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
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_{\parallel})
- 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

Radial

Tangential

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

- 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

Platform

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

Post and Beam Construction

Gravity Frame

Lateral System

Roof Purlins

Roof Sheathing

Floor Sheathing

Floor Joists
Typical Light-Frame Foundation: Slab-On-Grade

Bearing wall supporting gravity loads

Slab-on-grade

"Shovel" footing with minimal reinforcing

Sill bolts at pressure treated sill to foundation
Typical Light-Frame Foundation: Raised Floor

- Rim joist
- Bearing wall supporting gravity loads
- Supplemental blocking under shear wall boundary members
- Floor System
- Crawl space under "raised" floor
- Sill bolts at pressure treated sill to foundation
- 6" to 8" Stemwall
- CMU or Concrete
- "Shovel" footing with minimal reinforcing
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

\[ \sigma - \varepsilon \]

Instructional Material Complementing FEMA P-751, Design Examples
Sources of Ductility and Energy Dissipation in Wood Structures

Positive Wall Tie

HANGER NOT SHOWN FOR CLARITY
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

DEFLECTION (INCHES)

NAIL SHEAR (POUNDS)

-600 -500 -400 -300 -200 -100 0 100 200 300 400 500 600

-0.6 -0.5 -0.4 -0.3 -0.2 -0.1 0 0.1 0.2 0.3 0.4 0.5 0.6
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 structure 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.
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

Also referred to as “Conventional Construction”
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)

<table>
<thead>
<tr>
<th>Seismic Force Resisting System</th>
<th>Response Modification Coefficient, R</th>
<th>Seismic Design Category</th>
</tr>
</thead>
</table>
| 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)

<table>
<thead>
<tr>
<th>Seismic Force Resisting System</th>
<th>Response Modification Coefficient, R</th>
<th>Seismic Design Category</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shear walls with wood structural panels</td>
<td>7</td>
<td>B &amp; C: NL</td>
</tr>
<tr>
<td></td>
<td></td>
<td>D – F: 65 ft max</td>
</tr>
<tr>
<td>Shear walls with other materials</td>
<td>2 1/2</td>
<td>B &amp; C: NL</td>
</tr>
<tr>
<td></td>
<td></td>
<td>D: 35 ft max</td>
</tr>
<tr>
<td></td>
<td></td>
<td>E &amp; F: NP</td>
</tr>
</tbody>
</table>
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.”
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

![Shear Wall Tables](image-url)
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

1½" Lightweight concrete over plywood deck on joists at 16" o.c.
Example – Shear Wall Design

- Interior shear wall, 25 feet long, solid

- Perforated exterior wall
- 55 feet of net shear wall length, each side of corridor, distributed over length of building.
Shear Wall Design – Shear

First floor wall

\[ V_1 = 30.9 \text{ kips} \]
\[ v = \frac{30.9}{25} = 1.24 \text{ klf} \]

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

Nominal unit shear (SDPWS Table 4.3A), \( v_s = 1.74 \text{ klf} \)

Reduction factor, \( \varphi = 0.80 \)

Adjust for Hem-Fir (SG = 0.43)

1 - (0.5 - 0.43) = 0.93

\[ 0.93 \varphi_D v_s = 0.93(0.8)(1.74) = 1.29 \text{ klf} \quad \text{OK} \]
Shear Wall Anchorage and Load Path

Diaphragm to shear wall / shear transfer through floor

- **Edge Nailing to Blocking (4) Minimum**
- **Plywood Sheathing**
- **40# Felt**
- **Diaphragm Edge Nailing**
- **1"-4" Minimum**
- **Wall Sheathing / Nailing as Specified**
- **Wood Stud Wall**
- **2x Plate**
- **Continuous Rn. Joist with (3) 18d End Nail to Joist**
- **18d Toe Nail at 12" O.C.**
- **Wall Sheathing / Nailing as Specified**
- **Double 2x Plate**
- **Wood Stud Wall**

**Simpson A35 Where Called for on Plans**

**Simpson H5 at Each Block**

**Solid 2x Blocking with (3) 18d Each End at 48" O.C.**

**Instructional Material Complementing FEMA P-751, Design Examples**

**Wood Structures - 38**
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
\( v = 1.24 \text{ klf} \)

5/8-in. bolts in a 3\( \times \) 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 \( 2.4/[(1.24)/(12)] = 23.3 \text{ in.} \)

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 = $\Sigma vh$ (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
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

- Diaphragm Boundary
- Continuous Panel Edge
- Unblocked Edge
- Supported Edge
- Continuous Panel Edge Parallel to Load
- Direction of Load on Diaphragm
- "Field" nailing
- "Edge" nailing
- Diaphragm Sheathing
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)

- Perforated exterior wall
- 55 feet of net shear wall length, each side of corridor, distributed over length of building.

- Solid interior wall
- Solid end wall

- 30'-0"
- 30'-0"
- 15'-0"
- 25'-0"
- 56'-0"
- 148'-0"
- 84'-0"
Diaphragm Design – Shear

3rd floor diaphragm

\[ V_{\text{max}} = 13.9 \text{ kips} \]
\[ v = \frac{13.9}{56} = 0.25 \text{ klf} \]

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

Nominal unit shear (SDPWS Table 4.2A),
\[ v_s = 0.54 \text{ klf} \]

Reduction factor,
\[ \phi = 0.80 \]
\[ \phi_D v_s = 0.8(0.54) = 0.43 \text{ klf} \quad \text{OK} \]
Diaphragm Design – Chords

**3rd floor diaphragm**

\[ V = 46.7 \text{ kips} \]
\[ w = \frac{46.7}{148} \text{ ft} = 0.315 \text{ klf} \]
\[ M_{\text{max}} = wL^2/8 = 0.315(84)^2/8 \]
\[ = 278 \text{ k-ft} \]
\[ T = C = \frac{278}{56} = 4.96 \text{ kips} \]

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 $\Omega_0$ 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

\[ S_{DS} = 1.0, \ I = 1.0 \]
\[ W_p = 1.04 \text{ klf (tributary CMU wall wt)} \]

Therefore, \( F_p = 0.83 \text{ klf} \)

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

- $\frac{3}{4}$" dia. bolt at 2'-0" o.c.
- Coupler
- $\frac{3}{4}$" dia. threaded rod at 4'-0" o.c. extend through joists
- 10d nails at 6" o.c. at blocking
- Plate washer and nut at last joist
- 2x12 blocking on each side of threaded rod

$F_p$
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?
Title slide for Wood Design.
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

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.
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 to the actual strength of lumber.
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.”
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.
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.
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*.
Self explanatory. Note the accumulation potential of shrinkage perpendicular to grain in each floor over the height of the structure.
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.
The basic approach to the lateral design of wood structures is the same as for other structures.
Slide shows a stress strain curve for wood that is essentially linear elastic, with a brittle failure. There is virtually no ductility, and no energy dissipation capacity.
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

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

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

Self explanatory: List of sources of energy dissipation in wood structures.
Comment on how permanent crushing of wood around shank of nail leads to pinched nature of nail hysteresis.
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

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

The prescriptive, or conventional construction” design method is shown here but is not covered in this presentation.
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.
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, $\phi$, and a time effect factor, $\lambda$. For earthquake effects, $\lambda$ is 1.0.

The shear wall and diaphragm conversions are relatively straightforward.
This slide presents the coefficients and limitations for shear walls that are part of a bearing wall system.

<table>
<thead>
<tr>
<th>Seismic Force Resisting System</th>
<th>Response Modification Coefficient, R</th>
<th>Seismic Design Category</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shear walls with wood structural panels</td>
<td>6 ½</td>
<td>B &amp; C: NL</td>
</tr>
<tr>
<td></td>
<td></td>
<td>D – F: 65 ft max</td>
</tr>
<tr>
<td>Shear walls with other materials</td>
<td>2</td>
<td>B &amp; C: NL</td>
</tr>
<tr>
<td></td>
<td></td>
<td>D: 35 ft max</td>
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<td></td>
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<td>E &amp; F: NP</td>
</tr>
<tr>
<td>Walls with flat strap bracing</td>
<td>4</td>
<td>B &amp; C: NL</td>
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<tr>
<td></td>
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<td>D – F: 65 ft max</td>
</tr>
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This slide presents the coefficients and limitations for shear walls that are part of a bearing wall system.

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</table>
| 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 |
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.
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
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.
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.
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.
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.
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 from 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.
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.
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.
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).
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.
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.
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.
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.
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.
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.
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.
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.
A different design example 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.
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.
For walls anchored to flexible diaphragms, wall anchorage force per ASCE 7-05 Sec. 12.11.2.1 and Eq. 12.11-1 is:

\[ F_p = 0.8S_{DS}W_p \]

where

\[ S_{DS} = 1.0, \ i = 1.0 \]
\[ W_p = 1.04 \text{ klf (tributary CMU wall wt)} \]

Therefore, \( F_p = 0.83 \text{ klf} \)

Joists perpendicular to wall
If anchor every other joist, then \( F_p = (0.83)(4) = 3.32 \text{ kip / joist} \)

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

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.
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

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

"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

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

**Radial**

**Tangential**

Sample DFL perpendicular to grain design properties:
- Modulus of elasticity: 45,000 psi (2.5 ~ 5 % of E,I)
- 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

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

---

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

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

Post and Beam

- Roof Purlins
- Roof Sheathing
- Gravity Frame
- Lateral System
- Floor Sheathing
- Floor Joists

Typical Light-Frame Foundation: Slab-On-Grade

- Sill bolts at pressure treated sill to foundation
- Bearing wall supporting gravity loads
- Slab-on-grade
- "Shovel" footing with minimal reinforcing
Typical Light-Frame Foundation: Raised Floor

- Bearing wall supporting gravity loads
- Supplemental blocking under shear wall boundary members
- Rim joist
- Sill bolts at pressure treated sill to foundation
- Floor System
- 6" to 8" Stemwall CMU or Concrete
- "Shovel" footing with minimal reinforcing
- Crawl space under "raised" floor

Lateral Design Basics: Earthquake Behavior

- Resultant inertial forces
- Horizontal elements
- Vertical elements
- Ground Motion

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.
**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 structure 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: $F_s' = F_x C_y C_z \text{ etc}$
  - LRFD: $F_s' = F_x K_D \phi C_y C_z \text{ etc}$
- Shear walls and diaphragms
  - $V_{ASD} = \frac{v_s}{2}$
  - $V_{LRFD} = \phi_D v_s = 0.8 v_s$
Lateral Systems (Bearing Walls)

<table>
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<tr>
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<tbody>
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<td>Shear walls with wood structural panels</td>
<td>6 ½</td>
<td>B &amp; C: NL, D – F: 65 ft max</td>
</tr>
<tr>
<td>Shear walls with other materials</td>
<td>2</td>
<td>B &amp; C: NL, D: 35 ft max, E &amp; F: NP</td>
</tr>
<tr>
<td>Walls with flat strap bracing</td>
<td>4</td>
<td>B &amp; C: NL, D – F: 65 ft max</td>
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</tbody>
</table>

Lateral Systems (Building Frame)

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<td>Shear walls with wood structural panels</td>
<td>7</td>
<td>B &amp; C: NL, D – F: 65 ft max</td>
</tr>
<tr>
<td>Shear walls with other materials</td>
<td>2 ½</td>
<td>B &amp; C: NL, D: 35 ft max, E &amp; F: NP</td>
</tr>
</tbody>
</table>

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 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

Example – Shear Wall Design
- Interior shear wall, 25 feet long, solid
**Shear Wall Design – Shear**

First floor wall

\[ V_1 = 30.9 \text{ kips} \]

\[ v = 30.9/25 = 1.24 \text{ klf} \]

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

Nominal unit shear (SDPWS Table 4.3A), \( v = 1.74 \text{ klf} \)

Reduction factor, \( \phi = 0.80 \)

Adjust for Hem-Fir (SG = 0.43)

\[ 1-(0.5-0.43) = 0.93 \]

\[ 0.93 \phi v = 0.93(0.8)(1.74) = 1.29 \text{ klf OK} \]

**Shear Wall Anchorage and Load Path**

Diaphragm to shear wall / shear transfer through floor

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

$$v = 1.24 \text{ klf}$$

5/8-in. bolts in a 3× DFL sill plate

AF&PA NDS:

$$Z_{K_p,pl} = \frac{(1.11)(2.16/0.65)(0.65)(1.0)}{} = 2.40 \text{ kips per bolt}$$

Max spacing is $$2.4\left(\frac{1.24}{12}\right) = 23.3 \text{ in.}$$

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 Design – Chords & Anchorage

- Provide tension and compression chords for \( T = C = \nu h \)
  where, \( \nu = \) induced unit shear and \( h = \) shear wall height
- Where net tension is induced, provide anchorage for net tension force

First floor interior wall
OVERTURNING, \( M_{OT} = 517 \text{ k-ft} \)
STABILIZING, \( M_{ST} = (0.9 - 0.2 S_{ds}) M_{D} = 222 \text{ k-ft} \)
Therefore, net tension so uplift anchorage is req’d
Uplift anchorage = \( T \nu h \) (all 3 stories)
\( T = 16.0 \text{ kips} \)
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

- Field nailing
- Edge nailing
- Continuous Panel Edge
- Unblocked Edge
- Direction of Load on Diaphragm
- Supported Edge
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

\[ V_{\text{max}} = 13.9 \text{ kips} \]
\[ v = 13.9/56 = 0.25 \text{ klf} \]

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

Nominal unit shear (SDPWS Table 4.2A), \( v_s = 0.54 \text{ klf} \)

Reduction factor,
\[ \phi = 0.80 \]
\[ \delta V_s = 0.8(0.54) = 0.43 \text{ klf} \quad \text{OK} \]
**Diaphragm Design – Chords**

3rd floor diaphragm

\[ V = 46.7 \text{ kips} \]

\[ w = \frac{46.7}{148} \text{ ft} = 0.315 \text{ klf} \]

\[ M_{\text{max}} = wL^2/8 = 0.315(84)^2/8 = 278 \text{ k-ft} \]

\[ T = C = \frac{278}{56} = 4.96 \text{ kips} \]

Chord: 2x12 DFL

Splice: 12 16d nails

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**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 $\Omega_0$ 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:

$$F_p = 0.8S_{DS}W_p$$

where

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

Therefore, $F_p = 0.83 klf$

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

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?