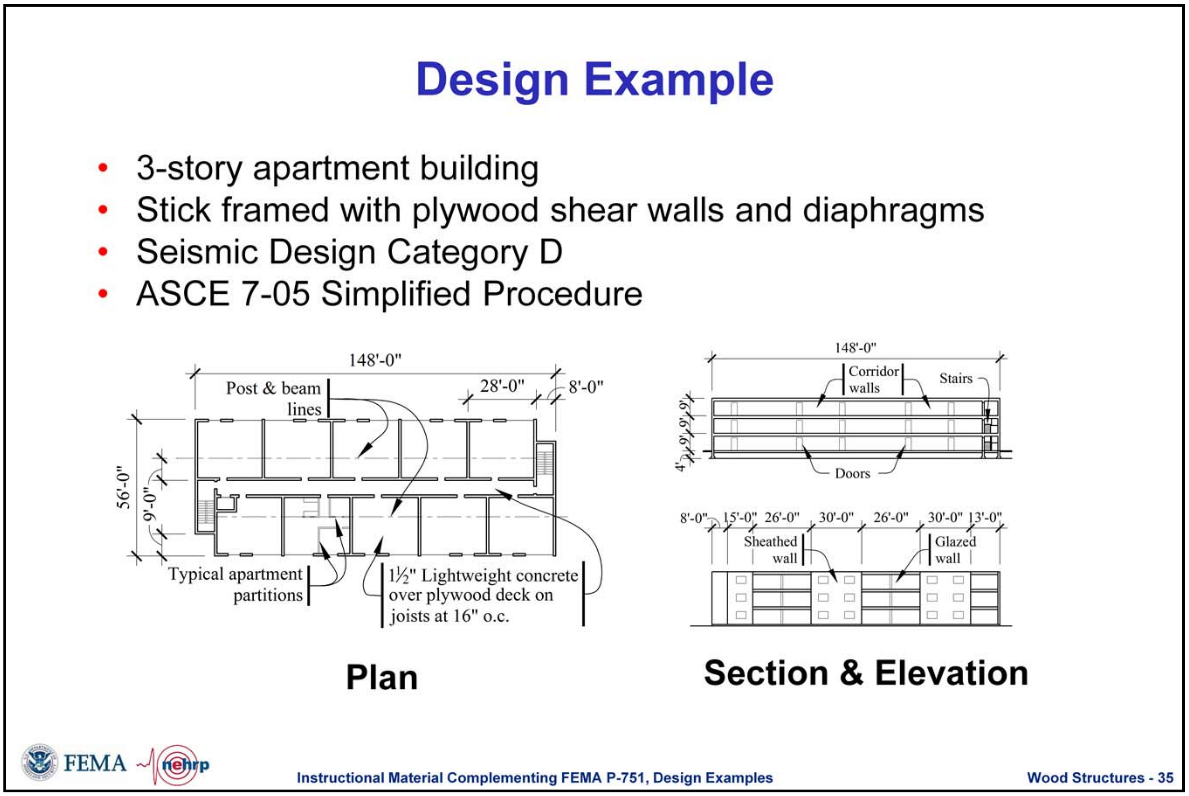


An important design feature of shear walls is the limitations on height to width aspect ratio and the three different design methods to deal with the aspect ratio.

The figure on the left represents the traditional method, where the wall segments are treated as independent, full height shear walls and the aspect ratio is based on floor-to-top plate height.

The middle figure shows how height to width ratios can be reduced by using the force transfer method around doors and windows. This method, while permitting more favorable application of the aspect ratios, requires lots of added strapping.

The figure on the right represents the “perforated shear wall” design method that is covered in the SDPWS. In this method, the entire wall length can be used for the aspect ratio and a reduction in overall shear capacity is taken to account for the openings.



First shear walls, then diaphragms will be illustrated using a design example taken from **Chapter 11** of the *NEHRP Recommended Provisions: Design Examples* (FEMA P-751).

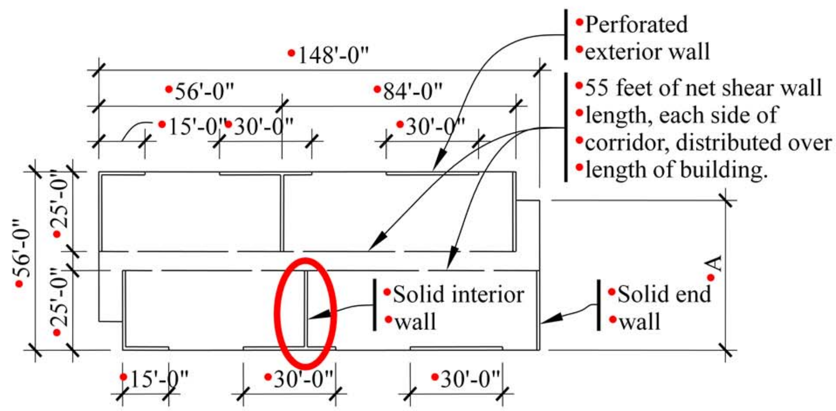
This example is representative of typical light-frame multifamily construction in regions of high seismic hazard.

Note that the example utilizes the simplified procedure of ASCE 7-05, partly to allow the building to be analyzed using the flexible diaphragm assumption.

In addition, the example utilizes LRFD for the design of the wood systems and connections.

Example – Shear Wall Design

- Interior shear wall, 25 feet long, solid



This presentation will show the design of a single, solid interior shear wall shown here. The example include the design of the wall sheathing and anchorage.

Shear Wall Design – Shear

First floor wall

V_1 = 30.9 kips

v = 30.9/25 = 1.24 klf

5/8" rated sheathing on 2x framing with 10d at 2" o.c.

Nominal unit shear (SDPWS Table 4.3A), v_s = 1.74 klf

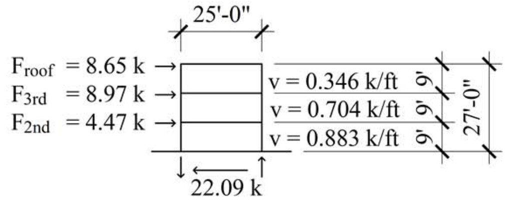
Reduction factor, φ = 0.80

Adjust for Hem-Fir (SG = 0.43)

1-(0.5-0.43) = 0.93

$0.93\varphi_D v_s$ = 0.93(0.8)(1.74)

= 1.29 klf OK



Wood-based Panels[4]

Sheathing Material	Minimum Nominal Panel Thickness (in.)	Minimun Fastener Penetration in Framing Member or Blocking (in.)	Fastener Type & Size	A SEISMIC – Panel Edge Fastener Spacing (in.)											
				6			4			3			2		
				v_s (plf)	G_a (kips/in.)		v_s (plf)	G_a (kips/in.)		v_s (plf)	G_a (kips/in.)		v_s (plf)	G_a (kips/in.)	
			Nail (common or galvanized box)		OSB	PLY		OSB	PLY		OSB	PLY		OSB	PLY
Wood Structural Panels - Structural I[4,5]	5/16	1-1/4	6d	400	13	10	600	18	13	780	23	16	1020	35	22
	3/8[2]	1-3/8	8d	460	19	14	720	24	17	920	30	20	1220	43	24
	7/16[2]			510	16	13	790	21	16	1010	27	19	1340	40	24
	15/32			560	14	11	860	18	14	1100	24	17	1460	37	23
	15/32	1-1/2	10d	680	22	16	1020	29	20	1330	36	22	1740	51	28
Wood Structural Panels – Sheathing[4,5]	5/16	1-1/4	6d	360	13	9.5	540	18	12	700	24	14	900	37	18
	3/8			400	11	8.5	600	15	11	780	20	13	1020	32	17
	3/8[2]	1-3/8	8d	440	17	12	640	25	15	820	31	17	1060	45	20
	7/16[2]			480	15	11	700	22	14	900	28	17	1170	42	21
	15/32			520	13	10	760	19	13	980	25	15	1280	39	20
	15/32	1-1/2	10d	620	22	14	920	30	17	1200	37	19	1540	52	23
	19/32			680	19	13	1020	26	16	1330	33	18	1740	48	22

FEMA nehrp

Instructional Material Complementing FEMA P-751, Design Examples

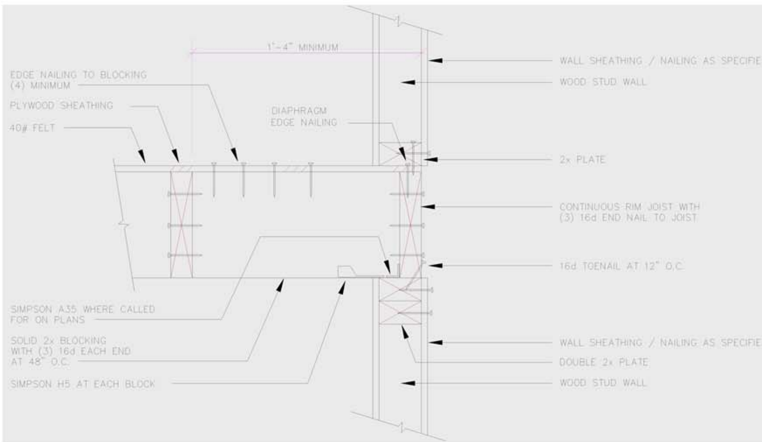
Wood Structures - 37

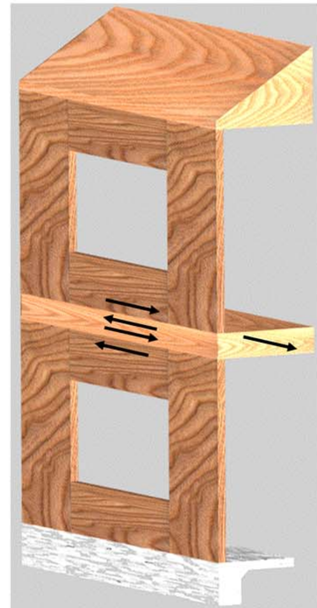
The shear wall shear demand is taken from the analysis, then a shear wall assembly is selected from the SDPWS table.

Note the shear reduction factor for Hem-Fir framing.

Shear Wall Anchorage and Load Path

Diaphragm to shear wall / shear transfer through floor

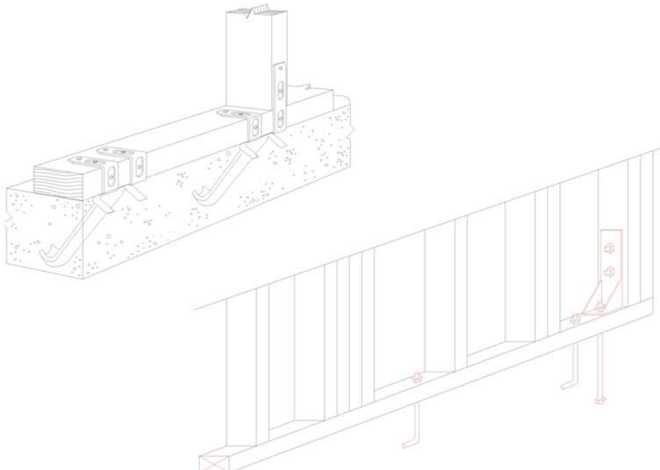


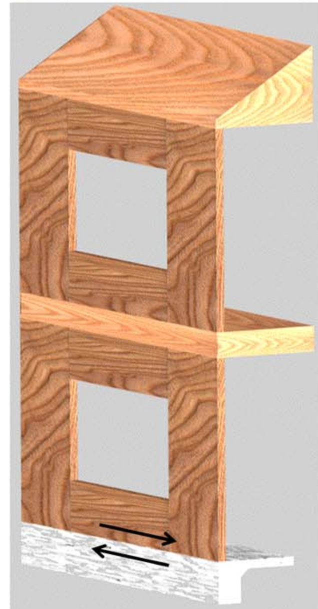


Load paths for shear through a platform can be complex. Shear must be transferred from the wall structural sheathing above, through its edge nailing to the single 2x sill plate, through nailing of the sill plate through the floor sheathing and into the rim joist below, out of the rim joist, and into the dbl top plate of the wall below, where it enters the wall structural sheathing through the edge nailing of the sheathing to the double top plate. Additionally, diaphragm shear must be removed form the diaphragm through the diaphragm edge nailing and into the rim joist, where it adds to the wall shear from above and then follows the same load path. Note that in this case we are showing the joists as continuous parallel to the wall. To provide for out of plane support for the wall, blocking between joists is called out, with a nailed connection to the diaphragm, and a metal connector to handle transfer of wall suction forces into the blocking and thus into the diaphragm.

Shear Wall Anchorage and Load Path

Shear transfer to foundation





The usual connection for transferring shear from the sill plate to the foundations is either ½" to 5/8" anchor bolts cast in place or post installed, or with cast in place prefabricated metal connectors.

Shear Wall Design – Foundation Anchorage

- Provide in-plane anchorage for induced shear force
- Anchor bolt in wood, 2005 AF&PA NDS
- Anchor bolt in concrete, ACI 318-08 Appendix D
- Plate washer (1/4 x 3 x 3 minimum)

First floor interior wall

v = 1.24 klf

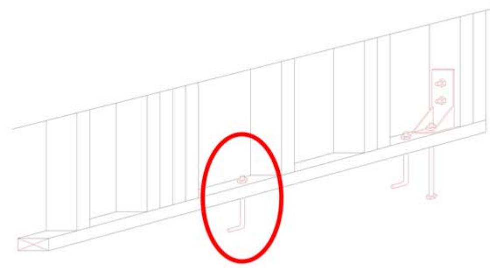
5/8-in. bolts in a 3× DFL sill plate

AF&PA NDS:

$ZK_F\phi\lambda$ = (1.11)(2.16/0.65)(0.65)(1.0)
= 2.40 kips per bolt

Max spacing is 2.4/[(1.24)/(12)] = 23.3 in.

Use 5/8 in. bolts at 16 in. on center



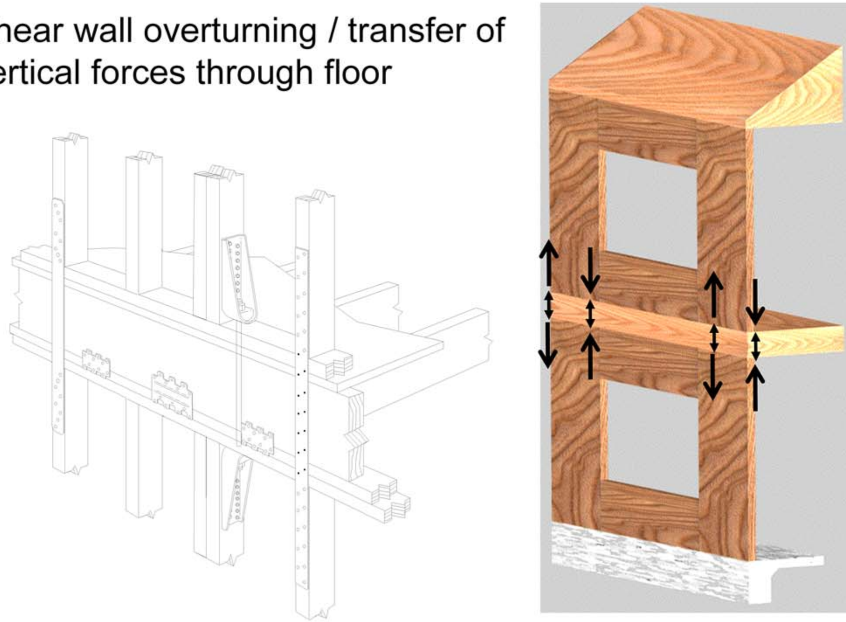
As an example of foundation anchorage, the sill plate bolting for the representative shear wall is illustrated here.

Note that the anchor bolt needs to be check for wood capacity (NDS) and concrete capacity (ACI).

The SDPWS specifies the sizes of plate washers that are required to preclude splitting of the sill plate.

Shear Wall Anchorage and Load Path

Shear wall overturning / transfer of vertical forces through floor



FEMA nehrp

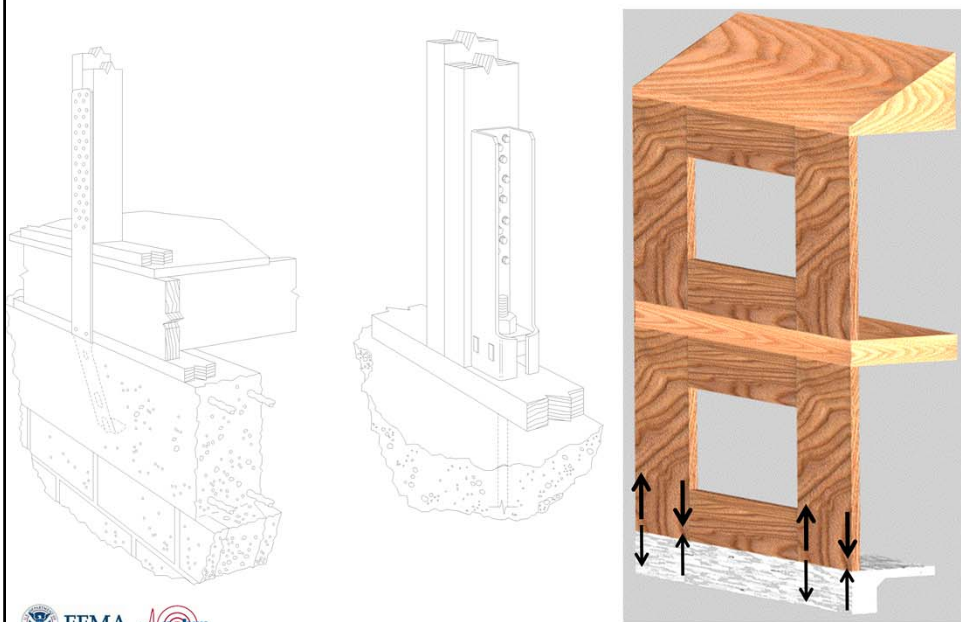
Instructional Material Complementing FEMA P-751, Design Examples

Wood Structures - 41

Discuss the need to support the shear wall chords for overturning compression via full bearing blocking between the floor sheathing and the double top plates below, particularly on highly loaded shear walls. A point could also be made here about perforated shear wall design, both for the approach in which shear transfer around the openings explicitly engineered, and the approach where this is not addressed (and the perforated shear wall reduction tables are used).

Shear Wall Anchorage and Load Path

Overturning tension/compression to foundation



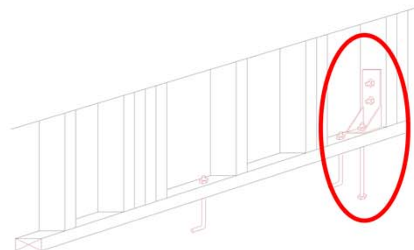
Two fundamental types of uplift restraint at the foundation: embedded straps and holdowns that connect to either a cast-in-place or post-installed anchor. Note that in addition to out-of plane post buckling on the compression side of a shear wall, due to gravity plus overturning loads, the interface between the chord bottom and the top of the sill plate must satisfy perpendicular-to-grain stress limitations.

Shear Wall Design – Chords & Anchorage

- Provide tension and compression chords for $T = C = vh$ where, v = induced unit shear and h = shear wall height
- Where net tension is induced, provide anchorage for net tension force

First floor interior wall

Overturning, $M_{OT} = 517$ *k-ft*
Stabilizing, $M_{ST} = (0.9 - 0.2Sds)M_D = 222$ *k-ft*
Therefore, net tension so uplift anchorage is req'd
Uplift anchorage = Σvh (all 3 stories)
T= 16.0 kips
Use pre-engineered hold down with manufacturer's capacities converted to LFRD
Check for eccentricity and net section at end post

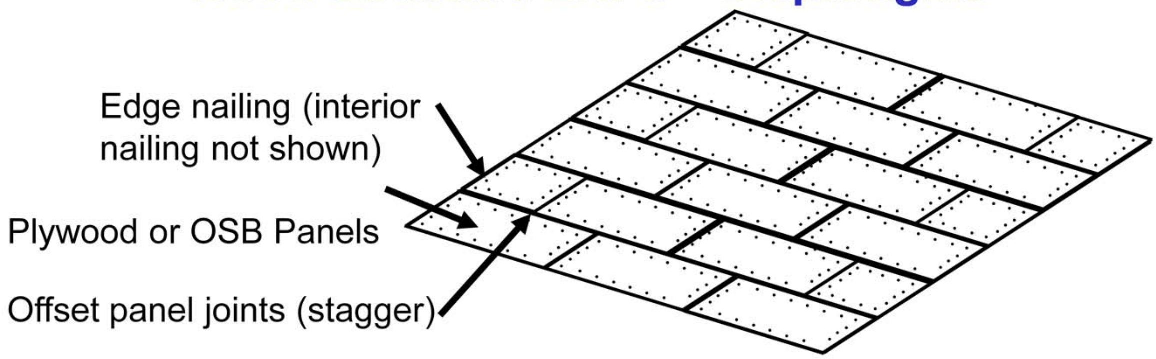


A representative hold down is designed in this slide. The uplift anchorage requirements are per the SDPWS.

Note that manufacturer's product information is generally in ASD format, so a conversion is required to get LRFD compatible capacities. There is a method in a design guide contained in the 1996 edition AF&PA LRFD. Alternatively, ASD could be used to get hold-down forces.

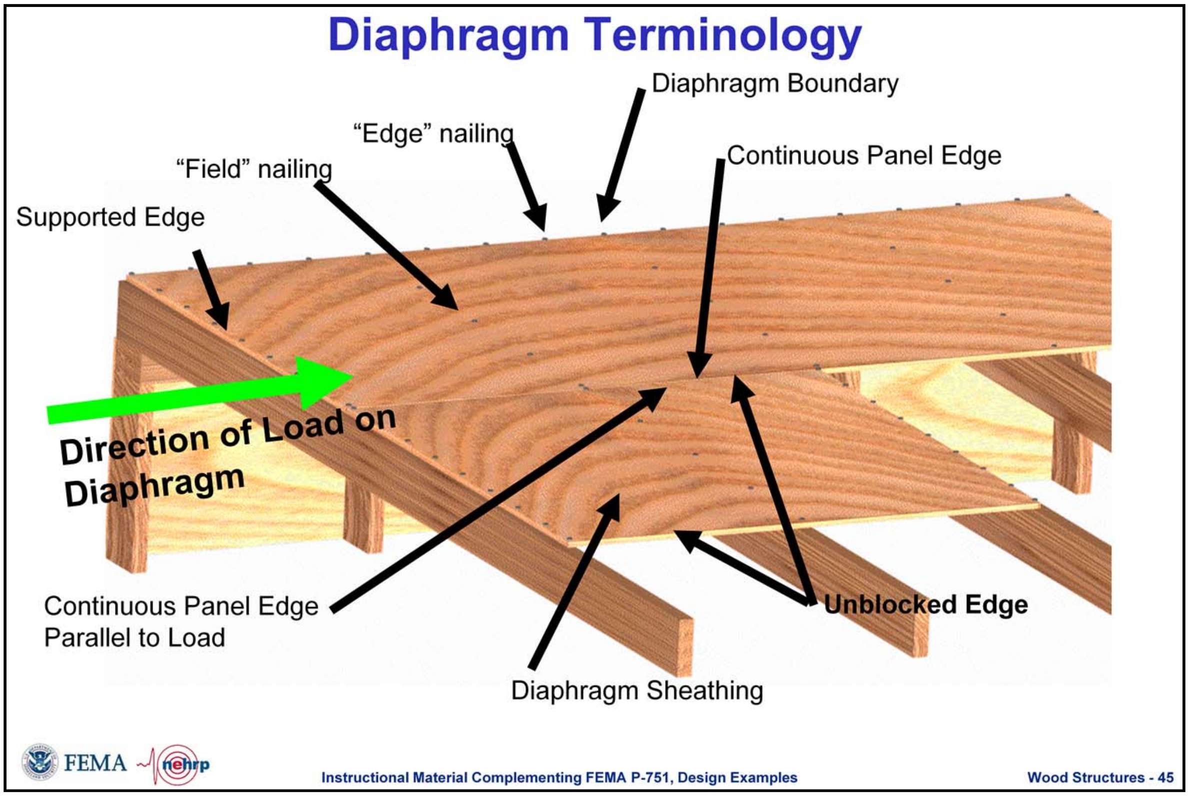
Note that it is critical to consider connection eccentricity on the hold-down post.

Wood Structure LRFS – Diaphragms



- Most structures rely on some form of nailed wood structural panels to act as diaphragms for the horizontal elements of the LFRS (plywood or oriented strand board – OSB)
- Capacity of diaphragm varies with sheathing grade and thickness, nail type and size, framing member size and species, geometric layout of the sheathing (stagger), direction of load relative to the stagger, and whether or not there is blocking behind every joint to ensure shear continuity across panel edges

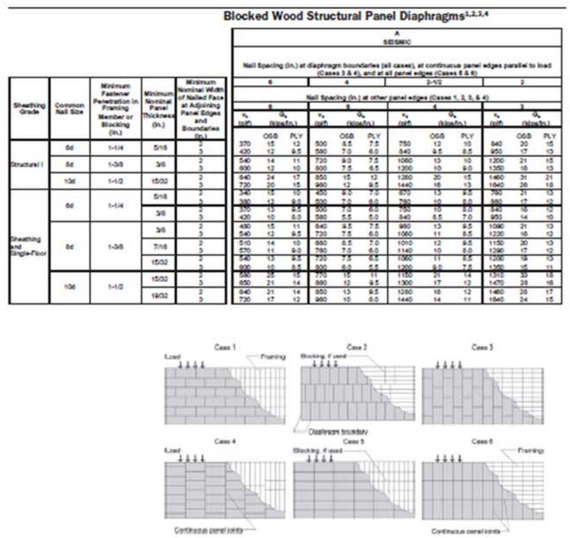
This section of the presentation covers diaphragms. While other types of wood diaphragms are available (single or double diagonal boards, for instance) nailed wood structural panels is by far the most common.



Note that a diaphragm boundary exists because of connectivity to a line of shear resistance containing vertical elements of the lateral force resisting system. Blocking is not shown at panel edges in this figure, but is often required to achieve higher design capacities.

Wood Structure LFRS: Diaphragms

- SDPWS Sec. 4.2
- Deflection determination
- Aspect ratio limitations
- Unit shear capacities (diaphragm tables)
- ASD & LRFD
- Tables are for DFL or SP – need to adjust values if framing with wood species with lower specific gravities
- Major divisions:
  - Structural 1 vs. rated sheathing
  - blocked vs. unblocked panel edges
  - high load diaphragms



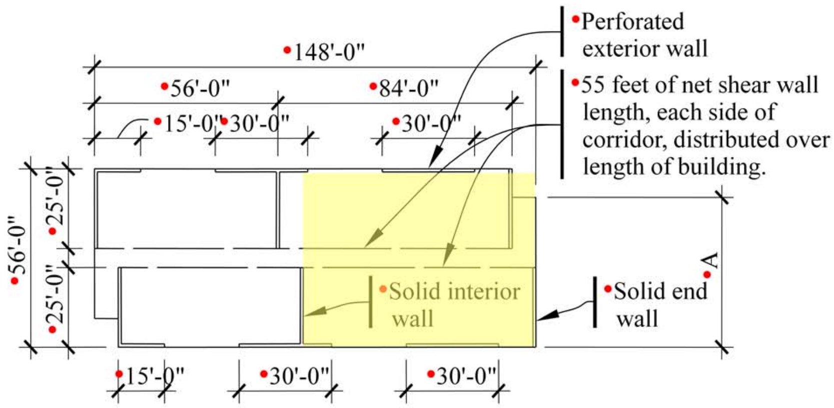
FEMA nehrp Instructional Material Complementing FEMA P-751, Design Examples Wood Structures - 46

Similar to the shear walls, this slide illustrates the design features for diaphragms as well as the table from the SDPWS.

Emphasize the reductions (footnotes) for non DFL or SP lumber, and be sure to note that when using metal plate connected wood trusses the species of top chord lumber needs to be confirmed.

Example – Diaphragm Design

- 3^{rd} floor diaphragm, 84 foot span (idealized)



FEMA nehrp Instructional Material Complementing FEMA P-751, Design Examples Wood Structures - 47

Using the design example a representative diaphragm will be illustrated (shaded portion).

Note that due to the shear wall plan offsets, the diaphragm is idealized for analysis and design.

Diaphragm Design – Shear

3rd floor diaphragm

V_{max} = 13.9 kips

v = 13.9/56 = 0.25 klf

1/2" rated sheathing on 2x DFL framing with 8d at 6" o.c.

Nominal unit shear (SDPWS Table 4.2A), v_s = 0.54 klf

Reduction factor, ϕ = 0.80

$\phi_D v_s$ = 0.8(0.54) = 0.43 klf OK

Blocked Wood Structural Panel Diaphragms[1,2,3,4]

Sheathing Grade	Common Nail Size	Minimum Fastener Penetration in Framing Member or Blocking (in.)	Minimum Nominal Panel Thickness (in.)	Minimum Nominal Width of Nailed Face at Adjoining Panel Edges and Boundaries (in.)	A SEISMIC: Nail Spacing (in.) at diaphragm boundaries (all cases), at continuous panel edges parallel to load (Cases 3 & 4), and at all panel edges (Cases 5 & 6): 6			4			2-1/2			2		
					Nail Spacing (in.) at other panel edges (Cases 1, 2, 3, & 4): 6			6			4			3		
					v_s (plf)	G_a (kips/in.) OSB	G_a (kips/in.) PLY	v_s (plf)	G_a (kips/in.) OSB	G_a (kips/in.) PLY	v_s (plf)	G_a (kips/in.) OSB	G_a (kips/in.) PLY	v_s (plf)	G_a (kips/in.) OSB	G_a (kips/in.) PLY
Structural I	6d	1-1/4	5/16	2	370	15	12	500	8.5	7.5	750	12	10	840	20	15
				3	420	12	9.5	560	7.0	6.0	840	9.5	8.5	950	17	13
	8d	1-3/8	3/8	2	540	14	11	720	9.0	7.5	1060	13	10	1200	21	15
				3	600	12	10	800	7.5	6.5	1200	10	9.0	1350	18	13
	10d	1-1/2	15/32	2	640	24	17	850	15	12	1280	20	15	1460	31	21
				3	720	20	15	960	12	9.5	1440	16	13	1640	26	18
Sheathing and Single-Floor	6d	1-1/4	5/16	2	340	15	10	450	9.0	7.0	670	13	9.5	760	21	13
				3	380	12	9.0	500	7.0	6.0	760	10	8.0	860	17	12
			3/8	2	370	13	9.5	500	7.0	6.0	750	10	8.0	840	18	12
				3	420	10	8.0	560	5.5	5.0	840	8.5	7.0	950	14	10
	8d	1-3/8	3/8	2	480	15	11	640	9.5	7.5	960	13	9.5	1090	21	13
				3	540	12	9.5	720	7.5	6.0	1080	11	8.5	1220	18	12
			7/16	2	510	14	10	680	8.5	7.0	1010	12	9.5	1150	20	13
				3	570	11	9.0	760	7.0	6.0	1140	10	8.0	1290	17	12
			15/32	2	540	13	9.5	720	7.5	6.5	1060	11	8.5	1200	19	13
				3	[illegible]	10	8.5	800	6.0	5.5	1200	9.0	7.5	1350	15	11
	10d	1-1/2	15/32	2	[illegible]	25	15	770	15	11	1150	21	14	1310	33	18
				3	[illegible]	21	14	860	12	9.5	1300	17	12	1470	28	16
			19/32	2	[illegible]	21	14	850	13	9.5	1280	18	12	1460	28	17
				3	[illegible]	17	12	960	10	8.0	1440	14	11	1640	24	15

This slide illustrates the design at the 3rd floor. Using the diaphragm shear from the analysis, a diaphragm assembly is selected from the SDPWS table.

Diaphragm Design – Chords

3rd floor diaphragm

V = 46.7 kips

w = 46.7/148 ft = 0.315 klf

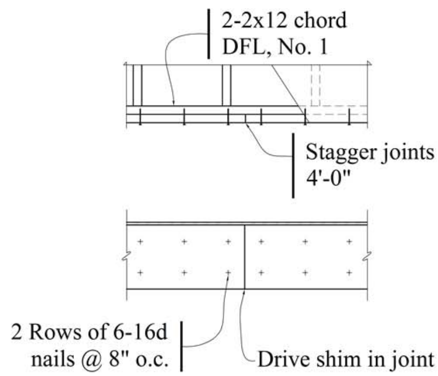
$M_{max} = wL^2/8 = 0.315(84)^2/8$

$= 278$ k-ft

$T = C$ = 278/56 = 4.96 kips

Chord: 2x12 DFL

Splice: 12 16d nails



Once the diaphragm is designed for shear, flexure is addressed by means of diaphragm chords. For a two-span diaphragm like this example, chords must be designed for the midspan ("positive" moment) and "negative" moment at the central shear wall. In this case the midspan moment governs.

Wood Diaphragms in Concrete and Masonry Buildings

Key wood components:

- Diaphragm strength and stiffness
- Chords and collectors
- Wall anchorage
- Sub-diaphragms and cross ties

FEMA nehrp Instructional Material Complementing FEMA P-751, Design Examples Wood Structures - 50

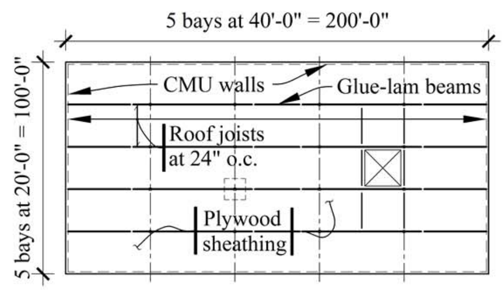
Since wood components are often used in buildings of non-wood construction, this presentation also includes significant design features.

Wood diaphragms in buildings with concrete or masonry walls is a common construction type, and has some important design features, in particular related to the wall anchorage system.

This slide points out the significant design aspects of these types of buildings.

Example – Masonry Wall Building

- 1-story warehouse building
- CMU walls with panelized wood roof system
- Seismic Design Category D

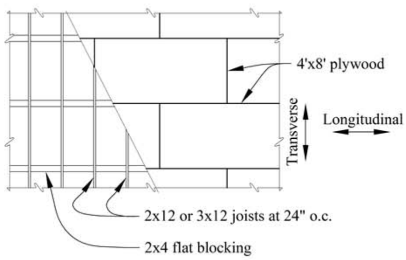


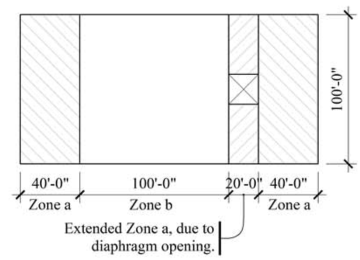
A different design example from the from **Chapter 11** of the *NEHRP Recommended Provisions: Design Examples* (FEMA P-751) will be used to illustrate the concepts.

This example features the design of a roof diaphragm and wall anchorage in a one-story building.

Example – Roof Diaphragm

- Construction and design generally similar to wood-framed buildings
- Due to large size of diaphragms, typically use different zones of nailing depending on magnitude of shear
- Chords and collectors similar to wood-framed buildings except that collector design requires consideration of Ω_0 for SDC C and above





Instructional Material Complementing FEMA P-751, Design Examples

Wood Structures - 52

The roof diaphragm design is similar to that of the wood building shown previously, except that the design shears are often much larger in buildings with heavy walls.

However, the design process is still the same: select a diaphragm assembly for the computed shear and design chord elements for the flexure.

Example – Wall Anchorage

For walls anchored to flexible diaphragms, wall anchorage force per ASCE 7-05 Sec. 12.11.2.1 and Eq. 12.11-1 is:

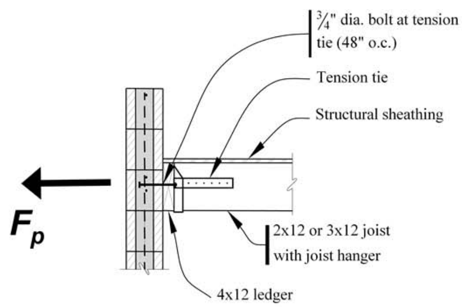
$F_p = 0.8S_{DS}IW_p$

where

$S_{DS} = 1.0$, $I = 1.0$
$W_p = 1.04$ klf (tributary CMU wall wt)

Therefore, F_p = 0.83 klf

<u>Joists perpendicular to wall</u>
If anchor ever other joist,
then F_p = (0.83)(4) = 3.32 kip / joist



Wall anchorage for heavy wall buildings with flexible diaphragms is an important design aspect. Note that the wall anchorage force for flexible diaphragms is twice that for rigid diaphragms to account for the amplification of diaphragm accelerations.

This slide shows a sample connection detail and wall anchorage force calculation. Note that there are many ways of designing the wall-to-roof connection.

Wall Anchorage

Wall anchorage design elements

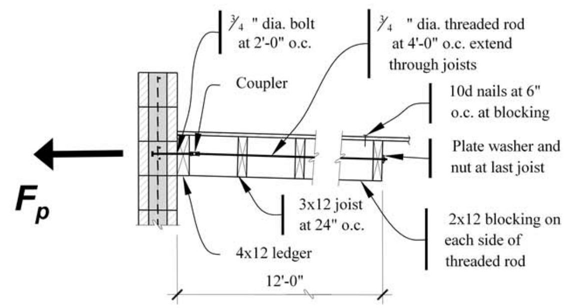
- Anchor bolt (ACI 530)
- Anchorage devise (manufacturer data or evaluation report)
- Joist tension (NDS)
- Joist nailing to diaphragm (NDS)

This slide illustrates the various components of the wall anchorage system that must be designed. The actual calculations are beyond the scope of the presentation, so direct the audience to the design example.

Wall Anchorage

Anchorage at joists parallel to wall

- Develop wall anchorage force into diaphragm across multiple joists
- Many acceptable details for this

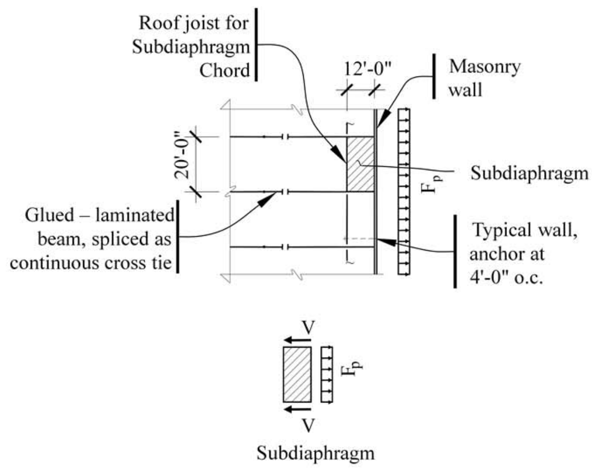


FEMA nehrp Instructional Material Complementing FEMA P-751, Design Examples Wood Structures - 55

This slide illustrates a typical wall anchorage connection where the roof joists run parallel to the exterior wall. Like the perpendicular condition, there are many ways to design and detail this connection.

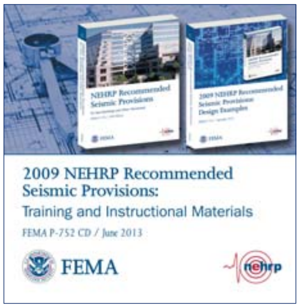
Sub-diaphragms

- Use to develop wall anchorage force into diaphragms
- Design for anchorage force between cross ties
- Maximum aspect ratio is 2.5 to 1



Another important part of the wall anchorage system is the concept of subdiaphragms. These are components within the overall diaphragm that are used to transfer the wall anchorage forces to continuous cross ties. ASCE 7 limits aspect ratio of these diaphragms, which impacts the spacing and length of cross ties and wall anchorage development.

Slide to prompt questions from participants.



11

Wood Design

Peter W. Somers, P.E., S.E.

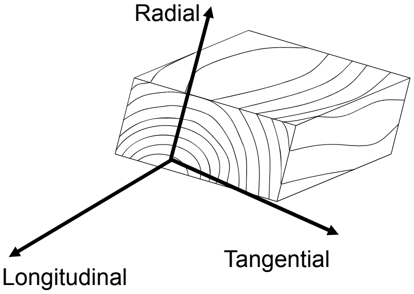
Includes materials developed by Steve Pryor, S.E.

WOOD STRUCTURES

NEHRP Recommended Provisions Wood Design Requirements

- Basic wood behavior
- Typical construction and framing methods
- Context in the *Provisions*
- Reference standards
- Analysis methods
- Lateral force resisting systems
- Shear walls and anchorage
- Diaphragms
- Concrete and masonry wall buildings

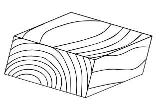
Basic Wood Material Properties



Wood is orthotropic

- Unique, independent, mechanical properties in 3 different directions
- Varies with moisture content
- Main strength axis is longitudinal - parallel to grain
- Radial and tangential are "perpendicular" to the grain - substantially weaker

Basic Wood Material Properties



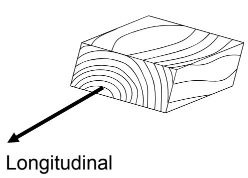
"Timber is as different from wood as concrete is from cement."

– Madsen, Structural Behaviour of Timber

Concept of "wood" as "clear wood": design properties used to be derived from clear wood with adjustments for a range of "strength reducing characteristics"

- Concept of "timber" as the useful engineering and construction material: "In-grade" testing (used now) determines engineering properties for a specific grade of timber based on full-scale tests of timber, a mixture of clear wood and strength reducing characteristics

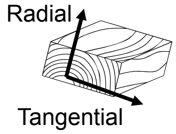
Basic Wood Material Properties



Sample DFL longitudinal design properties:

- Modulus of elasticity: 1,800,000 psi
- Tension (parallel to grain): 1,575 psi
- Bending: 2,100 psi
- Compression (parallel to grain): 1,875 psi

Basic Wood Material Properties



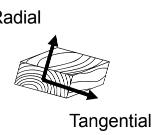
Sample DFL perpendicular to grain design properties:

- Modulus of elasticity: 45,000 psi (2.5 ~ 5 % of $E_{||}$!)
- Tension (perpendicular to grain): 180 to 350 psi FAILURE stresses

Timber is extremely weak for this stress condition. It should be avoided if at all possible, and mechanically reinforced if not avoidable.

- Compression (perpendicular to grain): 625 psi. Note that this is derived from a serviceability limit state of ~ 0.04" permanent deformation under stress in contact situations. This is the most "ductile" basic wood property.

Basic Wood Material Properties



Shrinkage

- Wood will shrink with changes in moisture content
- This is most pronounced in the radial and tangential directions (perpendicular to grain)
- May need to be addressed in the LFRS

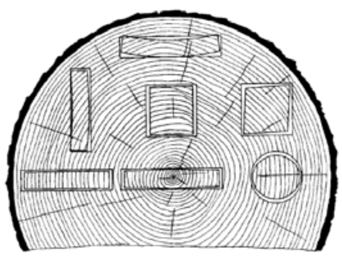
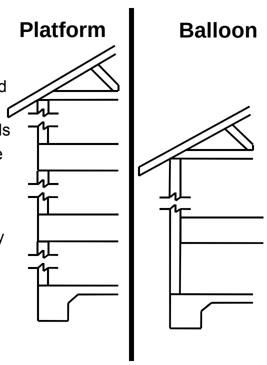


Figure 3–3. Characteristic shrinkage and distortion of flat, square, and round pieces as affected by direction of growth rings. Tangential shrinkage is about twice as great as radial.

(Wood Handbook, p. 58)

Wood Structure Construction Methods: Gravity



Platform:

- Walls are interrupted by floor "platforms"
- Floors support walls
- Most common type of light-frame construction today
- Economical but creates discontinuity in the load path
- Metal connectors essential for complete load path

Balloon:

- Walls feature foundation to roof framing members
- Floors supported by ledgers on walls or lapped with studs
- Not very common today

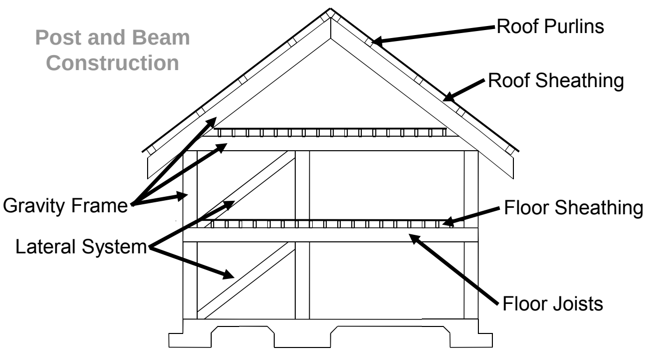
Wood Structure Construction Methods: Gravity

Post and Beam

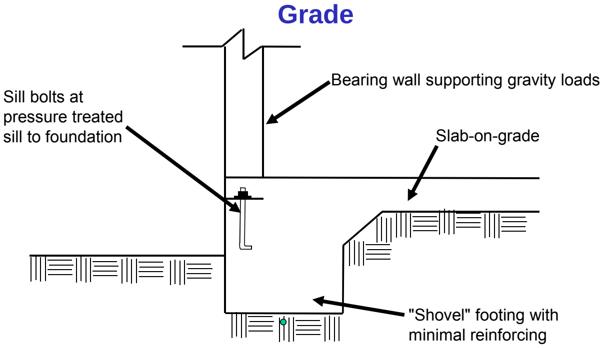
- Space frame for gravity loads
- Moment continuity at joint typically only if member is continuous through joint
- Lateral resistance through vertical diaphragms or braced frames
- Knee braces as seen here for lateral have no code design procedure for seismic

Six story main lobby Old Faithful Inn, Yellowstone, undergoing renovation work in 2005. Built in winter of 1903-1904, it withstood a major 7.5 earthquake in 1959.

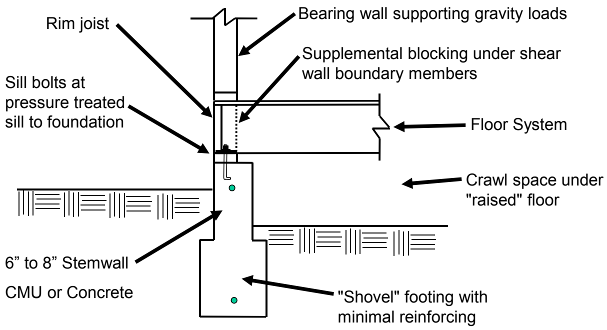
Wood Structure Construction Methods: Gravity



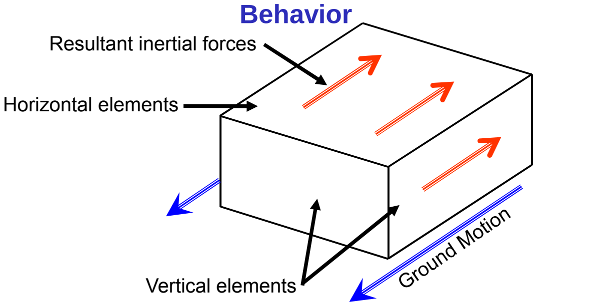
Typical Light-Frame Foundation: Slab-On-Grade



Typical Light-Frame Foundation: Raised Floor



Lateral Design Basics: Earthquake Behavior

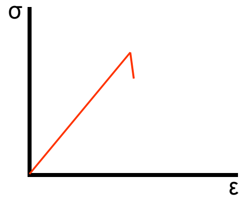


The basic approach to the lateral design of wood structures is the same as for other structures

Sources of Ductility and Energy Dissipation in Wood Structures

Stress in the wood

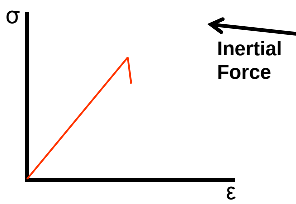
- Tension parallel to the grain: not ductile, low energy dissipation

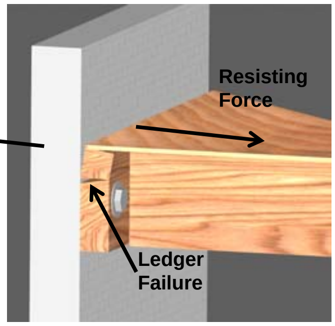


Sources of Ductility and Energy Dissipation in Wood Structures

Stress in the wood

- Tension perpendicular to the grain: not ductile, low energy dissipation

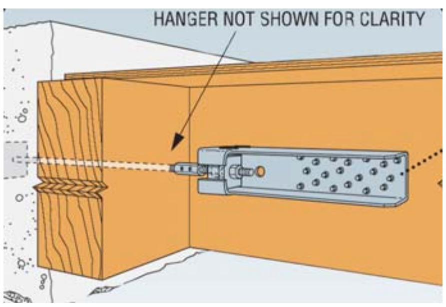




- Need to have positive wall ties to perpendicular framing

Sources of Ductility and Energy Dissipation in Wood Structures

Positive Wall Tie



Sources of Ductility and Energy Dissipation in Wood Structures

Stress in the wood

- Compression perpendicular to the grain: ductile, but not recoverable during an event – one way crushing similar to tension only braced frame behavior – ductile, but low energy dissipation
- Design allowable stress should produce ~0.04” permanent crushing

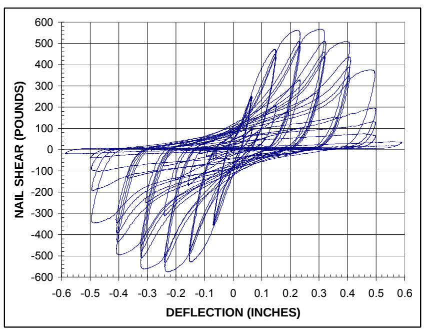
Sources of Ductility and Energy Dissipation in Wood Structures

Stress in the fastener

- Nailed joint between sheathing and framing is source of majority of ductility and energy dissipation for nailed wood structural panel shear walls
- The energy dissipation is a combination of yielding in the shank of the nail, and crushing in the wood fibers surrounding the nail
- Since wood crushing is nonrecoverable, this leads to a partial "pinching" effect in the hysteretic behavior of the joint.
- The pinching isn't 100% because of the strength of the nail shank undergoing reversed ductile bending yielding in the wood.
- As the joint cycles, joint resistance climbs above the pinching threshold when the nail "bottoms out" against the end of the previously crushed slot forming in the wood post

FEMA nehrp Instructional Material Complementing FEMA P-751, Design Examples Wood Structures - 19

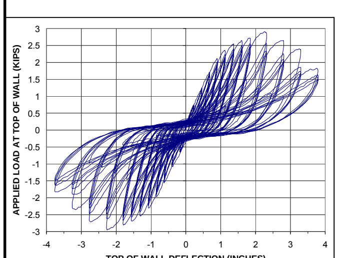
Sources of Ductility and Energy Dissipation in Wood Structures



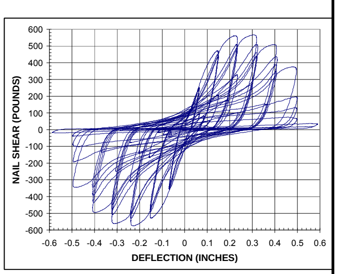
Individual nail test

FEMA nehrp Instructional Material Complementing FEMA P-751, Design Examples Wood Structures - 20

Sources of Ductility and Energy Dissipation in Wood Structures



Full-scale shear wall test



Individual nail test

FEMA nehrp Instructional Material Complementing FEMA P-751, Design Examples Wood Structures - 21

Lateral Design Basics: Complete Load Path

- Earthquakes move the foundations of a structure
- If the structure doesn't keep up with the movements of the foundations, failure will occur
- Keeping a structure on its foundations requires a complete load path from the foundation to all mass in a structure
- Load path issues in wood structures can be complex
- For practical engineering, the load path is somewhat simplified for a "good enough for design" philosophy

Lateral Design Basics: Complete Load Path

- Shear wall overturning
- Diaphragm to shear wall
- Overturning tension/ compression through floor
- Shear transfer through floor
- Shear transfer to foundation

Wood Structure LFRS Design Methods: Engineered

- If a structures does not meet the code requirements for "prescriptive" or "conventional" construction, it must be "engineered"
- As in other engineered structures, wood structures are only limited by the application of good design practices applied through principles of mechanics (and story height limitations in the code)
- A dedicated system of horizontal and vertical elements, along with complete connectivity, must be designed and detailed.

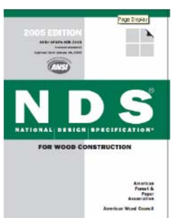
Wood Structure LFRS Design Methods: Prescriptive

Also referred to as "*Conventional Construction*"

- Traditionally, many simple wood structures have been designed without "engineering"
- Over time, rules of how to build have been developed, most recently in the 2009 International Residential Code (IRC)
- For the lateral system, the "dedicated" vertical element is referred to as a *braced wall panel*, which is part of a *braced wall line*
- Based on SDC and number of stories, rules dictate the permissible spacing between braced wall lines, and the spacing of braced wall panels within braced wall lines

Context in the Provisions

- ASCE 7-05 Sec. 12.2 Structural Systems
- ASCE 7-05 Sec. 14.5 Wood Structures
- AF&PA NDS – wood framing and connections
- AF&PA SDPWS – shears, diaphragms, and anchorage



2005 NDS / SDPWS

- Supports ASD and LRFD
- Framing and connections
  - ASD: $F'_x = F_x C_D C_y C_z$ etc
  - LRFD: $F'_x = F_x K_D \phi_x \lambda C_y C_z$ etc
- Shear walls and diaphragms
  - $v_{ASD} = v_s / 2$
  - $v_{LRFD} = \phi_D v_s = 0.8 v_s$

Lateral Systems (Bearing Walls)

Seismic Force Resisting System	Response Modification Coefficient, R	Seismic Design Category
Shear walls with wood structural panels	6 ½	B & C: NL D – F: 65 ft max
Shear walls with other materials	2	B & C: NL D: 35 ft max E & F: NP
Walls with flat strap bracing	4	B & C: NL D – F: 65 ft max

Lateral Systems (Building Frame)

Seismic Force Resisting System	Response Modification Coefficient, R	Seismic Design Category
Shear walls with wood structural panels	7	B & C: NL D – F: 65 ft max
Shear walls with other materials	2 1/2	B & C: NL D: 35 ft max E & F: NP

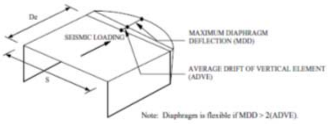
Typical Wood Structure Analysis Methods

Flexible vs Rigid Diaphragm

- Neither the rigid nor flexible diaphragm methods really represent the distribution of lateral resistance in a typical structure
- Both methods (typically) ignore the stiffness distribution of interior and exterior wall finishes
- Wood structural diaphragms are neither "flexible" or "rigid" – they are somewhere in between. "Glued and screwed" floor sheathing makes floors more rigid than flexible. The nailing of interior wall sill plates across sheathing joints has the same effect. Exterior walls can act as "flanges", further stiffening the diaphragm.
- However, encouraging rigid diaphragm analysis is also encouraging the design of structures with torsional response – may not be a good thing!

Diagrapm Flexibility

- ASCE 7-05 Sec. 12.3.1.3:
  "Diaphragms … are permitted to be idealized as flexible where the computed maximum in-plane deflection of the diaphragm under lateral load is more than two times the average story drift of adjoining vertical elements of the lateral force-resisting system of the associated story under equivalent tributary lateral load."
- SDPWS Sec. 2.2 (Terminology): Same as above.
- ASCE 7-05 Simplified Procedure (Sec. 12.14.5):
  "Diaphragms constructed of ... wood structural panels … are permitted to be considered flexible."



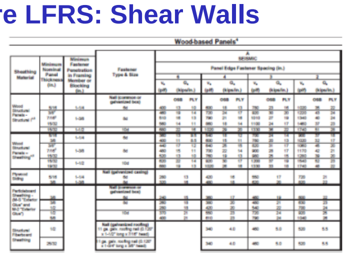
Wood Structure LFRS – Shear Walls

Per AF&PA Sec. 4.3, design provisions include
- Deflection determination
- Unit shear capacities (shear wall tables)
- Aspect ratios
- Anchorage
- Construction requirements

Wood Structure LFRS: Shear Walls

- Unit shear capacities (shear wall tables)
- Tables are for DFL or SP – need to adjust values if framing with wood species with lower specific gravities

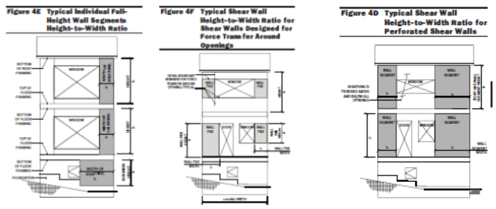
Major divisions:
- Structural 1 vs. rated sheathing Panels applied directly to framing vs. panels applied over gypsum wallboard
- Unblocked edges allowed in some conditions



Wood Structure LFRS: Shear Walls

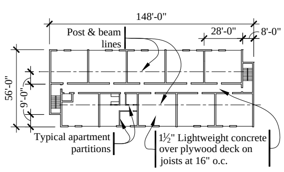
Aspect ratios

- Individual full-height segments
- Force transfer around openings
- Perforated shear walls

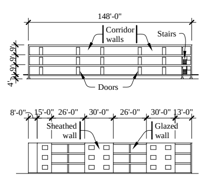


Design Example

- 3-story apartment building
- Stick framed with plywood shear walls and diaphragms
- Seismic Design Category D
- ASCE 7-05 Simplified Procedure



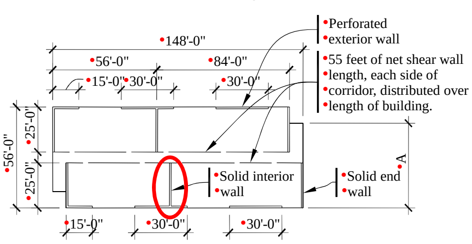
Plan



Section & Elevation

Example – Shear Wall Design

- Interior shear wall, 25 feet long, solid



Shear Wall Design – Shear

First floor wall

V_1 = 30.9 kips

v = 30.9/25 = 1.24 klf

5/8" rated sheathing on 2x framing with 10d at 2" o.c.

Nominal unit shear (SDPWS Table 4.3A), v_s = 1.74 klf

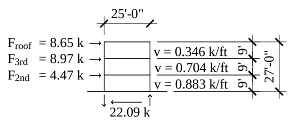
Reduction factor, φ = 0.80

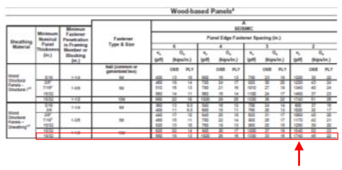
Adjust for Hem-Fir (SG = 0.43)

1-(0.5-0.43) = 0.93

$0.93\varphi_D v_s$ = 0.93(0.8)(1.74)

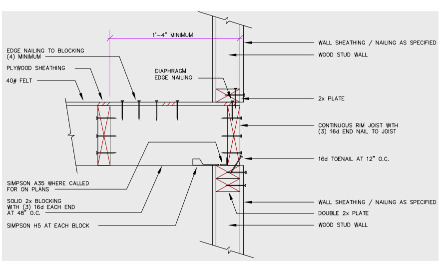
= 1.29 klf OK

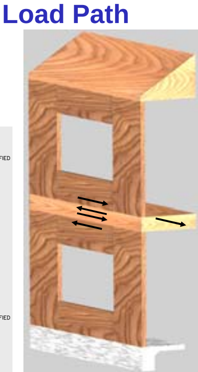




Shear Wall Anchorage and Load Path

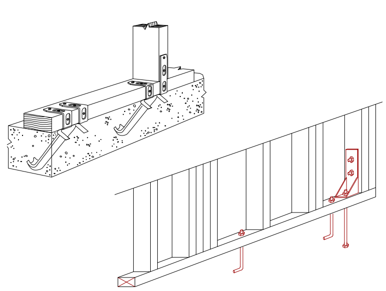
Diaphragm to shear wall / shear transfer through floor

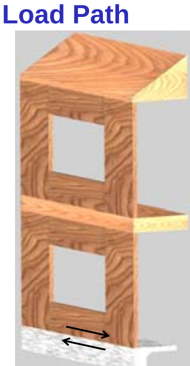




Shear Wall Anchorage and Load Path

Shear transfer to foundation





Shear Wall Design – Foundation Anchorage

- Provide in-plane anchorage for induced shear force
- Anchor bolt in wood, 2005 AF&PA NDS
- Anchor bolt in concrete, ACI 318-08 Appendix D
- Plate washer (1/4 x 3 x 3 minimum)

First floor interior wall

v = 1.24 klf

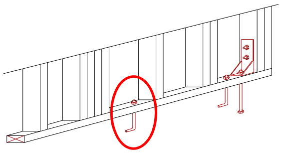
5/8-in. bolts in a 3× DFL sill plate

AF&PA NDS:

$ZK_F\phi\lambda$ = (1.11)(2.16/0.65)(0.65)(1.0)
= 2.40 kips per bolt

Max spacing is 2.4/[(1.24)/(12)] = 23.3 in.

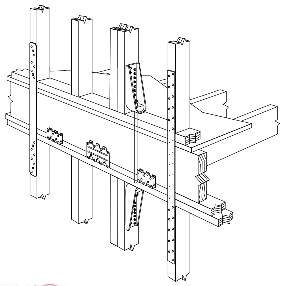
Use 5/8 in. bolts at 16 in. on center

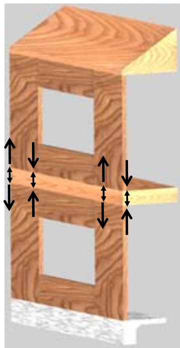


Instructional Material Complementing FEMA P-751, Design Examples — Wood Structures - 40

Shear Wall Anchorage and Load Path

Shear wall overturning / transfer of vertical forces through floor

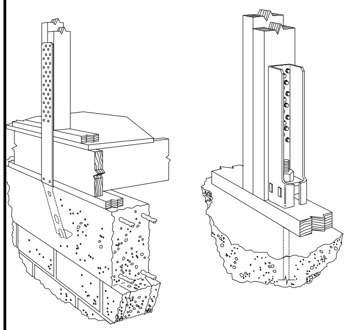




Instructional Material Complementing FEMA P-751, Design Examples — Wood Structures - 41

Shear Wall Anchorage and Load Path

Overturning tension/compression to foundation



Instructional Material Complementing FEMA P-751, Design Examples — Wood Structures - 42

Shear Wall Design – Chords & Anchorage

- Provide tension and compression chords for $T = C = vh$ where, v = induced unit shear and h = shear wall height
- Where net tension is induced, provide anchorage for net tension force

First floor interior wall

Overturning, $M_{OT} = 517$ k-ft

Stabilizing, $M_{ST} = (0.9 - 0.2S_{ds})M_D = 222$ k-ft

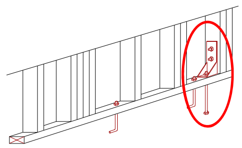
Therefore, net tension so uplift anchorage is req'd

Uplift anchorage = Σvh (all 3 stories)

T= 16.0 kips

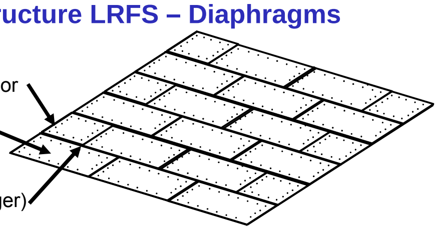
Use pre-engineered hold down with manufacturer's capacities converted to LFRD

Check for eccentricity and net section at end post



FEMA nehrp Instructional Material Complementing FEMA P-751, Design Examples Wood Structures - 43

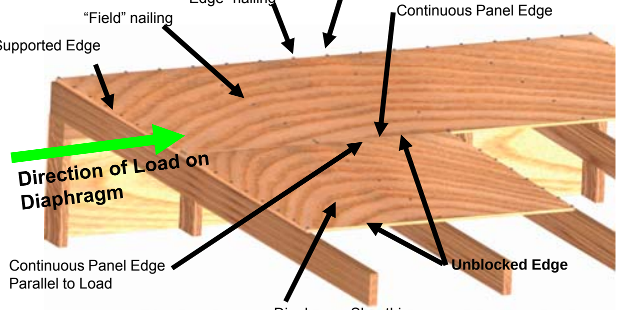
Wood Structure LRFS – Diaphragms



- Most structures rely on some form of nailed wood structural panels to act as diaphragms for the horizontal elements of the LFRS (plywood or oriented strand board – OSB)
- Capacity of diaphragm varies with sheathing grade and thickness, nail type and size, framing member size and species, geometric layout of the sheathing (stagger), direction of load relative to the stagger, and whether or not there is blocking behind every joint to ensure shear continuity across panel edges

FEMA nehrp Instructional Material Complementing FEMA P-751, Design Examples Wood Structures - 44

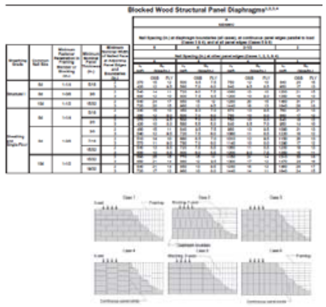
Diaphragm Terminology



FEMA nehrp Instructional Material Complementing FEMA P-751, Design Examples Wood Structures - 45

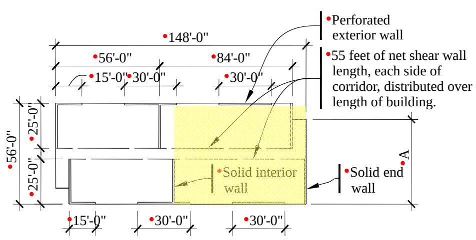
Wood Structure LFRS: Diaphragms

- SDPWS Sec. 4.2
- Deflection determination
- Aspect ratio limitations
- Unit shear capacities (diaphragm tables)
- ASD & LRFD
- Tables are for DFL or SP – need to adjust values if framing with wood species with lower specific gravities
- Major divisions:
  - Structural 1 vs. rated sheathing
  - blocked vs. unblocked panel edges
  - high load diaphragms



Example – Diaphragm Design

- 3rd floor diaphragm, 84 foot span (idealized)



Diaphragm Design – Shear

3rd floor diaphragm

V_{max} = 13.9 kips

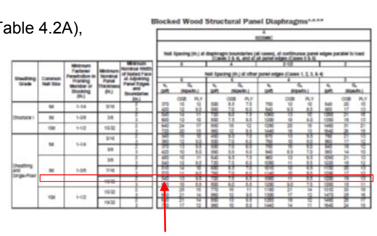
v = 13.9/56 = 0.25 klf

1/2" rated sheathing on 2x DFL framing with 8d at 6" o.c.

Nominal unit shear (SDPWS Table 4.2A), v_s = 0.54 klf

Reduction factor, ϕ = 0.80

$\phi_D v_s$ = 0.8(0.54) = 0.43 klf OK



Diaphragm Design – Chords

3rd floor diaphragm

V = 46.7 kips

w = 46.7/148 ft = 0.315 klf

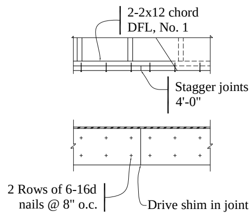
$M_{max} = wL^2/8 = 0.315(84)^2/8$

= 278 k-ft

$T = C$ = 278/56 = 4.96 kips

Chord: 2x12 DFL

Splice: 12 16d nails



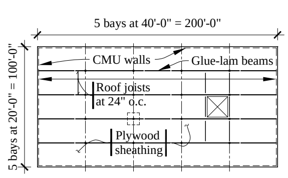
Wood Diaphragms in Concrete and Masonry Buildings

Key wood components:

- Diaphragm strength and stiffness
- Chords and collectors
- Wall anchorage
- Sub-diaphragms and cross ties

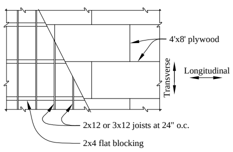
Example – Masonry Wall Building

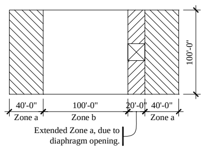
- 1-story warehouse building
- CMU walls with panelized wood roof system
- Seismic Design Category D



Example – Roof Diaphragm

- Construction and design generally similar to wood-framed buildings
- Due to large size of diaphragms, typically use different zones of nailing depending on magnitude of shear
- Chords and collectors similar to wood-framed buildings except that collector design requires consideration of Ω_0 for SDC C and above





Example – Wall Anchorage

For walls anchored to flexible diaphragms, wall anchorage force per ASCE 7-05 Sec. 12.11.2.1 and Eq. 12.11-1 is:

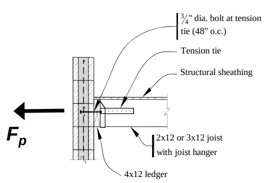
$F_p = 0.8 S_{DS} I W_p$

where

$S_{DS} = 1.0$, $I = 1.0$
$W_p = 1.04$ klf (tributary CMU wall wt)

Therefore, F_p = 0.83 klf

Joists perpendicular to wall
If anchor ever other joist,
then F_p = (0.83)(4) = 3.32 kip / joist



Wall Anchorage

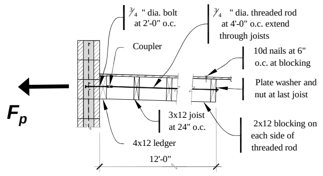
Wall anchorage design elements

- Anchor bolt (ACI 530)
- Anchorage devise (manufacturer data or evaluation report)
- Joist tension (NDS)
- Joist nailing to diaphragm (NDS)

Wall Anchorage

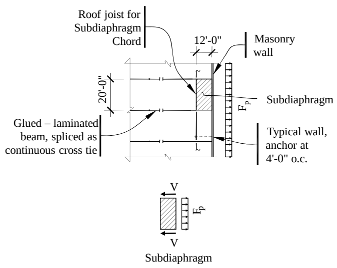
Anchorage at joists parallel to wall

- Develop wall anchorage force into diaphragm across multiple joists
- Many acceptable details for this



Sub-diaphragms

- Use to develop wall anchorage force into diaphragms
- Design for anchorage force between cross ties
- Maximum aspect ratio is 2.5 to 1



Questions?