Introduction to Design of Seismic Force-Resisting Systems in Wood Light-Frame Construction

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Includes materials developed by Peter Somers S.E. and Steve Pryor, S.E.
Wood Design Background Outline

• Introduction to wood design and construction & Basic wood properties
• Shear Walls
• Diaphragms
• Anchorage of concrete and masonry walls
Introduction to Wood Design and Construction
Wood Design and Construction: 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 International Residential 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
Wood Design and Construction: 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 Design and Construction

- ASCE 7-16
- AWC NDS, 2015 Edition – wood framing and connections
- AWC SDPWS, 2015 Edition – shears, diaphragms, and anchorage
Wood Design and Construction

- Roof Purlins
- Roof Sheathing
- Floor Sheathing
- Floor Joists
Wood Design and Construction

Resultant inertial forces

Horizontal elements

Vertical elements

Ground Motion
Wood Design and Construction - Seismic Response
Wood Design and Construction – Desired Seismic Response

![Applied Load at Top of Wall vs. Top of Wall Deflection](image)

- Applied Load at Top of Wall (KIPS)
- Top of Wall Deflection (INCHES)
Wood Design and Construction

Full-scale shear wall test

Individual nail test
Wood Design and Construction - Less Desirable Response

Inertial Force

Resisting Force

Ledger Failure

σ

ε
Wood Design and Construction

Positive Wall Tie
Wood Design and Construction

- ASCE 7-16
- AWC NDS, 2015 Edition – wood framing and connections
- AWC SDPWS, 2015 Edition – shears, diaphragms, and anchorage
Wood Design and Construction

• 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>
<tbody>
<tr>
<td>Shear walls with wood structural panels</td>
<td>$6 \frac{1}{2}$</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 (CFS Only)</td>
<td>4</td>
<td>B &amp; C: NL D – F: 65 ft max</td>
</tr>
</tbody>
</table>
## Lateral Systems (Building Frame)

<table>
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<th>Seismic Force Resisting System</th>
<th>Response Modification Coefficient, R</th>
<th>Seismic Design Category</th>
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</thead>
</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 |
Wood Design and Construction

Flexible vs Rigid Diaphragm – complexity:

• Neither rigid nor flexible diaphragm assumptions truly represent the distribution of seismic forces in a typical structure – both are simplifications and the actual behavior is “semi-rigid”

• Stiffness of the diaphragm relative to walls is important in determining whether behavior is more like rigid or more like flexible
Diaphragms Idealized As Flexible

- ASCE 7 Sec. 12.3.1.1: Diaphragms constructed of untopped steel deck or wood structural panels are permitted to be idealized as flexible if any of the following conditions exist:
  a. In structures where vertical elements are steel braced frames, steel and concrete composite braced frames, or concrete, masonry or steel and concrete composite walls
  b. In one- and two-family dwellings
  c. In structures of light-frame construction where all of the following conditions are met
     1. Nonstructural topping not greater than 1-1/2 inch
     2. Each line of vertical elements complies with drift limits
Diaphragms Calculated As Flexible

- ASCE 7 Sec. 12.3.1.3:
  “… the computed maximum in-plane deflection of the diaphragm under lateral load, $\delta_{MDD}$, is more than two times the average story drift of adjoining vertical elements of the lateral force-resisting system of the associated story, $\Delta_{ADVE}$, under equivalent tributary lateral load.”
The SDPWS 2015 Modifications:

- Coordinating with ASCE 7 flexible, rigid, and semi-rigid diaphragm designations
- Providing greater clarity to provisions for open front and torsionally irregular buildings
- Buildings with cantilevered diaphragms are open-front
- Requiring rigid or semi-rigid diaphragm analysis for torsionally irregular buildings (Sec. 4.2.5.1)
- Require rigid or semi-rigid diaphragm analysis for diaphragm cantilevers in excess of six feet (Sec. 4.2.5.2)
- Limit diaphragm cantilevers to maximum of 35 feet
Complete Load Path

- Provision of a complete load path is essential to performance of wood light-frame seismic force-resisting systems
- Due to nature of wood construction, this involves a number of connections
- Will be discussed in detail for shear walls and diaphragms
Shearwalls
Shear Walls

Three types of shear walls:

- **Segmented Shear Wall**
- **Shear Wall Designed for Continuity Around Openings**
- **Perforated Shear Wall**
Shear Walls

Per AF&PA Sec. 4.3, design provisions include

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

Shear wall table information
- Nominal unit shear capacities
- Tables are for DF-L or SP – need to adjust values if framing with wood species with lower specific gravities

Major divisions:
- Structural I vs. Rated Sheathing
- Panels applied directly to framing vs. panels applied over gypsum wallboard
- Seismic and wind tabulated separately
- Unblocked edges allowed in some conditions
Shear Walls

Aspect ratios

- Application varies by shear wall type
2015 SDPWS Sec. 4.3 – Force distribution to shear walls in a line

- 2005, 2008 SDPWS:
  - Distribute seismic/wind forces to provide same deflection where materials and construction are same

- 2015 SDPWS:
  - Where materials and construction are same, distribute seismic/wind forces proportional to shear capacity, adjust for slender piers
2015 SDPWS Sec. 4.3 – Shear walls with narrow piers

- Capacity Adjustment: Narrow wall pier adjusted for aspect ratio greater than 2:1:
  - Wood structural panel: \(1.25 - 0.125h/b_s\)
  - Fiberboard: \(1.09 - 0.09h/b_s\)
- Different deflection adjustment made to narrow pier when distributing force within wall line
Length of wood structural panel sheathing used to obtain $C_o$ (in $\Sigma L_i$) adjusted for ratio greater than 2:1 narrow wall pier:

- $2h/b_s$
Design Example: Shear Walls

- 3-story apartment building
- Stick framed with plywood shear walls and diaphragms
- Seismic Design Category D
- ASCE 7 Sec. 12.14 Simplified Procedure

Plan

Section & Elevation
Design Example: Shear Walls

- 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.
Design Example: Shear Walls

1. Wall design for in-plane shear
2. Horizontal shear load path
3. Overturning load path
## Design Example: Shear Walls

<table>
<thead>
<tr>
<th>Seismic Force</th>
<th>to Center 50% x0.50</th>
<th>Each Wall (strength level) x0.50</th>
</tr>
</thead>
<tbody>
<tr>
<td>( F_{\text{ROOF}} ) = 30.0 kips</td>
<td>= 15.0 kips</td>
<td>= 7.50 kips</td>
</tr>
<tr>
<td>( F_{3\text{RD}} ) = 46.7 kips</td>
<td>= 23.35 kips</td>
<td>= 11.68 kips</td>
</tr>
<tr>
<td>( F_{2\text{ND}} ) = 46.7 kips</td>
<td>= 23.35 kips</td>
<td>= 11.68 kips</td>
</tr>
</tbody>
</table>

\[
F_{\text{roof}} = 7.50 \text{ kips}
\]

\[
F_{3\text{rd}} = 11.68 \text{ kips}
\]

\[
F_{2\text{nd}} = 11.68 \text{ kips}
\]
Design Example: Shear Walls

First floor design for shear:
• \[ V = 7.5 + 11.68 + 11.68 = 30.86 \text{ kips} \]

For 25 foot shear wall shown
• Unit Shear \( v_{1st} = 30.86 \text{ kips/25 ft} = 1.236 \text{ klf} \)
• This is strength level demand
Design Example: Shear Walls

Capacity From SDPWS Table 4.3A for blocked wood structural panel shear walls

- 19/32 rated sheathing on Hem-Fir studs at 16” o.c.
- Nominal unit shear capacity $v_s = 1.740$ klf
- $\Phi = 0.80$ (SDPWS Sec. 4.3.3)
- Adjustment for stud species with S.G. = 0.43
  
  \[ = 1 - (0.5 - 0.43) = 0.93 \] (SDPWS Table 4.3A footnote)
- Adjusted capacity \( = (0.93)(0.8)(1.740) = 1.294 > 1.236 \) OK
- This shear wall requires 3x or stitched 2-2x framing members at abutting panel edges to avoid framing splitting during nail driving (SDPWS Sec. 4.3.7.1, Item 4)
- Design shear anchorage to the foundation
Design Example: Shear Walls

Strength level load combinations:
For $S_{DS} = 0.89$, the strength level design load combinations are as follows:

$(1.2 + 0.2S_{DS})D + 1.0QE + 0.5L + 0.2S = 1.38D + 1.0QE + 0.5L + 0.2S$

$(0.9 - 0.2SDS)D - 1.0QE = 0.72D - 1.0QE$

\[ F_{roof} = 7.50 \text{ kips} \]
\[ F_{3rd} = 11.68 \text{ kips} \]
\[ F_{2nd} = 11.68 \text{ kips} \]
Design Example: Shear Walls

Diaphragm to shear wall / shear transfer through floor

Diagram showing details of diaphragm to shear wall connection, including:
- Edge nailing to blocking (4) minimum
- plywood sheathing
- 40# felt
- Diaphragm edge nailing
- Wall sheathing / nailing as specified
- Wood stud wall
- 2x plate
- Continuous rim joist with (3) 16d end nail to joist
- 16d toenail at 12" O.C.
- Wall sheathing / nailing as specified
- Double 2x plate
- Wood stud wall
Design Example: Shear Walls

Shear wall overturning / transfer of vertical forces through floor
Diaphragms

Nailing along perimeter of sheathing panel into blocking between joists

Sheathing perpendicular to joists

Field nailing to each joist at 12 inches on center
Diaphragms

Diaphragm simplifying assumptions:
- Sheathing resists shear
- Chord resists tension, compression like beam flange
- Boundary element at every sheathing edge

[Diagram of a diaphragm with labels for Chord, Shear wall below, Length of span L, Uniform seismic load W, and Simple span beam model]
Diaphragms

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

Diaphragm simplifying assumptions:
- Collector resists tension & compression
- Continuity assumption may vary at interior vertical element
Diaphragms

Diaphragm sheathing: Blocked

- Nailing along perimeter of sheathing panel into blocking between joists
- Sheathing perpendicular to joists
- Field nailing to each joist at 12 inches on center
Diaphragms

Diaphragm sheathing: Unblocked

No nailing along perimeter of sheathing panel into blocking between joists

Sheathing perpendicular to joists

Field nailing to each joist at 12 inches on center
Diaphragms

Diaphragm boundary elements: Common chords and collectors

Figure 3-4. Wall top plate acting as chord boundary element. The same top plate can also act as the collector boundary element.
Diaphragms

Design of Boundary Elements

- Tension force in one load direction, compression when reversed
- Every panel edge at exterior or interior is diaphragm boundary
- Collectors parallel and perpendicular to primary framing direction
Diaphragms

Diaphragm boundary elements: Detailing at diaphragm openings

Figure 3-6. Wood light-frame diaphragm with opening. Supplemental boundary members are added around the opening.
Diaphragm Seismic Design Forces

- Inertial forces
  - generated by the seismic weight tributary to the diaphragm

\[ F_{px} = \frac{\sum_{i=x}^{n} F_i}{\sum_{i=x}^{n} w_i} w_{px} \]

where:
- \( F_{px} \) = the diaphragm (inertial) design force
- \( F_i \) = the (vertical element) design force, \( F_x \), applied at level \( i \)
- \( w_i \) = the weight tributary to level \( i \)
- \( w_{px} \) = the weight tributary to the diaphragm at level \( x \)
2015 SDPWS –
Horizontal distribution of shear

- Diaphragm not permitted to be classified as flexible for purposes of force distribution to vertical elements when:
  - Torsionally irregular
  - Diaphragm cantilevers greater than six feet
- 35 foot diaphragm cantilever limit
Diaphragm Design Forces – **NEW ALTERNATIVE – SEE CHAPTER 6 OF NEHRP DESIGN EXAMPLES** (Sec. 12.10.3)

- Seismic forces in the diaphragm are influenced by both the type of vertical elements and the type of diaphragm, but the Basic Method (Section 12.10.1.1) only recognizes the vertical elements as an influence.
- Section 12.10.3 takes into account the displacement capacity of the specific diaphragm type used.
- Diaphragm forces start from near-elastic level, and are divided by $R_s$, the *diaphragm design force reduction factor*, specific to the diaphragm type.
Diaphragm Seismic Design Forces

- Inertial forces
- Transfer forces
  - generated by discontinued vertical elements or
  - generated by changes in stiffness of vertical elements over height of structure
Diaphragm Seismic Design Forces

- Diaphragm design must be consistent with diaphragm classification – rigid, semi-rigid, flexible
- Sheathing
  - Design for in-plane shear in accordance with SDPWS
- Boundary members and connections
  - Design for tension and compression in accordance with NDS
- No overstrength forces for chords
- No overstrength forces for collectors for structures or portions thereof braced entirely by light-frame shear walls (ASCE 7-10, Sec. 12.10.2)
Diaphragm Seismic Design Forces

Per SDPWS Sec. 4.2, design provisions include:

- Deflection determination
- Unit shear capacities (diaphragm tables)
- Aspect ratios
- Boundary members
- Construction requirements

- Nailing along perimeter of sheathing panel into blocking between joists
- Sheathing perpendicular to joists
- Field nailing to each joist at 12 inches on center
Design Example: Diaphragm

Horizontal distribution of seismic force at roof:

\[ V_{\text{ROOF}} = 30 \text{ kips} - w_{\text{TRANS}} = \frac{30}{148 \text{ ft.}} = 0.202 \text{ klf} \]

\[ W = 0.202 \text{ klf} \]

SPAN = 88 ft
Design Example: Diaphragm

Horizontal distribution of seismic force at roof:

- $V_{\text{ROOF}} = 30$ kips
- $w_{\text{TRANS}} = 30/184 \text{ ft.} = 0.202 \text{ klf}$

For 88 foot span shown

- $R = w(L)/2 = 0.202(88 \text{ ft})/2 = 8.93$ kips
- Unit Shear $v_{\text{ROOF}} = 8.93$ kips$/56 \text{ ft} = 0.160 \text{ klf}$
- This is strength level demand
Design Example: Diaphragm

For 88 foot span shown
- Unit Shear $v_{ROOF} = 8.93$ kips/56 ft = 0.160 klf
- This is strength level demand

Capacity From SDPWS Table 4.2C for unblocked wood structural panel diaphragms
- Construct as load case 1 for transverse load direction, since this is longest span
- 15/32 rated sheathing on 2x DF-L framing
- Nominal unit shear capacity $v_s = 0.480$ klf
- $\Phi = 0.80$ (SDPWS Sec. 4.2.3)
- Adjusted capacity = $(0.8)(0.480) = 0.384 > 0.160$ OK
Anchorage of Concrete and Masonry Walls
Wall-to-Diaphragm Anchorage and Continuous Ties
Wall-to-Diaphragm Anchorage and Continuous Ties

- Tension perpendicular to grain results in brittle failures at low loads
- Does not provide a reliable load path
Wall-to-Diaphragm Anchorage and Continuous Ties
Wall-to-Diaphragm Anchorage and Continuous Ties

• Design Considerations
  – Substantial experience w/ earthquake performance
  – Numerous studies seismic demand on these connections
  – Even more recent construction may required retrofit
  – Objective is tie between exterior walls
Wall-to-Diaphragm Anchorage and Continuous Ties

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

\[ F_p = 0.4S_{DS}k_a l_e W_p \]

Where

\[ k_a = 1.0 + \frac{L_f}{100} \leq 2.0 \]

\[ L_f = \text{diaphragm span} = 200 \text{ ft} \]

\[ K_a = 1.0 + \frac{200}{100} = 3.0, \text{ use } 2.0 \text{ max} \]
Wall-to-Diaphragm Anchorage and Continuous Ties

\[ F_p = 0.4S_{DS}k_aI_eW_p \]

Where
\[ k_a = 2.0 \]
\[ S_{DS} = 1.43 \]
\[ I_e = 1.0 \]

Transverse walls:
\[ W_p = 65 \text{ psf} (16\text{ft}) = 1.04 \text{ klf} \]
\[ F_p = 0.4 (1.43) (2.0) (1.0) 1.04 = 1.19 \text{ klf} \]

Anchors at 4 ft = 1.19 (4.0) = 4.76 kips
Wall-to-Diaphragm Anchorage and Continuous Ties
Wall-to-Diaphragm Anchorage and Continuous Ties
Wall-to-Diaphragm Anchorage and Continuous Ties

The subdiaphragm concept:

- Cannot run tension ties at 4 ft on center across entire length of building, so develop into subdiaphragm
- Design subdiaphragm for anchorage force level
- Subdiaphragm reaction goes to major beam line
- Design continuous tie connections across major beam lines for anchorage force level
The subdiaphragm concept:

- 5 bays at 20'-0" = 100'-0"
- 5 bays at 40'-0" = 200'-0"
- 8" concrete masonry wall
- Typical glue-lam roof beam
- Plywood roof sheathing
- Wall anchorage to subdiaphragm at 4 ft.

Glulam beams and connections act as continuous ties

Subdiaphragm approx. 20 ft. x 20 ft.
Wall-to-Diaphragm Anchorage and Continuous Ties
Wall-to-Diaphragm Anchorage and Continuous Ties

Important items for wall anchorage of concrete and masonry walls SDC C and up (Section 12.11.2.2):

- Continuous ties required between diaphragm chords
- Subdiaphragms permitted as part of continuous tie system provided subdiaphragm aspect ratio $\leq 2.5$
- Wall anchor forces required through the entire continuous tie system
- Forces multiplied by 1.4 for steel elements of anchorage
- Diaphragm wood structural panel sheathing not permitted to be loaded in tension to provide continuous tie
- Embedded tension straps to be wrapped around or anchored to wall reinforcing
Questions?
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