A Design Example of a Wood Cantilever Diaphragm

By:
R. Terry Malone, PE, SE
Scott Breneman, PhD, PE, SE
Senior Technical Directors
Project Resources and Solutions Division
www.woodworks.org

E-mail: terrym@woodworks.org
(928) 775-9119
In Your Folders

- Colored flow chart
- Wood Solutions paper: 5-Over-2 Podium Design, Parts 1 and 2.
- Wood Solutions paper: Accommodating Shrinkage in Multi-story Wood-framed Structure
- The Analysis of Irregular Shaped Diaphragms

Slides: Education tab/Presentation Slide Archive/
Example and Method of Analysis:

- Currently, there are few, if any, examples or guidance available.
- No set path for design.
- Codes and standards only partially address open-front design issues.
- The method of analysis used in this example is based on our engineering judgement, experience, and interpretation of codes and standards as to how they might relate to open-front structures.
A variety of challenges often occur on projects due to:

- Fewer opportunities for shear walls at exterior wall lines
- Open-front diaphragm conditions
- Increased building heights, and
- Potential multi-story shear wall effects.
- Can be very flexible structures subject to drift, irregularity and stiffness issues (seismic or wind).

In mid-rise, multi-family buildings, corridor only shear walls are becoming very popular way to address the lack of capable exterior shear walls.

The goal of this presentation is to provide guidance on how to analyze a double open-front, or corridor only shear wall diaphragm, and help engineers better understand flexibility issues associated with these types of structures.
The analysis techniques provided in this presentation are intended to demonstrate one method of analysis, but not the only means of analysis. The techniques and examples shown here are provided as guidance and information for designers to consider to refine their own techniques.

- The workshop is a basic summary of the paper. It won’t always follow the paper flow exactly.
- The paper and workshop are open to further review and refinement by task groups and practicing engineers like you.
- Only partial calculations are provided to demonstrate how certain design/code checks are performed.
- Example page numbers will be provided at key points of this presentation.
Workshop Content

Part 1-Background:
- Introduction
- Horizontal distribution of shear and stiffness issues
- Questions needing resolution
- 2015 SDPWS open-front requirements-review
- Introduction to open-front example
- Preliminary design assumptions

15 minute break

Part 2-Design Example:
- Calculation of seismic forces and distribution
- Preliminary shear wall design
- Nominal shear wall stiffness
- Verification of shear wall design
- Diaphragm design

15 minute break

Part 3-Design Example (cont.):
- Maximum diaphragm chord force
- Diaphragm flexibility
- Story drift
- Torsional irregularity

Lunch

Part 4-Design Example (cont.):
- Amplification of accidental torsion
- Redundancy
- Transverse direction design
- Miscellaneous plan layouts and multi-story effects
Part 1-Background:

- Introduction
- Horizontal distribution of shear and stiffness issues
- Questions needing resolution
- 2015 SDPWS open-front requirements-review
- Introduction to open-front example
- Preliminary design assumptions
Questions

1. When does a loss in stiffness in the exterior walls cause an open-front diaphragm condition?

2. What is the deflection equation for open-front/cantilever diaphragms?

3. How is diaphragm flexibility defined for open-front/cantilever diaphragms vs. ASCE 7-16, Figure 12.3-1?

4. What are the available methods of distributing torsional forces into the diaphragm?

5. Do shear walls located along diaphragm chord lines affect the diaphragm chord forces?

6. Will the in-plane lateral forces of the exterior walls located at the ends of the cantilever increase chord forces, or is it acceptable to include these as part of the PSF lateral load?

7. How are torsional irregularities determined and addressed for open-front/cantilever diaphragms?
• Horizontal Distribution of shear
• Diaphragm/SW Stiffness Issues
• **Question 1:** Example-Changes in exterior wall stiffness
• 2015 SDPWS Open-front Diaphragm Requirements
Horizontal Distribution of Shear

Distribution of shear to vertical resisting elements shall be based on an analysis where the diaphragm is modeled as:

- **Idealized as flexible**-based on tributary area.
  - Can under-estimate forces distributed to the corridor walls (long walls) and over-estimate forces distributed to the exterior walls (short walls)
  - Can inaccurately estimate diaphragm shear forces

- **Idealized as rigid**-Distribution based on relative lateral stiffnesses of vertical-resisting elements of the story below.
  - More conservatively distributes lateral forces to corridor, exterior and party walls
  - Allows easier determination of building drift
  - Can over-estimate torsional drift
  - Can also inaccurately estimate diaphragm shear forces

- **Modelled as semi-rigid.**
  - Not idealized as rigid or flexible
  - Distributed to the vertical resisting elements based on the relative stiffnesses of the diaphragm and the vertical resisting elements accounting for both shear and flexural deformations.
  - In lieu of a semi-rigid diaphragm analysis, it shall be permitted to use an enveloped analysis.

Note:
Offsets in diaphragms can also affect the distribution of shear in the diaphragm due to changes in the diaphragm stiffness.
Force Distribution Due to Diaphragm/SW stiffness

If rectangular diaphragm

- Full support (SW rigid)
- Partial support (Decreasing SW stiffness)
- No support

Unit with Exterior Wall

- Condition A: Flexible diaphragm
- Condition B: Loads shift
- Condition C: No support

Podium

- Full cantilever, no exterior wall support
- Most load goes to corridor walls. Check Diaph./SW stiffness, use RDA to design diaphragm
- Can be idealized as flexible diaphragm

Consider SW multi-story effects

Full support (SW rigid)

Partial support (Decreasing SW stiffness)

No support

FTAO?

Traditional SW Vs. MBA SW
Review Stiffness at Offsets
Longitudinal Loads - Shear Wall A.R. = 1.5:1

Bending increases at start of offset

Base Line = 0

Disp. y (in)  Shear y (K)  Moment z (K-ft)

A.R. 1.5:1 wall
A.R. 2:1 wall
A.R. 3.5:1 wall

Ext. SW
Full cantilever

Base Line = 0

Disp. y (in)

51.13 k  46.4 k  43.21 k

A.R. 1.5:1 wall
A.R. 2:1 wall
A.R. 3.5:1 wall

Bending increases at start of offset


Distance From Start (ft)

526.55 k  414.2 k  692.1 k
Question 1 - When Does a Loss in Stiffness in the Exterior Walls Cause an Open-front Diaphragm Condition? **No magic bullet answer!**

**Example - Exterior Wall Stiffness**

**Study Assumptions:**
- Flexible Diaphragm.
- No torsion

**Starting point** - Exterior shear walls same number, length, stiffness and construction as corridor walls.
Study to Determine Open-front condition - 35’ Span

Objective is to determine point where loss of shear wall stiffness at exterior wall line causes an open-front condition

- Force distribution to walls based on nominal wall stiffness

- 2D FEA model used to visualize diaphragm displacement curves and force distribution

- Diaphragm 15/32” WSP w/ 10d@6” o.c.
  - Modelled as flexible
  - Continuous chords at corridor walls

- Shear walls with 15/32” WSP
  - Wall height=10’
  - Hold down anchors same for all walls
  - No gravity loads
  - Corridor walls (3)10’ w/ 10d@4” o.c.-constant through-out study (basis of design)

10d nails

$L=(3)10’$ walls
- 10d@3”o.c., Ga=37
- 10d@4”o.c., Ga=30
- 10d@6”o.c., Ga=22

$L=(3)8’$ walls
- 10d@3”o.c.
- 10d@4”o.c.
- 10d@6”o.c.

$L=(3)6’$ walls
- 10d@3”o.c.
- 10d@4”o.c.
- 10d@6”o.c.

$L=(3)4’$ walls
- 10d@3”o.c.
- 10d@4”o.c.
- 10d@6”o.c.

$L=(3)3’$ walls
- 10d@3”o.c.
- 10d@4”o.c.
- 10d@6”o.c.
35’ RDA Force Distribution-SW displ.

- Diaphragm stiffness flexible
- Shear wall stiffness-variable
- Seismic STR. Forces
- No torsion
- No gravity loads

- V=Shear to wall line
- k=Stiffness of wall line
- %=SW stiffness at exterior wall vs. corridor wall line

**Fixed support**

- **V=3.81k, k=40**
- **V=4.15k, k=40.71**

**(3) 10’ ext. walls**
- **ΣLsw=30’, A.R.=1:1**
- **V=4.35k, k=41.06**
- **V=4.31k, k=41.36**
- **V=4.82k, k=41.8**

**Partial support**

- **V=3.25k, k=30.66, %=77**
- **V=3.07k, k=28.05, %=70**
- **V=2.78k, k=24.08, %=60**

**Rigid support**

- **V=3.81k, k=40, %=100**
- **V=3.45k, k=33.86, %=85**

**If flexible, trib. Reaction force R=3810 lbs.**

**V=3.81k, k=40, %=100**

**V=3.45k, k=33.86, %=85**

**ΣLsw=24’, A.R.=1.25:1**

- **V=5.3k, k=42.43**
- **V=5.42k, k=42.58**
- **V=5.63k, k=42.81**

**ΣLsw=18’, A.R.=1.67:1**

- **V=6.39k, k=43.56**
- **V=6.45k, k=43.61**
- **V=6.55k, k=43.7**

**All partial support**

- **V=1.21k, k=8.2, %=21**
- **V=1.15k, k=7.74, %=19**
- **V=1.05k, k=6.98, %=17**

**10d nails**

- **10d @ 4” typical**
- **ΣLsw=12’, A.R.=2.5:1**

**Exterior Walls**

- All open-front Diaph.

**Prelim conclusion (This example only):**

- If walls near 44% or if k ≤ 20 consider open-font
- Magic 20’ SW
Minimum Design Check Considerations
(You make the judgement call)
Structures Are Also Susceptible to Wind Damage

- Too much flexibility?
- Lack of adequate shear walls
- Soft / Weak story issues?
- Insufficient load paths?
- Lack of proper connections?
Open-Front Diaphragms
Relevant 2015 SDPWS Sections

New definitions added:
• Open front structures
• Notation for L’ and W’ for cantilever Diaphragms

Relevant Revised sections:
• 4.2.5- Horizontal Distribution of Shears
• 4.2.5.1-Torsional Irregularity
• 4.2.5.2- Open Front Structures
• Combined open-front and cantilever diaphragms

Figure 4A Examples of Open Front Structures

Similar to MS-MF structures
SDPWS 4.2.5.2 Open Front Structures: (Figure 4A)

For resistance to *seismic* loads, wood-frame diaphragms in open front structures shall comply with all of the following requirements:

1. The diaphragm conforms to:
   a. WSP-L’/W’ ratio ≤ 1.5:1  4.2.7.1
   b. Single layer-Diag. sht. Lumber- L’/W’ ratio ≤ 1:1  4.2.7.2
   c. Double layer-Diag. sht. Lumber- L’/W’ ratio ≤ 1:1  4.2.7.3

2. The drift at edges shall not exceed the ASCE 7 allowable story drift when subject to *seismic* design forces including torsion, and accidental torsion (Deflection-strength level amplified by Cd.).

3. For open-front-structures that are also *torsionally irregular* as defined in 4.2.5.1, the L’/W’ ratio shall not exceed 0.67:1 for structures over one story in height, and 1:1 for structures one story in height.

4. For loading parallel to open side:
   a. Model as semi-rigid (min.), shall include shear and bending deformation of the diaphragm, or idealized as rigid.

5. The diaphragm length, L’, (normal to the open side) does not exceed 35 feet. *(2008 SDPWS: L’\text{max}=25’. Exception-if drift can be tolerated, L’ can be increased by 50%).* Could use an Alternative Materials, design and Methods Request (AMMR) to exceed 35’.

Currently no deflection equations or guidance on determination of diaphragm flexibility.
Design Example- Longitudinal Direction

Example plan selected to provide maximum information on design issues

Disclaimer:
The following information is an open-front diaphragm example which is subject to further revisions and validation. The information provided is project specific, and is for informational purposes only. It is not intended to serve as recommendations or as the only method of analysis available.
Open Front Structures Code Checks:

For resistance to seismic loads, wood-frame diaphragms in open front structures should comply with all of the following requirements:

1. Check stiffness of diaphragm and shear walls  
   ASCE 7 12.3.1, SDPWS 4.2.5.2 (3)
2. Verify aspect ratio  
   SDPWS 4.2.7.1-4.2.7.3
3. Check drift at edges  
   ASCE 7 12.12.1, SDPWS 4.2.5.1
4. Check for torsional irregularity  
   ASCE 7 12.3.2, SDPWS 4.2.5.1
   - Inherent torsion  
     ASCE 7 12.8.4.1
   - Accidental torsion  
     ASCE 7 12.8.4.2
   - Amplification of accidental torsion  
     ASCE 7 12.8.4.3
5. Check diaphragm flexibility  
   ASCE 7 12.3, SDPWS 4.2.5.2 (3)
6. Verify diaphragm length, L’  
   SDPWS 4.2.5.2(4)
7. Assume or verify redundancy  
   ASCE 7 12.3.4

For resistance to Wind loads:

1. ASCE 7-16 Section 27.4.5-Diaphragm flexibility-The structural analysis shall consider the stiffness of diaphragms and vertical elements of the MWFRS
2. Recommend Following SDPWS 4.2.5.2 (not required by code). Considered good engineering practice.
3. Show that the resulting drift at the edges of the structure can be tolerated.
Example Plan

Chord continuous at corridor walls

Walls receive shear forces from rigid body rotation (torsion).

Walls at grid lines 1 & 4 have no stiffness

Chord fixity at corridor walls

Chord continuous at corridor walls

Chord fixity at corridor walls

Shear panels or blocking over entire wall lines if framing is in this direction

Additional units as occurs

Longitudinal

Transverse

North

Page 5
Ledgered Roof Joist  Hangered Roof Joist  Alt.-Top Chord Bearing Truss

(Platform framing not shown)

Typical Exterior Wall Sections
Floor or roof sheathing

Blocking or continuous rim joist

Continuous rim joist, beam, special truss or double top plate can be used as strut / collector or chord.

Splice at all joints in boundary element

Trusses, top chord bearing with blocking between (shown)

Opening

Header

Bm./Strut

Bm.

Strut

Trusses, top chord bearing with blocking between (shown)

Platform framing

Semi-balloon framing

Typical Exterior Wall Sections at Grid Lines A and B
**Platform Framing at Corridor**

- Header collector
- SW
- Typical shear panel

**Semi-balloon Framing at Corridor**

- Header collector
- SW
- Blocking between trusses
- Strut/collector
- Optional struts between SW’s

**Section at Corridor**

- Corridor roof joists
- Roof truss
- Blocking
- Optional top flange hanger
- Roof sht’g.

**Section at Corridor**

(Similar to example)

**Typical Wall Sections at Corridor Walls**

- Alt.-extend WSP full hgt.
- eliminate Shear panels
Preliminary Assumptions

1. LFRS Layout - efficient / marginal / scary
2. Diaphragm Flexibility
3. Redundancy
4. Accidental torsion
5. Torsional Irregularities

Options: Pros and Cons of Assumptions

• Assume conservative values upfront:
  1. Design is conservative, leave as is
  2. Design is conservative, revise to reduce forces

• Assume minimum values upfront:
  1. Design meets demand, leave as is
  2. Design meets demand but is marginal, change to improve performance
  3. Design unconservative, revise design to meet demand
2. Diaphragm Flexibility-12.3.1

NEHRP Seismic Design Brief 10 and ASCE 7-16 commentary-”The diaphragms in most buildings braced by wood light-frame shear walls are semi-rigid”.

- The diaphragm stiffness relative to the stiffness of the supporting vertical seismic force-resisting system is important to define.

ASCE 7, C12.3.1.1 Flexible Diaphragm Condition is allowed provided:
- All light framed construction
- 1 ½” or less of non-structural concrete topping
- Each line of LFRS is less than or equal to allowable story drift

Compliance with story drift limits along each line of shearwalls is intended as an indicator that the shearwalls are substantial enough to share load on a tributary area basis and do not require torsional force redistribution.
3. **Redundancy**
   Assume $\rho = 1.3$ unless conditions of ASCE 7-16 Section 12.3.4.2 are met to justify $\rho = 1.0$.

4. **Accidental Torsion** 12.8.4.2

Accidental torsion shall be applied to all structures for determination if a horizontal irregularity exists as specified in Table 12.3-1.

- Applies to non-flexible diaphragms
- Design shall include the inherent torsional moment ($Mt$) plus the accidental torsional moments ($Mta$)
- Accidental torsional moment ($Mta$) = assumed displacement of the C.M. equal to 5% of the dimension of the structure perpendicular to the direction of the applied forces.
Accidental torsion moments \((M_{ta})\) need not be included when determining:

- Seismic forces \(E\) in the design of the structure, or
- Determination of the design story drift in Sections 12.8.6, 12.9.1.2, Chapter 16, or drift limits of Section 12.12.1.

**Exceptions:**

- Structures assigned to Seismic Category B with Type 1b horizontal structural irregularity.
- Structures assigned to Seismic Category C, D, E, and F with Type 1a or Type 1b horizontal structural irregularity.

Structures assigned to SDC C, D, E, or F, where Type 1a or 1b torsional irregularity shall have the effects accounted for by multiplying \(M_{ta}\) at each level by a torsional amplification factor \((A_x)\).

For our example, \(C.M = C.R.\) No inherent torsion. Only accidental torsion is applied.
Assume:

Plan A

\( A_X = 1.0 \)

\( \rho = 1.0 \)

Plan B

Assume:

\( A_X = 1.0 \)

\( \rho = 1.0 \)

Plan C

Assume:

\( A_X > 1.0 \)

\( \rho = 1.3 \)

Plan D-Example

Assume:

\( A_X > 1.0 \)

\( \rho = 1.3 \)

\( A_X = \text{Amplification of accidental torsion if torsional irregularity exists} \)

\( \rho = \text{Redundancy} \)
Diaphragm Design
- Calculate lateral (seismic) force
  - \( \rho = 1.3 \), \( Ax = 1.25 \)
- Shear wall design
  - Based on wall length
  - \( \rho = 1.3 \), \( Ax = 1.25 \)

Lateral load distribution

Assuming rigid diaphragm

Verify Rho

Story Drift

Diaphragm Flexibility

Verify Strength

Table 12.3-1

Shear wall design

- SW construction
  - Max. demand
  - \( \rho = 1.0 \), \( Ax = 1.0 \)

Increase Diaph./ SW Stiffness?

Establish nominal SW stiffness (D+E)

Use for remaining checks

Diaphragm construction based on max. demand (Sht’g. / nailing)

- Chord splice loc’s./slip
- Max. diaphragm chord forces

Flow Chart based on assumptions made. \( \rho \) and \( Ax \) as noted

Legend
- Engineering judgement required
- SW & Diaph. Design
- Determine flexibility, Drift
- Determine Tors. Irreg., \( \rho, Ax \)

ASD Design

STR Design

Example Plan

Longitudinal Design

Transverse

Step 4
Page 28

Diaphragm Design

(i.e. Diaph. or MSFRS Forces)

Diaphragm Inertial Design Force Fpx or MSFRS

Diaph. Inertial Design Force Fpx or MSFRS

Verify Final Diaph. Design

Verify Drift and Torsional Irreg.

Verify Rho

\( \rho \) and \( Ax \) not relevant

Lateral load based on wall length

Based on experience

\( \rho = 1.0 \), \( Ax = 1.25 \)

Step 1
Page 6

\( \rho = 1.0 \), \( Ax = 1.0 \)

Step 2
Page 7

\( \rho = 1.3, Ax = 1.25 \)

Step 3
Page 12

\( \rho = 1.0 \), \( Ax = 1.0 \)

Step 5
Page 39, 41

Diaphragm Flexibility

Diaphragm Flexibility

Verify Torsional Irregularity

Verify accidental ecc. ampl., \( Ax \)

Verify Rho

\( \rho = 1.0 \), \( Ax = 1.0 \)

Step 6
Page 44

Step 7
Page 51

Step 8
Page 54

Step 9
Page 54

Step 10
Page 58

Step 11
Page 60

Step 12-Page 61

\( \rho = 1.0, Ax = 1.0 \)

\( \rho = 1.3, Ax = 1.0 \)

\( \rho = 1.0, Ax = 1.0 \)

\( \rho = 1.3, Ax = 1.0 \)
Rigid Diaphragm Analysis

**Longitudinal Loading**

<table>
<thead>
<tr>
<th>Grid Line</th>
<th>kx</th>
<th>Ky</th>
<th>dx</th>
<th>dy</th>
<th>kf</th>
<th>Fv</th>
<th>FT</th>
<th>Fv+FT</th>
<th>Rho</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>43.54</td>
<td>3</td>
<td>130.63</td>
<td>391.89</td>
<td>8874.0</td>
<td>-527.1</td>
<td>8346.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>43.54</td>
<td>3</td>
<td>130.63</td>
<td>391.89</td>
<td>8874.0</td>
<td>557.1</td>
<td>9401.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>25.14</td>
<td>20</td>
<td>502.74</td>
<td>10054.73</td>
<td>2028.5</td>
<td>2028.5</td>
<td>0.0087</td>
<td>17748.0</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>25.14</td>
<td>20</td>
<td>502.74</td>
<td>10054.73</td>
<td>2028.5</td>
<td>2028.5</td>
<td>-0.081</td>
<td>17748.0</td>
<td></td>
</tr>
<tr>
<td>I</td>
<td>87.09</td>
<td>50.27</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>T=8430.3</td>
</tr>
</tbody>
</table>

**Transverse Loading**

<table>
<thead>
<tr>
<th>Grid Line</th>
<th>kx</th>
<th>Ky</th>
<th>dx</th>
<th>dy</th>
<th>kf</th>
<th>Fv</th>
<th>FT</th>
<th>Fv+FT</th>
<th>Rho</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>43.54</td>
<td>3</td>
<td>130.63</td>
<td>391.89</td>
<td>8874.0</td>
<td>277.4</td>
<td>277.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>43.54</td>
<td>3</td>
<td>130.63</td>
<td>391.89</td>
<td>8874.0</td>
<td>-277.4</td>
<td>-277.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>25.14</td>
<td>20</td>
<td>502.74</td>
<td>10054.73</td>
<td>2028.5</td>
<td>2028.5</td>
<td>0.399</td>
<td>17748.0</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>25.14</td>
<td>20</td>
<td>502.74</td>
<td>10054.73</td>
<td>2028.5</td>
<td>2028.5</td>
<td>0.311</td>
<td>17748.0</td>
<td></td>
</tr>
<tr>
<td>I</td>
<td>87.09</td>
<td>50.27</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>T=44370</td>
</tr>
</tbody>
</table>

Use this load combination for defining Nominal Stiffness values, $K_{eff}$. Then use these $K_{eff}$ values for all other analyses.

**Expected Dead + Seismic $D+Q_{E}$ (other terms if "expected" gravity loads as per ASCE 41-13, equation 7-3) $\rho=1.0, A_x=1.0$**

<table>
<thead>
<tr>
<th>Grid Line</th>
<th>SW</th>
<th>Ga</th>
<th>Rho</th>
<th>V on wall</th>
<th>v</th>
<th>T</th>
<th>C</th>
<th>$\delta_{sw}$</th>
<th>Crush.</th>
<th>Shrink</th>
<th>$\delta_{y}$</th>
<th>$\delta_{z}$</th>
<th>$\delta_{l}$</th>
<th>$\delta_{sw}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A &amp; B</td>
<td>37</td>
<td>1.0</td>
<td>87308.0</td>
<td>913.5</td>
<td>6390.85</td>
<td>13760.85</td>
<td>0.154</td>
<td>556.36</td>
<td>0.056</td>
<td>0.019</td>
<td>0.022</td>
<td>0.247</td>
<td>0.313</td>
<td>0.581</td>
</tr>
</tbody>
</table>

**Nominal wall stiffness**

$$
\delta_{sw}=F/K
$$

Calculate nominal stiffness by 3-term or 4-term deflection equation. $K=F/\delta$

**Diaphragm Deflection (STR) Right Cantilever**

<table>
<thead>
<tr>
<th>Splice Forces (In.)</th>
<th>L, slip</th>
<th>v unif.</th>
<th>v conc.</th>
<th>Ga</th>
<th>L'</th>
<th>W'</th>
<th>$\delta_{Diaph}$</th>
<th>$\delta_{total}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$F_{15}$</td>
<td>15</td>
<td>15.62</td>
<td>232.94</td>
<td>0.00</td>
<td>25.0</td>
<td>35.00</td>
<td>40.00</td>
<td>0.265</td>
</tr>
<tr>
<td>$F_{23}$</td>
<td>23</td>
<td>23.53</td>
<td>233.53</td>
<td>0.00</td>
<td>25.0</td>
<td>35.00</td>
<td>40.00</td>
<td>0.265</td>
</tr>
<tr>
<td>$F_{33}$</td>
<td>33</td>
<td>33.54</td>
<td>33.54</td>
<td>0.00</td>
<td>25.0</td>
<td>35.00</td>
<td>40.00</td>
<td>0.265</td>
</tr>
</tbody>
</table>

**Nails Req’d**

- 4.70
- 5.13
- 15.62

**Use Nails**

- 8
- 16
- 24

**Slip**

- 0.023
- 0.032
- 0.025

- EA=28050000, 2x6

- Includes effects of sw’s along chord line

- 8346.9
- 9401.1

- 235.72
- 2.19
- 16.03

- 235.72
- 231.34

- 111.4
- 0.005

- 8
- 16
- 24

Diaphragm Deflection (STR) Left Cantilever
Let’s Take a 15 Minute Break
Part 2-Design Example:

- Calculation of seismic forces and distribution
- Preliminary shear wall design
- Nominal shear wall stiffness
- Verification of shear wall design
- Diaphragm design
Assumptions Made: Page 8

- Diaphragm is rigid or semi-rigid in both directions
- Torsional irregularity Type 1a occurs in longitudinal direction, but not transverse, $A_x=1.25$.
- Horizontal irregularity Type 1b does not occur in either direction.
- No redundancy in both directions, $\rho=1.3$

Force Distribution to Shear Walls
Seismic- $\rho=1.3$, $A_x=1.25$
Basic Project Information

- Structure-Occupancy B, Office, Construction Type VB-Light framing:
  - Wall height=10’-Single story
  - L=76’, total length
  - W’=40’, width/depth
  - L’=35’, cantilever length (max.)
  - 6’ corridor width

- Roof DL (seismic)= 35.0 psf including wall/ partitions

- Wall DL = 13.0 psf (in-plane)

- Roof snow load = 25 psf > required roof LL=20 psf

- Roof (lateral)= roof + wall H/2 plus parapet
Lateral Load Calculations - Seismic

Calculate Seismic Forces - ASCE 7-16 Section 12.8 Equivalent Lateral Force Procedure, $F_x$

- Risk category II
- Importance factor, $I_e = 1.0$

Using USGS Seismic Design Map-Tool, 2015 NEHRP, 2016 ASCE 7-16:
  - Location - Tacoma, Washington
  - Site class D - stiff soil
    - $S_s = 1.355 \, g$, $S_1 = 0.468 \, g$
    - $S_{DS} = 1.084 \, g$, $S_{D1} = 0.571 \, g$
  - Seismic Design Category (SDC) = D

ASCE 7-16 Table 12.2-1, Bearing Wall System, A(15) light framed wood walls w/ WSP sheathing. $R = 6.5$, $\Omega_0 = 3$, $Cd = 4$, Maximum height for shear wall system = 65'.
Seismic Force Calculation results:

\[ C_s = \frac{S_{DS}}{R \left(\frac{I_e}{R}\right)} = 0.167 \text{ short period controls} \]

Basic lateral force MSFRS

\[ V = C_s W = 0.167(35)(76)(40) = 17769 \text{ lbs. STR} \]

\[ 7769(0.7) = 12438 \text{ lbs. ASD} \]

Rigid Diaphragm Analysis - \( \rho=1.3, \text{Ax}=1.25 \)

Initial wall stiffness will be based on wall length.

The final wall Nominal stiffness’s are used for all final analysis checks.

RDA Equations

\[ T = V(e)(Ax)(\rho) \text{ ft. lbs.} \]

\[ F_T = T \frac{kd}{\sum kd_x^2 + kd_y^2} \]

\[ F_{sw} = F_V + F_T \]

\[ F_V = F_x \frac{k}{\sum k} \]
Preliminary Shear Wall Design
Analysis Flow

Longitudinal Design

Translation
Rotation
Diaphragm deflection

Displacements
effected by wall
stiffness

Example Plan

- Drift
- Torsional Irreg.

Lateral load
distribution

Diaphragm Flexibility

Shear wall
design

ρ=1.3  Ax=1.25

Verify Strength

ρ=1.3  Ax=1.25

SW construction
Max. demand

ρ=1.0  Ax=1.0

Establish nominal
SW stiffness (D+E)

Use for remaining checks

ρ=1.3  Ax=1.25

Re-distribution
Lateral loads

Legend

Engineering judgement required

SW & Diaph. Design

Determine flexibility, Drift

Determine Tors. Irreg., ρ, Ax

ASD  Design

STR  Design

Design Shear Walls

Seismic- ρ=1.3, Ax=1.25

Page 12
Preliminary Shear wall Design (ASD): ASCE 7-16 Section 2.3.6-Seismic

- Determine shear wall chord properties:
  
  2x6 DF-L no. 1 framing used throughout.
  E = 1,700,000 psi, wall studs @ 16” o.c.

  EA = 42,075,000 lbs. at grid line A,B = (3)2x6 D.F., KD, studs @16” o.c. boundary elem.

  EA = 28,050,000 lbs. at grid line 2,3 = (2)2x6 D.F., KD, studs @16” o.c. boundary elem.

- Check aspect ratio, If A.R.>2:1, reduction is required per SDPWS Section 4.3.4.

- Hold downs = pre-manufactured bucket style with screw attachments Same H.D used at all SW locations
  
  o Manuf. table gives Allowable ASD hold down capacity and displacement at capacity (ESR Reports)

  o Displacement at hold down = \( \frac{T(\text{Allow.Displ})}{\text{ASD Capacity}} \)

  o Min. wood attachment thickness = 3” per table
Load Combinations (ASD):

$LC_8 = 1.152D + 0.7\rho Q_E$

$LC_9 = 1.114D + 0.525\rho Q_E + 0.75S$

$LC_{10} = 0.448D + 0.7\rho Q_E$

Full dead loads shown, 1.0D
Based on initial Relative Wall Stiffness’s, ASD, ρ=1.3, Ax=1.25 –by wall lengths

Longitudinal Direction, e=4.75’, T = 76806.5 ft. lbs.

<table>
<thead>
<tr>
<th>SW Line</th>
<th>Ky k/in</th>
<th>Kx k/in</th>
<th>Dx Ft.</th>
<th>Dy Ft.</th>
<th>Kd</th>
<th>Kd²</th>
<th>Fv Lbs.</th>
<th>Ft Lbs.</th>
<th>Total Lbs.</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>-------</td>
<td>16</td>
<td>-------</td>
<td>20</td>
<td>320</td>
<td>6400</td>
<td>0</td>
<td>1842.4</td>
<td>1842.4</td>
</tr>
<tr>
<td>B</td>
<td>-------</td>
<td>16</td>
<td>-------</td>
<td>20</td>
<td>320</td>
<td>6400</td>
<td>0</td>
<td>-1842.4</td>
<td>-1842.4</td>
</tr>
<tr>
<td>2</td>
<td>30</td>
<td>-------</td>
<td>3</td>
<td>-------</td>
<td>90</td>
<td>270</td>
<td>8084.9</td>
<td>-518.2</td>
<td>7566.7</td>
</tr>
<tr>
<td>3</td>
<td>30</td>
<td>-------</td>
<td>3</td>
<td>-------</td>
<td>90</td>
<td>270</td>
<td>8084.9</td>
<td>518.2</td>
<td>8603.1</td>
</tr>
</tbody>
</table>

ΣKy=60  ΣKx=32  J=16169.8

Transverse Direction, e=2.5’, T = 40424.5 ft. lbs.

<table>
<thead>
<tr>
<th>SW Line</th>
<th>Ky k/in</th>
<th>Kx k/in</th>
<th>Dx Ft.</th>
<th>Dy Ft.</th>
<th>Kd</th>
<th>Kd²</th>
<th>Fv Lbs.</th>
<th>Ft Lbs.</th>
<th>Total Lbs.</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>-------</td>
<td>16</td>
<td>-------</td>
<td>20</td>
<td>320</td>
<td>6400</td>
<td>8084.9</td>
<td>969.7</td>
<td>9054.6</td>
</tr>
<tr>
<td>B</td>
<td>-------</td>
<td>16</td>
<td>-------</td>
<td>20</td>
<td>320</td>
<td>6400</td>
<td>8084.9</td>
<td>-969.7</td>
<td>7115.2</td>
</tr>
<tr>
<td>2</td>
<td>30</td>
<td>-------</td>
<td>3</td>
<td>-------</td>
<td>90</td>
<td>270</td>
<td>0</td>
<td>-272.7</td>
<td>-272.7</td>
</tr>
<tr>
<td>3</td>
<td>30</td>
<td>-------</td>
<td>3</td>
<td>-------</td>
<td>90</td>
<td>270</td>
<td>0</td>
<td>272.7</td>
<td>272.7</td>
</tr>
</tbody>
</table>

ΣKy=60  ΣKx=32  J=16169.8

Page 14
Preliminary Shear Wall Design—Distribution based on wall lengths

Adding Gravity Loads to Shear Walls

- Can have a significant impact on horizontal shear wall deflections and stiffness.
- Results in wall stiffness \((K = \frac{F}{\delta})\) relationships which are non-linear with the horizontal loading applied.

**ASD Load Combination:** \(\text{LC10} = 0.448D + 0.7\rho Q_E\)
\(\rho = 1.3, A_x = 1.25\)

---

**Transverse Loading**

Shear Walls Along Grid Lines A and B

**Longitudinal Loading**

Shear Walls Along Grid Lines 2 and 3
Calculated results by wall length
\[ V_{SW\ A,B} = 565.9 \text{ plf} \]
\[ V_{SW\ 2,3} = 286.8 \text{ plf} \]

Shear Wall Capacity-Wood Based Panels

**Blocked**

Table 4.3A  Nominal Unit Shear Capacities for Wood-Framed Shear Walls

<table>
<thead>
<tr>
<th>Wood Based Panels(^4)</th>
<th>Sheathing Material</th>
<th>Minimum Nominal Panel Thickness (in.)</th>
<th>Minimum Fastener Penetration In Framing Member or Blocking (in.)</th>
<th>Fastener Type &amp; Size (common or Galvanized box)</th>
<th>Panel Edge Fastener Spacing (in.)</th>
<th>Panel Edge Fastener Spacing (in.)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>A Seismic</td>
<td></td>
<td>B Wind</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Panel Edge Fastener Spacing (in.)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>6</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(plf)</td>
<td>(plf)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(kips/in.)</td>
<td>(kips/in.)</td>
</tr>
<tr>
<td>Wood (^4,5) Structural Panels-Sheathing</td>
<td>15/32</td>
<td>1-3/8</td>
<td>8d</td>
<td>Vs Galvanized Ply</td>
<td>520 13 10</td>
<td>Vs Galvanized Ply</td>
</tr>
<tr>
<td>15/32</td>
<td>19/32</td>
<td>1-1/2</td>
<td>10d</td>
<td></td>
<td>620 22 14</td>
<td>920 30 17</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>680 19 13</td>
<td>1020 26 161330 33 181740 48 28</td>
</tr>
</tbody>
</table>

Increasing stiffness to account for drift, torsion, etc. requires engineering judgement.

**SW\(_{A,B}\):** Use 15/32” OSB w/ 10d@3” o.c., \(v_s = (1200)/2 = 600 \text{ plf, Ga} = 37\)

**SW\(_{2,3}\):** Use 15/32” OSB w/ 10d@4” o.c., \(v_s = (920)/2 = 460 \text{ plf, Ga} = 30\)

Maximum tension force, \(T = 4570 \text{ lbs. - Use HD} = 4565 \text{ lbs. (0.1\% under-check later)}\)

ASD, \(\Delta a = 0.114” @ \text{capacity}\)

STR, \(\Delta a = 0.154” @ \text{capacity}\)
Combining RDA & shear wall deflection calculations is problematic due to non-linearities.

- In RDA, distribution of load to the walls depends on relative stiffness of walls.
- Since deflection is “non-linear”.... the stiffness can vary with the loading, even when using 3-term deflection equation.

Whenever changing:
- Load combinations
- Vertical or lateral loads,
- Direction of loading
- Redundancy, or
- Accidental torsion

...it can effect the distribution of loads to the shear walls which will effect the shear wall deflections. This can lead to a different set of stiffness values that may not be consistent.

Requires an Iterative search for the point of convergence, which is not practical for multi-story structures.

Sources of non-linearities:
- Hold-down slip at uplift (e.g. shrinkage gap)
- Hold-down system tension and elongation
- Compression crushing. Non-linear in NDS
- Shrinkage
- 4-term deflection equation
Load for Shear Wall Deflection & Stiffness Calculations

- 3-term equation is a linear simplification of the 4-term equation, calibrated to match the applied load at 1.4 ASD.
- This simplification removes the non-linear behavior of $e_n$.
- Similar approach can be used to remove non-linear effects of $\Delta a$ by calculating the wall stiffness at strength level capacity of the wall, not the applied load.

![Example 3-Term vs 4-Term Shear Wall Deflection](image)

**Method allows having only one set of nominal stiffness values.**
Objective: Use a single rational vertical and lateral load combination to calculate deflections and **Nominal** shear wall stiffness at maximum wall capacity.

A simplification of gravity loads are applied similar to nonlinear procedures in ASCE 41-13 in ASCE 41-13 Eq. 7-3.

Gravity:

For this *Single-Story* Example we used $1.0D$, using $\rho = 1.0$ and $Ax = 1.0$. Vertical seismic loading not included. ($E_V = 0.2S_{dsD}$)

For multi-story buildings, suggest $1.0D + \alpha L$ as in ASCE 7-16 Section 16.3.2- Nonlinear analysis

Results in single vertical loading condition to use when calculating shear wall deflections and nominal shear wall stiffnesses.

Proposing:

1. Stiffness calculated using 3-term eq. and LC $1.0D + Qe$, with $\rho = 1.0$ and $Ax = 1.0$.

2. Use stiffness calculated at 100% Maximum Seismic Design Capacity of the Wall for all Load Combinations and Drift Checks from RDA using 3 term equation.

3. Use nominal stiffness for all other analysis checks, calculating wall deflection, $\delta_{SW} = \frac{F}{K}$

4. Maximum wall capacity $= \max.$ allow. Shear (nailing) or HD capacity whichever is less.
Nominal Shear Wall Stiffness’s (STR) $\rho=1.0$, $A_x=1.0$

Load Combination: $1.0D + Q_E$

<table>
<thead>
<tr>
<th>Grid Line</th>
<th>Ga</th>
<th>V on wall</th>
<th>v</th>
<th>T</th>
<th>C</th>
<th>$\Delta_a$</th>
<th>$F_c$</th>
<th>Crush.</th>
<th>Shrink</th>
<th>$\delta_B$</th>
<th>$\delta_S$</th>
<th>$\delta_{Rot}$</th>
<th>$\delta_{SW}$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>A</strong></td>
<td>37</td>
<td>7308.0</td>
<td>913.5</td>
<td>6391</td>
<td>13770</td>
<td>0.154</td>
<td>556.36</td>
<td>0.056</td>
<td>0.019</td>
<td>0.022</td>
<td>0.247</td>
<td>0.313</td>
<td>0.581</td>
</tr>
<tr>
<td><strong>B</strong></td>
<td>37</td>
<td>7308.0</td>
<td>913.5</td>
<td>6391</td>
<td>13770</td>
<td>0.154</td>
<td>556.36</td>
<td>0.056</td>
<td>0.019</td>
<td>0.022</td>
<td>0.247</td>
<td>0.313</td>
<td>0.581</td>
</tr>
</tbody>
</table>

Calculate Stiffness of Walls on 2 & 3 using LRFD Loading

<table>
<thead>
<tr>
<th>Grid Line</th>
<th>Ga</th>
<th>V on wall</th>
<th>v</th>
<th>T</th>
<th>C</th>
<th>$\Delta_a$</th>
<th>$F_c$</th>
<th>Crush.</th>
<th>Shrink</th>
<th>$\delta_B$</th>
<th>$\delta_S$</th>
<th>$\delta_{Rot}$</th>
<th>$\delta_{SW}$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>2</strong></td>
<td>30</td>
<td>7022.0</td>
<td>702.2</td>
<td>6391</td>
<td>8341</td>
<td>0.154</td>
<td>505.50</td>
<td>0.045</td>
<td>0.019</td>
<td>0.020</td>
<td>0.234</td>
<td>0.230</td>
<td>0.484</td>
</tr>
<tr>
<td><strong>3</strong></td>
<td>30</td>
<td>7022.0</td>
<td>702.2</td>
<td>6391</td>
<td>8341</td>
<td>0.154</td>
<td>505.50</td>
<td>0.045</td>
<td>0.019</td>
<td>0.020</td>
<td>0.234</td>
<td>0.230</td>
<td>0.484</td>
</tr>
</tbody>
</table>

Wall Capacity based on hold down

Max. capacity check (STR):

Shear$_{A,B}=0.8(1200)(8)=7680$ lbs.
Shear$_{2,3}=0.8(920)(10)=7360$ lbs.

H.D.$_{A,B,2,3}=6391$ lbs.(STR),
$\Delta a=0.154''$

Set tension force=H.D. cap. and solve for allowable V.

V allow. $A,B=7308$ lbs. controls
V allow. 2,3= 7022 lbs. controls
Verification of Wall Strength (ASD)
Based on selected wall construction and Nominal Wall Stiffness

### Longitudinal Direction, e=4.75’, T = 76806.5 ft. lbs. \( \rho=1.3, \text{Ax}=1.25 \)

<table>
<thead>
<tr>
<th>SW Line</th>
<th>Ky k/in</th>
<th>Kx k/in</th>
<th>Dx Ft.</th>
<th>Dy Ft.</th>
<th>Kd</th>
<th>Kd²</th>
<th>Fv Lbs.</th>
<th>Ft Lbs.</th>
<th>Total Lbs.</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>-------</td>
<td>25.14</td>
<td>-------</td>
<td>20</td>
<td>502.8</td>
<td>10056</td>
<td>0</td>
<td>1848.1</td>
<td>1848.1</td>
</tr>
<tr>
<td>B</td>
<td>-------</td>
<td>25.14</td>
<td>-------</td>
<td>20</td>
<td>502.8</td>
<td>10056</td>
<td>0</td>
<td>-1848.1</td>
<td>-1848.1</td>
</tr>
<tr>
<td>2</td>
<td>43.54</td>
<td>-------</td>
<td>3</td>
<td>-------</td>
<td>130.62</td>
<td>391.86</td>
<td>8084.9</td>
<td>-480.1</td>
<td>7604.8</td>
</tr>
<tr>
<td>3</td>
<td>43.54</td>
<td>-------</td>
<td>3</td>
<td>-------</td>
<td>130.62</td>
<td>391.86</td>
<td>8084.9</td>
<td>480.1</td>
<td>8565.0</td>
</tr>
</tbody>
</table>

\[ \Sigma\text{Ky}=87.08 \quad \Sigma\text{Kx}=50.28 \]

\[ J=20895.72 \]

### Transverse Direction – e=2.5’, T = 40424.5 ft. lbs. \( \rho=1.3, \text{Ax}=1.25 \)

<table>
<thead>
<tr>
<th>SW</th>
<th>Ky k/in</th>
<th>Kx k/in</th>
<th>Dx Ft.</th>
<th>Dy Ft.</th>
<th>Kd</th>
<th>Kd²</th>
<th>Fv Lbs.</th>
<th>Ft Lbs.</th>
<th>Total Lbs.</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>-------</td>
<td>25.14</td>
<td>-------</td>
<td>20</td>
<td>502.8</td>
<td>10056</td>
<td>8084.9</td>
<td>972.7</td>
<td>9057.6</td>
</tr>
<tr>
<td>B</td>
<td>-------</td>
<td>25.14</td>
<td>-------</td>
<td>20</td>
<td>502.8</td>
<td>10056</td>
<td>8084.9</td>
<td>-972.7</td>
<td>7112.2</td>
</tr>
<tr>
<td>2</td>
<td>43.54</td>
<td>-------</td>
<td>3</td>
<td>-------</td>
<td>130.62</td>
<td>391.86</td>
<td>0</td>
<td>252.7</td>
<td>252.7</td>
</tr>
<tr>
<td>3</td>
<td>43.54</td>
<td>-------</td>
<td>3</td>
<td>-------</td>
<td>130.62</td>
<td>391.86</td>
<td>0</td>
<td>-252.7</td>
<td>-252.7</td>
</tr>
</tbody>
</table>

\[ \Sigma\text{Ky}=87.08 \quad \Sigma\text{Kx}=50.28 \]

\[ J=20895.72 \]

Nominal stiffness values used
ASD Load Combination: \( LC10 \ 0.448D + 0.7\rho Q_E \)
\( \rho = 1.3, \ A_x = 1.25 \)

Shear Wall Grid A and B

Shear Walls Along Grid Lines A and B
Transverse Loading - Nominal Strength

\[ \text{vs} = \frac{4528.8}{8} = 566.1 \ \text{plf} < 600 \ \text{plf allowed} \quad \therefore \text{o.k.} \]

\[ T = 4579.2 \ \text{lbs.} \approx 4565 \ \text{lbs. allowed, 0.3\% over} \quad \therefore \text{hold down o.k. –check later} \]

Shear Wall Grid 3

Shear Walls Along Grid Lines 2 and 3
Longitudinal Loading - Nominal Strength

\[ \text{vs} = \frac{2855.3}{10} = 285.5 \ \text{plf.} < 460 \ \text{plf allowed} \quad \therefore \text{o.k.} \]

\[ T = 2557.1 \ \text{lbs.} < 4565 \ \text{lbs. allowed} \quad \therefore \text{hold down o.k.} \]
SW Design Checks

• A.R. = 1.25:1 < 3.5:1 Since the A.R. does not exceed 2:1, no reduction is required per SDPWS Section 4.3.4.

• Wall shear: \( V_{sw\ A,\ B} = \frac{V_{wall\ line}}{2} \) Lbs. each wall segment, \( v_s = \frac{V_{wall}}{L_{wall}} \) plf

• Check anchor Tension force \( \leq \) Allowable. \( \therefore \) okay?

Calculate actual anchor slip, \( \text{slip} = \frac{\text{Max slip at capacity (T)}}{\text{Strength capacity}} \)

• Sill plate shrinkage:

Dimensional change = 0.0025 inches per inch of cross-sectional dimension for every 1 percent change in MC.

Shrinkage = \((0.0025)(D)(\text{Starting MC} - \text{End MC})\)

Where: \( D \) is the dimension of the member in the direction under consideration, in this case the thickness of a wall plate.
• Sill plate crushing:

  $F_{c\perp}'$ values in AWC 2018 NDS section 4.2.6 are based on 0.04” deformation/crushing limit for a steel plate bearing on wood.

  Adjustment factor = 1.75 for parallel to perpendicular grain wood to wood contact.

  Boundary values for bearing perpendicular to grain stresses and crushing-D.F.

  $F_{c\perp0.02} = 0.73F_{c\perp} = 0.73(625) = 456.3$ psi

  $F_{c\perp0.04} = F_{c\perp} = 625$ psi

  When $f_{c\perp} \leq F_{c\perp0.02}$

   \[
   \Delta_{crush} = 0.02 \left( \frac{f_{c\perp}}{F_{c\perp0.02}} \right)
   \]

  When $F_{c\perp0.02} \leq f_{c\perp} \leq F_{c\perp0.04}$

   \[
   \Delta_{crush} = 0.04 - 0.02 \left( \frac{1 - f_{c\perp}}{F_{c\perp0.04}} \right) \left( \frac{1}{0.27} \right)
   \]

  When $f_{c\perp} > F_{c\perp0.04}$

   \[
   \Delta_{crush} = 0.04 \left( \frac{f_{c\perp}}{F_{c\perp0.04}} \right)^3
   \]

  If $f_{c\perp} = \left( \frac{C}{A_{chord}} \right) < 456.3$ psi, Crushing = 0.02$\left( \frac{f_{c\perp}}{456.3} \right)$(1.75)
Shear Wall Rotation
Proposed nomenclature of next edition of SDPWS

Current term = \( \frac{h\Delta_a}{b} \)

Wall rotation:
- Hold down slip/elongation
- Sole plate shrinkage
- Sole plate crushing

\( SW_{rot} = \frac{h\Delta_a}{b_{eff}} \) or \( SW_{rot} = \frac{h\Delta_{a\,eff}}{b} \)

Where
- \( h \)=wall height (ft.)
- \( b_{eff} \)=Wall rotation arm (ft.)
- \( b \)=Wall width (ft.)

\( \Delta_{a\,eff} \)=Sum of vertical displacements at anchorage (in.)

\( \Delta_a \)=Sum of vertical displacements at tension edge of wall

\( \Delta_a = 0.25'' \)

\( \Delta_{a\,eff} = \frac{0.25(8)}{7.5} = 0.267'' \)

\( SW_{rot} = \frac{10(0.25)}{7.5} = 0.333'' \)

\( SW_{rot} = \frac{10(0.267)}{8} = 0.333'' \)
• Nominal Shear Wall Deflection-calculated using:

Traditional 4 term deflection equation

$$\delta_{SW} = \frac{8vh^3}{EAb} + \frac{vh}{G_at_v} + 0.75he + \frac{h\Delta_a}{b_{eff}} \quad \text{C4.3.2-1}$$

SDPWS combines

Bending

Nail slip

Rod elongation (Wall rotation)

Shear

SDPWS 3 term deflection equation

$$\delta_{SW} = \frac{8vh^3}{EAb} + \frac{vh}{1000Ga} + \frac{h\Delta_a}{b_{eff}} \quad 4.3-1 \text{ Alt.}$$

Bending

Vertical elongation

- Device elongation
- Rod elongation

Apparent shear stiffness

- Nail slip
- Panel shear deformation

Calculate deflection $$\delta_{swA,B} = \frac{F}{k}$$ to be used after

Nominal stiffness has been established

Where

- v=wall unit shear (plf)
- h=wall height (ft.)
- b_{eff}=Wall rotation width (ft.)
- b=Wall width (ft.)
- Ga=apparent shear stiffness (k/in.)
- $$\Delta_a$$=Sum of vertical displacements at anchorage and boundary members (in.)
Diaphragm Design Forces: MSFRS or $F_{px}$
Diaphragm Design

Max. diaphragm chord forces

ρ = 1.0, Ax = 1.25
ρ = 1.3, Ax = 1.25

Analysis Flow

Longitudinal Design

Example Plan

Diaphragm construction based on max. demand (Sht’g. / nailing)

Chord splice loc’s./slip

Step 4

Diaphragm Design

ρ = 1.0, Fpx, or
ρ = 1.3, Ax = 1.25

Step 5

Diaphragm Flexibility

Design Diaphragm

Seismic- ρ = 1.0, Ax = 1.25 or
ρ = 1.3, Ax = 1.25

Legend

- Engineering judgement required
- SW & Diaph. Design
- Determine flexibility, Drift
- Determine Tors. Irreg., ρ, Ax

ASD Design
STR Design
Verification of Compliance with SDPWS 4.2.5.2-Open Front Structures:

For resistance to seismic loads, wood-frame diaphragms in open front structures shall comply with all of the following requirements:

1. The diaphragm conforms to: WSP-L’/W’ ratio ≤ 1.5:1  A.R. = 0.875 OK

2. For open-front-structures that are also torsionally irregular L’/W’ ratio shall not exceed 1:1 for structures one story in height.  A.R. = 0.875 OK

3. The drift at edges shall not exceed the ASCE 7 allowable story drift when subject to seismic design forces including torsion, and accidental torsion (Deflection-strength level amplified by Cd.).  To be verified later

4. For loading parallel to open side: Model as semi-rigid or rigid  Assumed to be rigid both directions.  To be verified later

5. The diaphragm length, L’, (normal to the open side) does not exceed 35 feet.  L’max = 35’ OK
12.10.1.1 Diaphragm Design Forces.

The diaphragm must be designed to the maximum of these two:

- MSFRS Diaphragm (structure) Load \((F_x)\) or,
- Controlling Diaphragm inertial Design Load \((F_{px})\) Per Eq. 12.10-1 as follows:

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

(12.10-1)

where

- \(F_{px}\) = the diaphragm design force at level \(x\)
- \(F_i\) = the design force applied to level \(i\)
- \(w_i\) = the weight tributary to level \(i\)
- \(w_{px}\) = the weight tributary to the diaphragm at level \(x\)

The force shall not be less than \(F_{px} = 0.2S_{DSIE}w_{px}\)

(12.10-2)

The force need not exceed \(F_{px} = 0.4S_{DSIE}w_{px}\)

(12.10-3)

For inertial forces calculated in accordance with Eq. 12.10-1, \(\rho=1.0\) per ASCE 7-16 Section 12.3.4.1, Item 7.

For a single story structure \(F_x = F_{px} = \frac{S_{DSIE}}{R} w_{px}\)

Because the MSFRS design load is increased by \(\rho = 1.3\) for redundancy in the strength design, \(\rho/R\) of the MSFRS is \(1.3/6.5 = 0.2\), which matches the 0.2 of ASCE 7 Eq. 12.10-2.
**Torsional Distribution**

Not mandatory

(Question 4) \( \rho=1.3, \Delta x=1.25 \)

Method 2B will be used for diaphragm design
(To answer questions 5 and 6)

Method 2A will be used for all other checks

**Method 2A**

212.76 plf

\[ T = 76,806.5 \text{ ft. lbs.} \]

\[ T_{\text{net}} = 2880.6 \text{ ft. lbs.} \]

**Method 2B**

214.76 plf

Alt.

2.0 plf

38'

C.R.

application of in-plane wall force. Walls which have no stiffness.

Wall Load

553.2

181.65 plf

185.65 plf

7604.8

8565

Tnet = 2880.6 ft. lbs.
Using method 2B- $\rho=1.3$, $A_x=1.25$:

$F_T = \text{Torsion forces only at corridor walls, gridlines 2 and 3}$

$M_{\text{net}} = 480.1(6 \text{ ft.}) = 2880.6 \text{ ft. lbs.}$  \text{Net moment}$

The in-plane forces of the longitudinal walls applied at grid lines 1, 2, 3 and 4 are calculated:

$F_{1,2,3,4} = 0.167(0.7)(1.3)(13 \text{ psf}) \left(\frac{10}{2} + 2\right)(40) = 553.2 \text{ lbs.}$

$V_{\text{net}} = V_{\text{base}} - F_{1,2,3,4} = 12438.3(1.3) - 4(553.2) = 13957 \text{ lbs.}$

$W = \frac{13957}{76} = 183.65 \text{ plf uniform load}$

$W_T = \frac{2880.6}{38(38)} = 2.0 \text{ plf: equivalent uniform torsional load acting as } M_{\text{net}}$

$W_1 = 183.65 - 2.0 = 181.65 \text{ plf: uniform load minus torsional load=net uniform load left cantilever}$

$W_2 = 183.65 + 2 = 185.65 \text{ plf}$ \text{Right cantilever}$

Calculate Loads to Diaphragm \text{ASD}
**Sign Convention**

Additional units as occurs

**Method-2B**

**Wall Load**

553.2 plf

181.65 plf

185.65 plf

553.2 plf

**Sym. C.L.**

553.2

**Loads**

12'

8'

15'

553.2

**Chord splice**

**Vsw**

**Sym.**

**Vsw**

**W’**

40'

**L’=35’**

**L=76’**

**Longitudinal**

**Transverse**

**A**

**B**

5'
Chord 1

A - 12' 15' 8' 23'

Direction of diaphragm transfer shears (Bending)

Diaphragm transfer shears

Moment Diagram and Chord Forces Bending – All chord forces are positive

Values (Tension)

Forces = $\frac{M_x}{d}$

Wall Load

553.2

Vsw

Line

1848.1 lbs.

Diaphragm Loading and Torsional SW/Strut forces

Shear Diagram V

Method 2B

Combine

Page 34
### Table 4.2A  Nominal Unit Shear Capacities for Wood-Framed Diaphragms

<table>
<thead>
<tr>
<th>Sheathing and Single floor</th>
<th>Common nail Size</th>
<th>Minimum Fastener Penetration In Framing Member or Blocking (in.)</th>
<th>Minimum Nominal Panel Thickness (in.)</th>
<th>Minimum Nominal width Of nailed face At adjoining Panel edges and boundaries (in.)</th>
<th>A Seismic Nail spacing (in.) at boundaries (all cases), at continuous panel edges parallel to load (cases 3 &amp; 4), and at all panel edges (cases 5 &amp; 6).</th>
<th>B Wind Panel Edge Fastener Spacing (in.)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>8d</td>
<td>1-3/8</td>
<td>7/16</td>
<td>3</td>
<td>570 11 9 760 7 6 1140 10 8 1290 17 12 800 1065 1595 1805</td>
<td></td>
</tr>
<tr>
<td></td>
<td>15/32</td>
<td>2</td>
<td>540 13 9.5 720 7.5 6.5 1060 11 8.5 1200 19 13 755 1010 1485 1680</td>
<td>6 4 2 2 3 6 6 4 3 6 6 4 3 3 6 6 4 3</td>
<td>OSB PLY</td>
<td>OSB PLY</td>
</tr>
<tr>
<td></td>
<td>15/32</td>
<td>3</td>
<td>600 10 8.5 800 6 5.5 1200 9 7.5 1350 15 11 840 1120 1680 1890</td>
<td>OSB PLY</td>
<td>OSB PLY</td>
<td></td>
</tr>
<tr>
<td></td>
<td>10d</td>
<td>1-1/2</td>
<td>580 25 15</td>
<td>770 15 11 1150 21 14 1310 33 18 810 1080 1610 1835</td>
<td>15/32</td>
<td>810 1080 1610 1835</td>
</tr>
<tr>
<td></td>
<td>19/32</td>
<td>2</td>
<td>650 21 14</td>
<td>860 12 9.5 1300 17 12 1470 28 16 910 1205 1820 2060</td>
<td>15/32</td>
<td>810 1080 1610 1835</td>
</tr>
<tr>
<td></td>
<td>19/32</td>
<td>3</td>
<td>640 21 14</td>
<td>850 13 9.5 1280 18 12 1460 28 17 895 1190 1790 2045</td>
<td>15/32</td>
<td>895 1190 1790 2045</td>
</tr>
<tr>
<td></td>
<td>15/32</td>
<td>3</td>
<td>720 17 12</td>
<td>960 10 8 1440 14 11 1640 24 15 1010 1345 2015 2295</td>
<td>15/32</td>
<td>1010 1345 2015 2295</td>
</tr>
</tbody>
</table>

| Roof framing-D.F. 1, E = 1,700,000 psi, roof joists @ 16” O.C. |

**Unit torsional shear = 24.32 plf**

\[
V_{\text{Max diaph}} = 176.3 + 24.3 = 200.6 \text{ plf.}
\]

200.6 plf < vs = 0.5(580) = 290 plf. o.k.

Ga = 25, blocked
Let’s Take a 15 Minute Break

Mass Timber Project
Part 3-Design Example (cont.):

- Maximum diaphragm chord force
- Diaphragm flexibility
- Story drift
- Torsional irregularity
Visual Aid-Shear

Sheathing element symbol for 1 ft x 1 ft square piece of sheathing in static equilibrium (typ.)

Positive Direction

Longitudinal Direction (shown)

Shears Applied to Sheathing Elements

Transfer shears

↑ Unit shear acting on sheathing element (plf)

↑ Unit shear transferred from the sheathing element into the boundary element (plf)

Shears Transferred Into Boundary Elements

The Visual Shear Transfer Method. How to visually show the distribution of shears through the diaphragm
Determine Maximum Chord Force
(Answer questions 5 and 6)
By inspection, the walls along the chord line affect the chord forces by a small amount, 364.8 lbs.

Calculations show that the conc. wall force at end of cantilever increase the chord force by +21% at the 15’ splice diminishing to +9% increase at 23’, and +1% at the support. Walls had a larger effect.
### Diaphragm Chords

#### Diaphragm Deflection (ASD)

<table>
<thead>
<tr>
<th>Splice Forces (Lbs.)</th>
<th>$\Sigma \delta_{\text{slip}}$</th>
<th>$v_{\text{unif.}}$</th>
<th>$v_{\text{conc.}}$</th>
<th>Ga</th>
<th>$L'$</th>
<th>$W'$</th>
<th>$\delta_{\text{Diaph Unif}}$</th>
<th>$\delta_{\text{Diaph conc}}$</th>
<th>Total $\delta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>F 15</td>
<td>1094.3</td>
<td>186.75</td>
<td>13.83</td>
<td>25.0</td>
<td>35.00</td>
<td>40.00</td>
<td>0.072</td>
<td>0.225</td>
<td>0.248</td>
</tr>
<tr>
<td>F 23</td>
<td>1180.9</td>
<td>186.75</td>
<td>13.83</td>
<td>25.0</td>
<td>35.00</td>
<td>40.00</td>
<td>0.072</td>
<td>0.225</td>
<td>0.248</td>
</tr>
<tr>
<td>F 35</td>
<td>3253.7</td>
<td>186.75</td>
<td>13.83</td>
<td>25.0</td>
<td>35.00</td>
<td>40.00</td>
<td>0.072</td>
<td>0.225</td>
<td>0.248</td>
</tr>
</tbody>
</table>

Nails Req'd: 4.84, 5.23, 14.40
Use Nails: 8, 16, 24
Slip: 0.023, 0.013, 0.023

Wall Load: 553.2, 553.2, 553.2, 185.64

**Method 2B**

- Maximum chord force = 3338.5 lbs.
- Using (2)2x6 DF-Larch No.1 wall top plates as the diaphragm chords: 2015 NDS Supplement Table 4A Ft = 675 psi, Fc// = 1500 psi. Only one 2x6 plate resists the chord forces due to the nailed splice joint.

$$ f_t = \frac{F_{\text{chord}}}{(1)2x6}, \text{ Number of nails } = \frac{F_{\text{chord}}}{226}, $$

where 226 lbs. is adjusted lateral design value, Z' (ASD), for 16d nails (face nailed).

Compression stresses OK by inspection. Chords braced about both axes.
Check for Effects of Full Length Shear Walls on Chord Forces

Uniform torsional shears vs. Shear Wall Shears

Similar to APA Example
- No fixity at support
- No chord bending
- No net rotational shears
- If partial length end walls, will develop strut forces
Diaphragm Flexibility, $\rho=1.0, Ax=1.25$

How does this relate to this?
Check Diaphragm Flexibility

Seismic- ρ=1.0, Ax=1.25
A matter of Stiffness

Seismic:
ASCE 7-16 Section 12.3.1- Diaphragm flexibility-The structural analysis shall consider the relative stiffnesses of diaphragms and the vertical elements of the seismic force resisting system.

Wind:
ASCE 7-16 Section 27.4.5- Diaphragm flexibility-The structural analysis shall consider the relative stiffness of diaphragms and vertical elements of the MWFRS.

Flexible structures are susceptible to damage from wind or seismic forces

Can require engineering judgement
**ASCE7-16 Section 12.3 Diaphragm Flexibility Seismic**

Section 12.3.1- The structural analysis shall consider the relative stiffnesses of diaphragms and the vertical elements of the seismic lateral force resisting system.

**Table: Diaphragm Flexibility**

<table>
<thead>
<tr>
<th>Is any of the following true?</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 &amp; 2 family Dwelling</td>
</tr>
<tr>
<td>Light framed construction</td>
</tr>
<tr>
<td>Envelope Method</td>
</tr>
<tr>
<td>Allowed for semi-rigid modelling</td>
</tr>
</tbody>
</table>

**Diagram: Diaphragm Flexibility Flowchart**

- **Start:** Is diaphragm untopped steel decking or Wood Structural Panels?
  - Yes: Is diaphragm concrete slab or concrete filled steel deck?
    - Yes: Idealize as flexible
    - No: Average drift of walls
  - No: Idealize as flexible

- **Yes:** Is span to depth ratio \( \leq 3 \) and having no horizontal irregularities?
  - Yes: Idealize as rigid
  - No: Maximum diaphragm deflection

- **Maximum diaphragm deflection:** Is maximum diaphragm deflection (MDD) >2x average story drift of vertical elements, using the Equivalent Force Procedure of Section 12.8?

**Structural analysis must explicitly include consideration of the stiffness of the diaphragm (i.e. semi-rigid modeling), or calculated as rigid in accordance with 2018 IBC Section 1604.4 or ASCE 7-16 Section 12.3.1.3.**
Is diaphragm untopped steel decking, concrete filled steel decks or concrete slabs, each having a span-to-depth ratio of two or less?

Yes: Diaphragm can be idealized as rigid

No: Is diaphragm of Wood Structural Panels?

Yes: Diaphragm can be idealized as flexible

No: Is diaphragm untopped steel decking, concrete filled steel decks or concrete slabs, each having a span-to-depth ratio greater than two?

Yes: Justify by Calculation as flexible, semi-rigid or rigid per 2015 IBC Section 1604.4 or ASCE 7-10 Section 12.3.1.3.

Open-Front-Wind

- Recommend Following SDPWS 4.2.5.2 (not required by code):
  1. Considered good engineering practice
  2. Diaphragm should meet semi-rigid or rigid stiffness requirements
  3. Show that the resulting drift at the edges of the structure can be tolerated.
Determination of Cantilever Diaphragm Flexibility *(Question 3):*

Use the drift of adjacent wall line supporting the Cantilever

(a) ASCE 7-16 Figure 12.3-1

(b) Corridor Walls Only

Preferred Method – Simplifies Check
Based on adjacent SW only

Diaphragm Deflection Typ. ($\delta_{\text{MDD}}$)

Diaphragm Deflection Typ. ($\delta_{\text{MDD}}$)

Cantilevers from this wall line

$\delta_{\text{Diaph Rigid/Semi-rigid}}$

$\delta_{\text{Diaph Flexible}}$

L’ = 35’ Max

Open-front Diaphragm

(d) Diaphragm flexibility Shear Wall One Side
Cantilever Diaphragm Deflection Equations (Question 2):

Three-term equation for uniform load:

\[ \delta_{Diaph\ Uni} = \frac{3vL'^3}{EA W'} + \frac{0.5vL'}{1000G_a} + \frac{\sum x\Delta_c}{W'} \]

Four-term equation for uniform load:

\[ \delta_{Diaph\ Uni} = \frac{3vL'^3}{EA W'} + \frac{0.5vL'}{Gvtv} + 0.376 L' e_n + \frac{\sum x\Delta_c}{W'} \]

Three-term equation for point load:

\[ \delta_{Diaph\ Conc} = \frac{8vL'^3}{EA W'} + \frac{vL'}{1000G_a} + \frac{\sum x\Delta_c}{W'} \]

Four-term equation for point load:

\[ \delta_{Diaph\ Conc} = \frac{8vL'^3}{EA W'} + \frac{vL'}{Gvtv} + 0.75 L' e_n + \frac{\sum x\Delta_c}{W'} \]

For method 2B, the maximum diaphragm deflection is equal to the sum of the uniform load deflection plus the concentrated load deflection:

EA chords =28,050,000 lbs., 2-2x6 wall top plate.

Where:

- \( L' \) = cantilever diaphragm length, ft
- \( W' \) = cantilever diaphragm width, ft
- \( E \) = modulus of elasticity of diaphragm chords, psi
- \( A \) = area of chord cross-section, in.²
- \( v_{max} \) = induced unit shear at the support from a uniform applied load, lbs/ft
- \( G_a \) = apparent diaphragm shear stiffness from nail slip and panel shear deformation, kips/in
- \( Gvtv \) = Panel rigidity through the thickness
- \( x \) = distance from chord splice to the free edge of the diaphragm, ft
- \( \Delta_c \) = diaphragm chord splice slip, in.
- \( \delta_{Diaph\ Uni} \) = calculated deflection at the free edge of the diaphragm, in.
- \( e_n \) = Nail slip per SDPWS C4.2.2D for the load per fastener at \( v_{max} \)
- \( \delta_{Diaph\ Conc} \) = calculated deflection at the free edge of the diaphragm, in.
### Longitudinal Loading

Grid Line | kx | Ky | dx | dy | kd | kd^2 | Fv | FT | Fv+FT |
---|---|---|---|---|---|---|---|---|---|
2 | 43.54 | 3 | 130.63 | 391.89 | 8884.5 | -527.7 | 8356.8 |
3 | 43.54 | 3 | 130.63 | 391.89 | 8884.5 | 527.7 | 9412.2 |
A | 25.14 | 20 | 502.74 | 10054.73 | 2030.9 | 2030.9 |
B | 25.14 | 20 | 502.74 | 10054.73 | -2030.9 | -2030.9 |
Σ | 87.09 | 50.27 | J= 20893.23 | 17769 |

### Walls at Grid Corridor

#### Walls A & B

---

### Diaphragm Deflection (STR)

<table>
<thead>
<tr>
<th>Splice Forces (Lbs.)</th>
<th>Σδ_slip</th>
<th>v unif</th>
<th>v conc.</th>
<th>Ga</th>
<th>L'</th>
<th>W'</th>
<th>δDiaph Unif</th>
<th>δDiaph conc</th>
<th>Total δ</th>
</tr>
</thead>
<tbody>
<tr>
<td>1064.6</td>
<td>1159.7</td>
<td>3533.5</td>
<td>0.075</td>
<td>233.22</td>
<td>0.00</td>
<td>25.0</td>
<td>35.00</td>
<td>40.00</td>
<td>0.265</td>
</tr>
</tbody>
</table>

EA = 28050000, (2)2x6

**Use Nails =**

- 4.71
- 5.13
- 15.64

**Slip =**

- 8
- 16
- 24

**Nails Req'd =**

- 0.023
- 0.012
- 0.025

---

### Flexibility and Drift

Page 43
Diaphragm Deflection-Method 2A, $\rho=1.0$, $Ax=1.25$

$$\delta_{Diaph\ Unif} = \frac{3v_{max}L'^3}{EAW'} + \frac{0.5v_{max}L'}{1000G_a} + \frac{\Sigma A_CX_C}{W'}$$  Three-term equation for uniform load

Wall displacements from Spreadsheet:

$$\delta_{Diaph\ left} = 0.26\" \ , \ \delta_{Diaph\ right} = 0.265\"$$

Deflection at grid line 3 = 0.216"

$$2 \times \Delta_3 = 0.432\"$$

$$0.265\" < 0.432\" \therefore \text{Diaphragm can be idealized as Rigid}$$

Diaphragm Flexibility – Wind

- ASCE 7-16, Chapter 27, Section 27.5.4-DIAPHRAGM FLEXIBILITY-requires that the structural analysis \textbf{shall consider} the stiffness of diaphragms and vertical elements of the main wind force resisting system (MWFRS).

- Section 26.2 - Definitions, DIAPHRAGM, diaphragms constructed of WSP are permitted to be idealized as flexible.

- There is no drift limit requirement in the code for wind design.
Story Drift, $\rho=1.0$, $Ax=1.25$
Analysis Flow
Longitudinal Design

Example Plan

Legend
- Engineering judgement required
- SW & Diaph. Design
- Determine flexibility, Drift
- Determine Tors. Irreg., \( \rho, Ax \)

Longitudinal Transverse

Check Story Drift
Seismic- \( \rho = 1.0, Ax = 1.25 \)
Page 44
Story Drift

Regular structures:

- Story drift ($\Delta$) shall be computed as the difference of the deflections at the centers of mass at the top and bottom of the story under consideration (Fig. 12.8-2).
- For structures assigned to SDC C, D, E, or F that have horizontal irregularity Type 1a or 1b of Table 12.3-1, the design story drift, $\Delta$, shall be computed as the largest difference of the deflections of vertically aligned points at the top and bottom of the story under consideration along any of the edges of the structure.

SDPWS Section 4.2.5.2 (4): Open-front structures, loading parallel to the open side:

- Maximum story drift at each edge of the structure $\leq$ ASCE 7-16 allowable story drift (Seismic) including torsion and accidental torsion and shall include shear and bending deformations of the diaphragm computed - strength level basis amplified by $C_d$.

$$\delta_x = \frac{C_d \delta_{xe}}{I_e}$$  \hspace{1cm} (12.8-15)
\[ \Delta \text{Drift} = \delta_T + (\delta_D - \delta_{RL}) \]

\[ \delta_T = 0.204'' \]

\[ \Delta \text{Drift} = \delta_T + (\delta_D + \delta_{RL}) \]

\[ + \delta_{RL} = 0.154'' \]

\[ \delta_D = 0.265'' \]

\[ \Delta_T = 0.204'' \]

231.61 plf

236 plf

Diaphragm deflection

\[ \Delta_1 = 0.192'' \]

\[ \Delta_2 = 0.216'' \]

\[ \delta_{RT} = 0.081'' \]

\[ \delta_{MDD} = 0.265'' \]

\[ \delta_{D} = 0.26'' \]

\[ \delta_{RL} = 0.154'' \]

\[ \Delta \text{Drift} = \delta_T + (\delta_D - \delta_{RL}) \]

\[ \Delta \text{Drift} = \delta_T + (\delta_D + \delta_{RL}) \]

\[ \Delta_1 = 0.192'' \]

\[ \Delta_2 = 0.216'' \]

\[ \delta_{RT} = 0.081'' \]
Drift-Method 2A  \( \rho=1.0, \ Ax=1.25 \)

\[ \text{Drift } \Delta = \delta_{Diaph} + \delta_{Rotation} + \delta_{Translation} \]

\( \delta_2 = 8.357 \text{ k} / 43.54 \text{ k/in} = 0.192 \text{ in} \),

\( \delta_3 = 9.412 \text{ k} / 43.54 \text{ k/in} = 0.216 \text{ in} \),

\( \delta_A = 2.031 \text{ k} / 25.14 \text{ k/in} = 0.081 \text{ in} \),

\( \delta_B = -2.031 \text{ k} / 25.14 \text{ k/in} = -0.081 \text{ in} \)

\( \Delta_{Diaph} = 0.265`` \\

\( \Delta_{Average} = 0.204`` \) (Translation)

\[ \delta_{RL} = \frac{2\Delta_{SW,AB}(L' + 3')}{W'} = \frac{2(0.081)(35' + 3')}{40} = 0.154`` , \ \delta_{RT} = 0.081`` \]

\[ \text{Drift } \Delta = \sqrt{(\delta_T + \delta_D \pm \delta_{RL})^2 + (\delta_{RT})^2} \]

\[ \text{Drift } \Delta_4 = \sqrt{(0.204 + 0.265 + 0.154)^2 + (0.081)^2} = 0.628`` \]

\[ \text{Drift } \Delta_1 = \sqrt{(0.204 + 0.26 - 0.154)^2 + (0.081)^2} = 0.320`` \]

\( C_d = 4, \ L_e = 1 \)

\[ \delta_M = \frac{C_d \delta_{max}}{L_e} = \frac{4(0.628)}{1} = 2.51`` \]
<table>
<thead>
<tr>
<th>Structure</th>
<th>Risk Category</th>
<th>Risk Category</th>
<th>Risk Category</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structures, other than masonry shear wall structures, four stories or</td>
<td>I or II</td>
<td>III</td>
<td>IV</td>
</tr>
<tr>
<td>less above the base as defined in Section 11.2, with interior walls</td>
<td>0.025hsx</td>
<td>0.020hsx</td>
<td>0.015hsx</td>
</tr>
<tr>
<td>partitions, ceilings, and exterior wall systems that have been designed</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>to accommodate the story drifts.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Masonry cantilever shear wall structures</td>
<td>0.010hsx</td>
<td>0.010hsx</td>
<td>0.010hsx</td>
</tr>
<tr>
<td>Other masonry shear wall structures</td>
<td>0.007hsx</td>
<td>0.007hsx</td>
<td>0.007hsx</td>
</tr>
<tr>
<td>All other structures</td>
<td>0.020hsx</td>
<td>0.015hsx</td>
<td>0.010hsx</td>
</tr>
</tbody>
</table>

- Depends on the non-structural components and detailing.
- Most sheathed wood framed walls can undergo the 2.5% drift level while providing life safety performance at the seismic design level.
- 0.025hsx limit - interior walls, partitions, ceilings, and exterior walls can accommodate the higher story drift limit. The selection of the higher 2.5% drift limit should be taken only with consideration of the non-structural wall and window performance.
- Otherwise, the 2% drift limit requirements should be used.

\[0.025hsx = 0.025(10)(12) = 3.0” > 2.51” \therefore \text{drift O.K.} \]
\[0.02hsx = 0.02(10)(12) = 2.4” < 2.51” \therefore \text{drift not O.K. for 2% drift} \]
Solutions if drift is exceeded:

Additional stiffness must be provided in either the diaphragm or in the shear walls:

a. Diaphragms-
   - Increasing nail size, spacing and/or sheathing thickness can increase shear capacity but it will not, in most cases, increase the diaphragm stiffness, if using the 3 term eq.
   - The largest deflection comes from shear deflection and nail slip.
   - SDPWS Table 4.2A shows that the apparent shear stiffness diminishes as you decrease the boundary nail spacing from a 6/6/12 nailing pattern until you get to a 2/3/12 nailing pattern.
   - If using plywood, switch to OSB which has a higher Ga

**Table 4.2A  Nominal Unit Shear Capacities for Wood-Framed Diaphragms**

<table>
<thead>
<tr>
<th>Sheathing Grade</th>
<th>Common Nail Size</th>
<th>Minimum Fastener Penetration In Framing Member or Blocking (in.)</th>
<th>Minimum Nominal Panel Thickness (in.)</th>
<th>Minimum Nominal width Of nailed face At adjoining Panel edges and boundaries (in.)</th>
<th>A Seismic Nail spacing (in.) at boundaries (all cases), at continuous panel edges parallel to load (cases 3 &amp; 4), and at all panel edges (cases 5 &amp; 6).</th>
<th>B Wind Panel Edge Fastener Spacing (in.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8d</td>
<td>1-3/8</td>
<td>7/16</td>
<td>3</td>
<td>570 11 9 760 7 6 1140 10 8 1290 17 12 800 1065 1595 1805</td>
<td>vs 4 2 2½ 6 4 2½ 6 6 6 4 3 OSB OSB OSB OSB OSB PLY OSB PLY OSB PLY OSB PLY OSB PLY</td>
<td></td>
</tr>
<tr>
<td>15/32</td>
<td>2</td>
<td>540 13 9.5 720 7.5 6.5 1060 11 8.5 1200 19 13 1350 15 11 755 1010 1485 1680 1890 2</td>
<td>vs 4 2 2½ 6 4 2½ 6 6 6 4 3 OSB OSB OSB OSB OSB PLY OSB PLY OSB PLY OSB PLY OSB PLY</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>600 10 8.5 800 6 5.5 920 9 7.5 1350 15 11 840 1120 1680 1890 21 14</td>
<td>vs 4 2 2½ 6 4 2½ 6 6 6 4 3 OSB OSB OSB OSB OSB PLY OSB PLY OSB PLY OSB PLY OSB PLY</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10d</td>
<td>1-1/2</td>
<td>15/32</td>
<td>2</td>
<td>580 25 15 770 15 11 1150 21 14 1310 33 18 810 1080 1610 1835</td>
<td>vs 4 2 2½ 6 4 2½ 6 6 6 4 3 OSB OSB OSB OSB OSB PLY OSB PLY OSB PLY OSB PLY OSB PLY</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>650 21 14 860 12 9.5 1300 17 12 1470 28 16 910 1205 1820 2060 33 16</td>
<td>vs 4 2 2½ 6 4 2½ 6 6 6 4 3 OSB OSB OSB OSB OSB PLY OSB PLY OSB PLY OSB PLY OSB PLY</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>640 21 14 850 13 9.5 1280 18 12 1460 28 17 895 1190 1790 2045 33 16</td>
<td>vs 4 2 2½ 6 4 2½ 6 6 6 4 3 OSB OSB OSB OSB OSB PLY OSB PLY OSB PLY OSB PLY OSB PLY</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>19/32</td>
<td>2</td>
<td>720 17 12 960 10 8 1440 14 11 1640 24 15 1010 1345 2015 2295 33 16</td>
<td>vs 4 2 2½ 6 4 2½ 6 6 6 4 3 OSB OSB OSB OSB OSB PLY OSB PLY OSB PLY OSB PLY OSB PLY</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>640 21 14 850 13 9.5 1280 18 12 1460 28 17 895 1190 1790 2045 33 16</td>
<td>vs 4 2 2½ 6 4 2½ 6 6 6 4 3 OSB OSB OSB OSB OSB PLY OSB PLY OSB PLY OSB PLY OSB PLY</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*SDPWS Table 4.2A shows that the apparent shear stiffness diminishes as you decrease the boundary nail spacing from a 6/6/12 nailing pattern until you get to a 2/3/12 nailing pattern.*
b. **Shear walls**- Contrary to the diaphragm, decreasing the nail spacing on the shear walls would increase the wall stiffness, reference SDPWS Table 4.3A. The apparent shear stiffness, $G_a$, increases as the nail spacing decreases.

c. **Other options to increase stiffness:**
   - Increase the wall lengths.
   - Increase the number of shear walls in the lateral line of force-resistance.
   - Apply sheathing to both sides of the walls at grid lines A & B or decrease nail spacing.
   - Decrease nail spacing at corridor walls.
   - Increase the size of the hold downs (with smaller $\Delta a$) to lessen rod elongation and wall rotation.
   - Increase the number of boundary studs (decrease bearing perpendicular to grain stresses, crushing).
   - Add additional interior shear walls to decrease forces on other shear walls.

d. **Calculation Method:** A final option which may increase the calculated system stiffness and reduce the deflections is to use the four-term deflection equation for the shear wall and diaphragm deflections to avoid introducing an artificial bias in the results by selectively combining three-term and four-term deflection calculations.
Solution for 2% drift issue: Page 50

Following option (d), the 2% drift limit can potentially be achieved by using the four-term deflection equation, which reduces diaphragm deflection and drift, as noted below.

\[ \delta_{\text{Diaph Unif}} = \frac{3vL'^3}{EAW'} + \frac{0.5vL'}{Gvtv} + 0.376 L' e_n + \frac{\Sigma x \Delta_c}{W'} \]

Where:

\[ e_n = \left( \frac{V_n}{769} \right)^{3.276} = \left( \frac{116.6}{769} \right)^{3.276} = 0.002 \text{ in} \]

SDPWS Table C4.2.2D

where 116.6 is max. load per nail, 10d nails, dry lumber assumed.

\[ Gvtv = 35000 \text{ lb/in depth, 4-ply} \]

SDPWS Table C4.2.2A

\[ v = 233.2 \text{ plf} \]

\[ 2 \Sigma x \Delta_c = \frac{2[15(0.023) + 23(0.012) + 35(0.025)]}{40} = 0.075 \text{ in} \]

\[ \frac{\Sigma x \Delta_c}{W'} = 0.075 \text{ in} \]

Drift \[ \Delta_4 = \sqrt{(0.204 + 0.245 + 0.153)^2 + (0.081)^2} = 0.608 \text{ in} \]

\[ \delta_M = \frac{C_d \delta_{\text{max}}}{I_e} = \frac{4(0.608)}{1} = 2.434 \text{ in.} \approx 2.4 \text{ in.} \]

Close enough to comply with the 2% drift limitation. Drift can also be improved if \( \rho \) or \( A_x \) decreases (See Section 7.6.1).
Check for Wind Drift
Simplified Procedure Chapter 28, Part 1 Low-rise Buildings, Enclosed

ASCE 7-16 Section 2.3, STR LC 0.9D+1.0W
2.4 ASD LC 0.6D+0.6W

Risk Category II, $V_{ult}=115$ MPH
Exposure C

Figure 26.5-1B

$P = Q_h[(G_{Cp})-(G_{Cpi})]$ MWFRS

28.3.1 Design wind pressure

$P = 61.15$ psf

$K_d = 0.85$ Wind directionality factor
$G_{Cpi} = +/-0.18$ Internal pressure coeff.
$K_z = 2.01 \left( \frac{z}{z_g} \right)_{\alpha}$ Velocity pressure exp. coeff.

$K_z = 0.78 @ h=10'$
$Q_h = 0.00256 K_z K_{zt} K_d V^2 = 22.4$ psf

Figure 28.3-1

<table>
<thead>
<tr>
<th>Surface</th>
<th>1</th>
<th>4</th>
<th>1E</th>
<th>4E</th>
</tr>
</thead>
<tbody>
<tr>
<td>$G_{Cpi}$</td>
<td>0.4</td>
<td>-0.29</td>
<td>0.61</td>
<td>-0.43</td>
</tr>
<tr>
<td>$P$ (psf)</td>
<td>8.96</td>
<td>6.5</td>
<td>13.66</td>
<td>9.63</td>
</tr>
</tbody>
</table>

Parapet

$P_p = Q_p(G_{Cpn})$

$K_z = 0.85 @ 15'$ Top of parapet
$Q_p = 24.46$ psf
$G_{Cpn} \text{ ww}=1.5, G_{Cpn} \text{ lw}=-1.0$
$P_{pw} = 36.69$ psf, $P_{pl} = 24.46$ psf
$\sum P_p = 61.15$ psf
\[
\Delta \text{Drift} = \delta_T + (\delta_D - \delta_{RL})
\]

\[
\delta_T = 0.204''
\]

\[
\Delta \text{Drift} = \delta_T + (\delta_D + \delta_{RL})
\]

\[
\delta_D = 0.48''
\]

\[
\delta_{RL} = 0.02''
\]

\[
\text{Diaphragm deflection}
\]

\[
\delta_{MDD} = 0.487''
\]

\[
\text{Drift} \Delta = \sqrt{(\delta_T + \delta_D \pm \delta_{RL})^2 + (\delta_{RT})^2}
\]

\[
\text{Drift} \Delta_1 = \sqrt{(0.405 + 0.48 + 0.02)^2 + (0.01)^2} = 0.905'' (0.628'')
\]

\[
\text{Drift} \Delta_2 = \sqrt{(0.405 + 0.48 - 0.02)^2 + (0.01)^2} = 0.865'' (0.320'')
\]

\[
\Delta_T = 0.405''
\]

\[
	ext{Diaphragm is rigid}
\]

\[
0.48 < 2(0.406) = 0.812
\]

\[
\delta_{RT} = 0.01''
\]

\[
\text{Drift-Similar to Method 2A}
\]

\[
\Delta \text{Drift}
\]

\[
\delta_T = 0.204''
\]

\[
\Delta \text{Drift} = \delta_T + (\delta_D + \delta_{RL})
\]

\[
\delta_D = 0.48''
\]

\[
\delta_{RL} = 0.02''
\]

\[
\Delta \text{Drift}
\]

\[
\text{Diaphragm deflection}
\]

\[
\delta_{MDD} = 0.487''
\]

\[
\text{Drift} \Delta = \sqrt{(\delta_T + \delta_D \pm \delta_{RL})^2 + (\delta_{RT})^2}
\]

\[
\text{Drift} \Delta_1 = \sqrt{(0.405 + 0.48 + 0.02)^2 + (0.01)^2} = 0.905'' (0.628'')
\]

\[
\text{Drift} \Delta_2 = \sqrt{(0.405 + 0.48 - 0.02)^2 + (0.01)^2} = 0.865'' (0.320'')
\]

\[
\Delta_T = 0.405''
\]

\[
\text{Diaphragm is rigid}
\]

\[
0.48 < 2(0.406) = 0.812
\]

\[
\delta_{RT} = 0.01''
\]

\[
\text{Drift-Similar to Method 2A}
\]
Allowable Drift Wind? H/600, H/400, H/240 ???
(Nothing defined in code)

Assuming window manufacturers allowable tolerance (movement) = 0.25”
(Check with window manufacturer)

10’ wall hgt.

H/600 = 0.2” < 0.25 OK by inspection

H/400 = 0.3” at top of wall

Maximum displacement at top of window = 0.21” < 0.25” : OK

H/240 = 0.5”, at Top of wd. = 0.35” > 0.25 N.G.

9’ wall hgt.

H/400 = 0.27” at top of wall

Maximum displacement at top of window = 0.21” < 0.25” : OK

For resistance to **Wind** loads:

1. ASCE 7-16 Section 27.4.5-Diaphragm flexibility-The structural analysis shall consider the stiffness of diaphragms and vertical elements of the MWFRS

2. Show that the resulting drift at the edges of the structure can be tolerated.
Torsional Irregularities

\[ \mathbf{A} \]

\[ \mathbf{B} \]
Verify Torsional Irregularity

Seismic- $\rho=1.0$, $Ax=1.0$
Torsional Irregularities $\rho = 1.0$ and $A_x = 1.0$

ASCE 7-16 Table 12.3-1, Type 1a and 1b irregularities note that $A_x=1.0$ when checking for torsional irregularities.

In many cases, open-front structures will result in torsional irregularities because of rotational effects.

SDPWS Section 4.2.5.1 addresses ASCE 7-16 torsional irregularity requirements.

Torsional Irregularity Type 1a – seismic - Maximum story drift, $\Delta_{\text{MAX}}$, (including accidental torsion with $A_x=1.0$), $> 1.2 \times \Delta_{\text{ADVE}}$

- Model as semi-rigid or idealized as rigid
- Torsional irregularity, Type 1a, is allowed in structures assigned to SDC B, C, D, E, or F.

Torsional Irregularity Type 1b - seismic: Extreme torsionally irregular, Maximum story drift, $\Delta_{\text{MAX}}$ $> 1.4 \times \Delta_{\text{ADVE}}$

- An extreme torsional irregularity Type 1b is allowed in structures assigned to Seismic Design Categories B, C, and D, but not in SDC E, or F.
ASCE 7-16: Table 12.3-1 Horizontal Structural Irregularity

**Requirement References**

**1a. Torsional Irregularity $\Delta_{\text{MAX}} > 1.2x \Delta_{\text{ADVE}}$**
- 12.3.3.4: 25% increase in forces - D, E, and F
- 12.7.3: Structural modeling - B, C, D, E, and F
- 12.8.4.3: Amplification of accidental torsion - C, D, E, and F
- 12.12.1: Drift - C, D, E, and F

**1b. Extreme Torsional Irregularity $\Delta_{\text{MAX}} > 1.4x \Delta_{\text{ADVE}}$**
- 12.3.3.1 Type 1b is not permitted in E and F
- 12.3.3.4: 25% increase in forces – D
- 12.3.4.2: Redundancy factor – D
- 12.7.3: Structural modeling - B, C, and D
- 12.8.4.3: Amplification of accidental torsion - C and D
- 12.12.1: Drift - C and D
### Longitudinal Loading

Grid Line  | kx  | Ky  | dx  | dy  | kd  | kd²  | Fv  | Ft  | Fv+Ft  
|-------|-----|-----|-----|-----|-----|------|-----|-----|-------
| 2     | 43.54 | 3   |     |     | 130.63 | 391.89 | 8884.5 | -422.2 | 8462.3  
| 3     | 43.54 | 3   |     |     | 130.63 | 391.89 | 8884.5 | 422.2 | 9306.7  
| A     | 25.14 | 20  |     |     | 502.74 | 10054.73 |       | 1624.7 | 1624.7  
| B     | 25.14 | 20  |     |     | 502.74 | 10054.73 |       | -1624.7 | -1624.7  
| Σ     | 87.09 | 50.27 |     |     |       |       | J= | 20893.23 | 17769  

- Walls at Grid Corridor Lines A & B
- Walls at Grid Corridor Lines A & B
- Walls at Grid Corridor Lines A & B

### Diaphragm Deflection (STR) ρ=1.0, Ax=1.0

<table>
<thead>
<tr>
<th>Splice Forces (Lbs.)</th>
<th>Σδ_slip</th>
<th>v unif</th>
<th>v conc</th>
<th>Ga</th>
<th>L'</th>
<th>W'</th>
<th>δDiaph Unif</th>
<th>δDiaph conc</th>
<th>Total δ</th>
</tr>
</thead>
<tbody>
<tr>
<td>F 15</td>
<td>983.2</td>
<td>0.075</td>
<td>227.49</td>
<td>0.00</td>
<td>25.0</td>
<td>35.00</td>
<td>40.00</td>
<td>0.260</td>
<td>0.260</td>
</tr>
<tr>
<td>F23</td>
<td>1236.9</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F35</td>
<td>3542.8</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Nail Req'd= 4.35, 5.47, 15.68
- Use Nails = 8, 16, 24
- Slip = 0.021, 0.013, 0.025

EA= 28050000, (2)2x6

Inclu des effects of sw's along chord line

### Diaphragm Deflection (STR)

<table>
<thead>
<tr>
<th>Splice Forces (Lbs.)</th>
<th>Σδ_slip</th>
<th>v unif</th>
<th>v conc</th>
<th>Ga</th>
<th>L'</th>
<th>W'</th>
<th>δDiaph Unif</th>
<th>δDiaph conc</th>
<th>Total δ</th>
</tr>
</thead>
<tbody>
<tr>
<td>332.0</td>
<td>1855.1</td>
<td>3617.4</td>
<td>0.073</td>
<td>224.42</td>
<td>0.00</td>
<td>25.0</td>
<td>35.00</td>
<td>40.00</td>
<td>0.256</td>
</tr>
<tr>
<td>1.47</td>
<td>8.21</td>
<td>16.01</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.00</td>
</tr>
<tr>
<td>0.007</td>
<td>0.020</td>
<td>0.026</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.026</td>
</tr>
</tbody>
</table>

Rt. Cantilever

Lft. Cantilever

### Torsional Irregularity Check - Method 2A

- Use Nails = 8, 16, 24
- Slip = 0.007, 0.020, 0.026
\[ \Delta_{\text{Drift}} = \delta_T + (\delta_D - \delta_{RL}) \]

\[ \delta_D = 0.256" \]

\[ \delta_{RL} = 0.124" \]

\[ \delta_T = 0.207" \]

\[ \Delta_{ADVE} = 0.204" \]

\[ \Delta_1 = 0.194" \]

\[ \Delta_2 = 0.214" \]

\[ \delta_{RT} = 0.065" \]

\[ \delta_{MDD} = 0.26" \]

\[ \delta_D + \delta_{RL} = 0.26" \]

\[ \delta_T - \delta_{RL} = 0.124" \]

\[ \Delta = \text{Drift} \]

**Torsion (Question 7):**
Check for Torsional Irregularity Type 1a - \( \rho=1.0, \ Ax=1.0 \)

SDPWS 4.2.5.2 (2):

- A.R. \( \leq 1:1 \) if torsional irregularity - one-story structure
- A.R. = 0.67:1 - multi-story structure

A.R. = 0.875 < 1, \( \therefore \) O.K. Had this been a multi-story structure, the A.R. would have been exceeded and adjustments made accordingly.

\[ \Delta_2 = 0.194", \quad \Delta_3 = 0.214" \]

\[ \Delta_{Aver} = \frac{0.194 + 0.214}{2} = 0.204" \]

\[ \delta_{SWA,B} = 0.065" = \delta_{RT} \quad \text{Transverse displacement at Lines A and B from rigid diaphragm rotation} \]

\[ \delta_{RL} = \frac{2\delta_{SWA,B}(L'+3')}{W'} = 0.124" \quad \text{Vertical component of rotation} \]

Diaphragm deflections:

\[ \delta_{D,1} = 0.256" \]

\[ \delta_{D,4} = 0.260" \]
\[ \Delta = \sqrt{(\delta_T + \delta_D \pm \delta_{RL})^2 + (\delta_{RT})^2} \]

Drift \( \Delta_4 = \sqrt{(0.204 + 0.260 + 0.124)^2 + (0.065)^2} = 0.592'' \)

Drift \( \Delta_1 = \sqrt{(0.204 + 0.256 - 0.124)^2 + (0.065)^2} = 0.342'' \)

\[ \Delta_{Aver} = \frac{0.592 + 0.342}{2} = 0.467'' \]

0.592 > 1.2(0.467) = 0.56'', \.: Horizontal torsional irregularity Type 1a does exist in this direction.

0.592 < 1.4(0.467) = 0.654'', \.: Horizontal torsional irregularity Type 1b does not exist in this direction.
Lunch
Part 4-Design Example (cont.):

- Amplification of accidental torsion
- Redundancy
- Transverse direction design
- Miscellaneous plan layouts and multi-story effects
Amplification of Accidental Torsion

Seismic - $\rho=1.0$, $Ax=1.0$
Verify accidental ecc., Ax

Verify Rho \( \rho \)

Legend
- Engineering judgement required
- SW & Diaph. Design
- Determine flexibility, Drift
- Determine Tors. Irreg., \( \rho \), Ax

ASD Design  STR Design

Analysis Flow
Longitudinal Design

Example Plan

Legend

Step 8
Verify accidental ecc. ampl., Ax

Verify Rho \( \rho \)

Verify Torsional Irregularity

\( \rho=1.0 \)
\( Ax=1.0 \)

Verify Amplification of Accidental Torsion, Ax
Seismic- \( \rho=1.0, Ax=1.0 \)
ASCE 7-16 12.8.4.3 Amplification of Accidental Torsional Moment. Structures assigned to Seismic Design Category C, D, E, or F, where Type 1a or 1b torsional irregularity exists as defined in Table 12.3-1 shall have the effects accounted for by multiplying $M_{ta}$ at each level by a torsional amplification factor ($A_x$) as illustrated in Fig. 12.8-1 and determined from the following equation:

$$A_x = \left( \frac{\delta_{max}}{1.2\delta_{avg}} \right)^2$$

Where

- $\delta_{max}$ = maximum displacement at level $x$ computed assuming $A_x = 1$
- $\delta_{avg}$ = average of the displacements at the extreme points of the structure at level $x$ computed assuming $A_x = 1$.
- $M_{ta}$ = accidental torsional moment

From torsion section:

$$A_x = \left( \frac{\delta_{max}}{1.2\delta_{avg}} \right)^2 = \left( \frac{0.592}{1.2(0.467)} \right)^2 = 1.116 < 1.25 \text{ assumed.}$$

∴ Can recalculate if desired.

ASCE 7-70 (1st printing) 12.8.4.1 Inherent Torsion Exception below is not in 3rd printing of ASCE 7-10 or ASCE 7-16

Most diaphragms of light-framed construction are somewhere between rigid and flexible for analysis purposes, that is, semi-rigid. Such diaphragm behavior is difficult to analyze when considering torsion of the structure. As a result, it is believed that consideration of the amplification of the torsional moment is a refinement that is not warranted for light-framed construction.
Verify Redundancy, $\rho$

Seismic- $\rho=1.0$, $Ax=1.0$
Redundancy
Seismic- $\rho=1.0$, $A_x=1.0$

- The application of rho relates directly to increasing the capacity of the walls only, or adding more walls.
- The rho factor has an effect of reducing $R$, for less redundant structures which increases the seismic demand.
- Shear wall systems have been included in Table 12.3-3 so that either an adequate number of walls are included, or a proper redundancy factor has been applied.

ASCE 7-16 Redundancy Flow Chart
Figure C12.3-6
12.3.4.1 Conditions Where Value of $\rho$ is 1.0. The value of $\rho$ is permitted to equal 1.0 for the following:

2. Drift calculation and P-delta effects.

5. Design of collector elements, splices, and their connections for which the seismic load effects including over-strength factor of section 12.4.3 are used.

6. Design of members or connections where seismic load effects including over-strength factor of section 12.4.3 are required for design.

7. Diaphragm loads, $F_{px}$, determined using Eq. 12.10-1, including min. & max. values.

12.3.4.2 Redundancy Factor, $\rho$, for Seismic Design Categories D through F.

- For structures assigned to Seismic Design Category D and having extreme torsional irregularity as defined in Table 12.3-1, Type 1b, $\rho$ shall equal 1.3.

- For other structures assigned to Seismic Design Category D and for structures assigned to Seismic Design Categories E or F, $\rho$ shall equal 1.3 unless one of the following two conditions (a. or b.) is met, whereby $\rho$ is permitted to be taken as 1.0.

  a. Each story resisting more than 35% of the base shear in the direction of interest shall comply with Table 12.3-3.

Let's check condition b. first
b. Structures that are regular in plan at all levels $\rho = 1.0$ provided:

- SFRS consist of at least two bays of perimeter SFRS framing on each side of the structure in each orthogonal direction at each story resisting more than 35% of the base shear.

- The number of bays for a shear wall $= \frac{L_{sw}}{h_{sx}}$, or $2 \frac{L_{sw}}{h_{sx}}$, for light-frame construction.

Although the plan is regular, in the longitudinal direction, there are no SFRS walls at all exterior wall lines.

For this example, it is apparent that in the longitudinal direction the structure does not comply with condition “b”.

Therefore condition “a” must be met.

**Condition a. Table 12.3-3.**

Removing one wall segment with A.R. $> 1:1$

- No wall with A.R. $> 1:1$
- No reduction in story strength $> 33\%$ limit.
- Removing 1 wall at line A will not result in extreme torsional irregularity, Type 1b.
\[ \Delta \text{Drift} = \delta_T + (\delta_D - \delta_{RL}) \]

\[ \delta_T = \Delta \text{ADVE} \]

\[ \frac{H}{L} = \frac{10}{8} = 1.25 \geq 1.0 \]

\[ \therefore \text{remove} \]

231.22 plf

236.38 plf

\[ K = 12.57 \]

\[ \sum K = 43.54 \]

\[ \delta_{MDD} \]

\[ \delta \]

\[ \delta_{swA} \]

\[ \delta_{swB} \]

\[ \rho = 1.0 \]

\[ Ax = 1.0 \]

\[ \bar{Y} = \frac{15.875(40)}{3(15.875)} = 13.33' \]
Redundancy Study

Spreadsheet results

<table>
<thead>
<tr>
<th></th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>FA</td>
<td>1595</td>
</tr>
<tr>
<td>FB</td>
<td>1595</td>
</tr>
<tr>
<td>F2</td>
<td>8263</td>
</tr>
<tr>
<td>F3</td>
<td>9506</td>
</tr>
</tbody>
</table>

Check

\[
\Delta_{Rot} = \frac{0.127(38)}{26.667} = 0.181"
\]

\[
\Delta_T = \frac{0.190 + 0.218}{2} = 0.204"
\]

\[
Drift_\Delta = \sqrt{(0.204 + 0.260 + 0.181)^2 + (0.127)^2} = 0.657"
\]

\[
Drift_1 = \sqrt{(0.204 + 0.256 - 0.181)^2 + (0.127)^2} = 0.307"
\]

\[
\Delta_{Aver} = \frac{0.657 + 0.307}{2} = 0.482"
\]

0.657 < 1.4(0.482) = 0.674", \(\therefore\) Horizontal torsional irregularity Type 1b does not exist in this direction and \(\rho = 1.0\)
Struts and Collectors - Seismic

Struts / collectors and their connections shall be designed in accordance with ASCE 7-10 sections:

12.10.2 SDC B - Collectors can be designed w/o over-strength but not if they support discontinuous walls or frames.

12.10.2.1 SDC C thru F - Collectors and their connections, including connections to the vertical resisting elements require the over-strength factor of Section 12.4.3, except as noted:

Shall be the maximum of:

\[ \begin{align*}
\Omega_o F_x & \quad - \text{Forces determined by ELF Section 12.8 or Modal Response Spectrum Analysis procedure 12.9} \\
\Omega_o F_{px} & \quad - \text{Forces determined by Diaphragm Design Forces (F_{px}), Eq. 12.10-1 or} \\
F_{px\ min} & = 0.2 S_{DSi} I_{e w_{px}} \quad - \text{Lower bound seismic diaphragm design forces determined by Eq. 12.10-2 (F_{px\ min}) using the Seismic Load Combinations of section 12.4.2.3 (w/o over-strength)-do not require the over-strength factor.} \\
F_{px\ max} & = 0.4 S_{DSi} I_{e w_{px}} \quad - \text{Upper bound seismic diaphragm design forces determined by Eq. 12.10-2 (F_{px\ max}) using the Seismic Load Combinations of section 12.4.2.3 (w/o over-strength)-do not require the over-strength factor.}
\end{align*} \]

Exception:

1. In structures (or portions of structures) braced entirely by light framed shear walls, collector elements and their connections, including connections to vertical elements need only be designed to resist forces using the standard seismic force load combinations of Section 12.4.2.3 with forces determined in accordance with Section 12.10.1.1 (Diaphragm inertial Design Forces, F_{px}).
ASD, $p=1.3$, $Ax=1.25$

V sw = 253.5 plf
Vnet = 253.5 - 172.8 - 13.82 - 3.53 = 63.35 plf

V sw = 285.5 plf
Vnet = 285.5 - 176.3 - 24 - 13.82 = 71.38 plf

If center SW removed, strut forces are increased

Diaphragm Shears

0.141 k
3.53 plf

7.051 k 176.3 plf
0.553 k typ.
Design Example - Transverse Direction

Unit 1

Unit 2

Unit 3

Unit 4
12.3.1.1- (c), **Light framed construction**, diaphragms meeting all the following conditions are allowed to be idealized as flexible:

1. All Light framed construction
2. Non-structural concrete topping ≤ 1 ½” over wood structural panels (WSP).
3. Each elements of the seismic line of vertical force-resisting system complies with the allowable story drift of Table 12.12-1
Drift
\[ \rho = 1.0, \ Ax = 1.25 \]

Torsional and Redundancy Check
\[ \rho = 1.0, \ Ax = 1.0 \]
**Diaphragm Flexibility**, Resulting numbers: $\rho=1.0$, $A_x=1.25$

$W = \frac{17769}{76} = 444.1$ plf (ASD)

$V_A = 9057.6$ lbs.

$V_{\text{max Diaph}} = \frac{9057.6}{76} = 119.2$ plf < 464 plf :: O.K

From spreadsheet (STR)

$\delta_{\text{Diaph}} = 0.066^\prime$

$\Delta_{SW_A} = 0.396^\prime$, $\Delta_{SW_B} = 0.311^\prime$, $2\times \Delta_{\text{Average}} = 0.707^\prime$

$0.066^\prime < 0.707^\prime$ :: Rigid diaphragm, as initially assumed.

**Check Story Drift**

$\rho = 1.0$ and $A_x = 1.25$

$C_d = 4$, $I_e = 1$

$\delta_{SWA} = 0.396$ in from spreadsheet

$\delta_M = \frac{C_d \delta_{\text{max}}}{I_e} = \frac{4(0.396)}{1} = 1.58$ in

$0.20 h_{sx} = 0.020(10)(12) = 2.4$ in > 1.58 in, :: Drift OK
Check for Torsional Irregularity $\rho=1.0$, $Ax=1.0$

Rigid diaphragm, $\rho =1.0$ and $Ax = 1.0$ as required by ASCE 7 Table 12.3-1

From spreadsheet

$\delta_{SWA} = 0.387"$

$\delta_{SWB} = 0.319"$

$\Delta_{Average} = \frac{0.387+0.319}{2} = 0.353"$ From spreadsheet

$0.387 < 1.2(0.353) = 0.424", \therefore$ No torsional irregularity exists in this direction, as assumed.
Redundancy Check $\rho=1.0$, $Ax=1.0$

Table 12.3-3 Requirements

- Removal of SW with $H/L > 1.0$
  1. Will not result in $> 33\%$ reduction in strength
  2. Will not result in extreme torsional irregularity

- $\delta_A = 0.775''$
- $\delta_B = 0.320''$

$$\Delta_{Aver} = \frac{0.775 + 0.320}{2} = 0.547''$$

Only 25% decrease in story strength.

$0.775'' > 1.4(0.547) = 0.765''$ :: Type 1b :: $\rho=1.3$
Preliminary Assumptions Made:

- Diaphragm is rigid or semi-rigid in both directions.  Correct
- Torsional irregularity Type 1a occurs in longitudinal direction, but not transverse, Correct
- $A_x=1.25$ assumed. Incorrect, $A_x=1.121$
- Horizontal irregularity Type 1b does not occur in either direction. Correct, however, when checking redundancy, it occurs in the transverse direction by the removal of 1 wall.
- No redundancy in both directions, $\rho=1.3$ Incorrect:
  - $\rho = 1.0$ Longitudinal
  - $\rho = 1.3$ Transverse

Other Design Requirements:

- Drift $< $ allowable
Corridor Walls One Side Only

Rotation transfer shears

Shear panels, blocking or framing members over entire wall line to transfer diaphragm shears down into the shear walls

Torsion + Amplified Accidental Torsion

Non-shear wall

Lateral force

Vsw Line (Torsion)

W' = 40'

L' = 35'

Page 64, 65
Multi-Story, Stiffness Issues
Consideration of Shear Wall Multi-story Effects - Not in paper

Typical Floor Plan

Torsional Irregularity?

Unsymmetrical Floor Plan

Multi-story SW Effects ???
What happens at the upper floors ???

Vs.

Traditional SW  MBA SW

FTAO?

Unsymmetrical Floor Plan

Not in example
Current Examples of Shear Wall Multi-story Effects and Mid-rise Analysis

Current Examples of Mid-rise Analysis-Traditional Method

• Thompson Method-Woodworks Website
  Webinar  [http://www.woodworks.org/education/online-seminars/](http://www.woodworks.org/education/online-seminars/)


Current Examples of Mid-rise Analysis-Mechanics Based Approach

• Shiotani/Hohbach Method-Woodworks Slide archive

• FPInnovations-Website NEW
  "Seismic Analysis of Wood-Frame Buildings on Concrete Podium", Newfield

• 2016 WCTE: A Comparative Analysis of Three Methods Used For Calculating Deflections For Multi-storey Wood Shear Walls: Grant Newfield, Jasmine B. Wang

• FPInnovations-Website
  "A Mechanics-Based Approach for Determining Deflections of Stacked Multi-Storey Wood-Based Shear Walls”, Newfield

• Design Example: ”Design of Stacked Multi-Storey Wood-Based Shear Walls Using a Mechanics-Based Approach ”, Canadian Wood Council

• APEGBC Technical & Practice Bulletin Revised April 8, 2015
  “5 and 6 Storey Wood Frame Residential Building Projects (Mid-Rise)”-Based on FPInnovations Mechanics Based Approach
New Research and Analytical methods-Tall Shear Walls

Currently not addressed or required by code: Engineering preference and/or judgement

Testing shows that the traditional deflection equation is less accurate for walls with aspect ratios higher than 2:1. (Dolan)

- Current research suggests that the traditional method of shear wall analysis might be more appropriate for low-rise structures.

- Multi-story walls greater than 3 stories should:
  - Consider flexure and wall rotation.
  - Rotation and moment from walls above and wall rotation effects from walls below.

\[
\frac{1}{2} \sum M_i H_i^2 + \frac{1}{3} \sum V_i (H_i^3)
\]

\[\sum M_i H_i^2 \]

\[\Delta \text{Allow story drift} \]

\[\text{Total displ.} \text{ of Tall Wall, More flexible.} \]

\[\text{Tall Shear Wall MBA} \]

\[\text{Tall SW} \]

\[\text{Stiffness based approach} \]

Allowable story drift for traditional and tall shear walls is checked floor to floor.

Total displ. of Tall Wall. More flexible.

A.R.=3.5:1 flr.-flr.

A.R.=2:1 flr.-flr.

Acting as a continuous wall

Traditional based on A.R.

MBA based on stiffness

Floor to floor A.R.’s and Stiffness of Shear Walls

Not in example
Flexibility does not allow dead load to aid in resisting wall rotation.

Stiffness might allow dead load to aid in resisting wall rotation, provided joints are strategically placed. (justify by calculation)

Diaphragm out-of-plane flexibility

If diaphragm out-of-plane stiffness = Flexible
Analyze entire wall as a tall wall

If diaphragm out-of-plane stiffness = Rigid (steel beam, conc. beam)
Analyze entire wall as traditional floor to floor
Deflection-Bending + Rotation translates to top

Deflection-Wall rotation translates to top

Note:
Increased wall flexibility can increase the period of the building, lowering the seismic force demands.
Core Structures

- Light framed
- CLT
• The Analysis of Irregular Shaped Structures: Diaphragms and Shear Walls-Malone, Rice-Book published by McGraw-Hill, ICC

• Woodworks Presentation Slide Archives-Workshop-Advanced Diaphragm Analysis


• SEAOC Seismic Design Manual, Volume 2


• Woodworks-Guidelines for the Seismic Design of an Open-Front Wood Diaphragm (paper). Complete Example
Method of Analysis and Webinar References

Offset Diaphragms

Offset Shear Walls

Diaphragms Openings

Example Results
https://vimeo.com/woodproductscouncil/review/149198464/c1183f2cf8

Shear Walls with Openings

Mid-rise Design Considerations

Information on Website: Presentation Slide Archives, Workshops, White papers, research reports

https://vimeo.com/woodproductscouncil/review/114574994/b64da97f09

https://vimeo.com/woodproductscouncil/review/217888849/e3018a496a

https://vimeo.com/woodproductscouncil/review/149198464/c1183f2cf8

https://vimeo.com/woodproductscouncil/review/217888849/e3018a496a

https://vimeo.com/woodproductscouncil/review/212986898/17ca94ef6f

https://vimeo.com/woodproductscouncil/review/220727334/516f37ce1e
Questions?

This concludes Woodworks Presentation on:
Guidelines for the Seismic Design of an Open-Front Wood Diaphragm

Your comments and suggestions are valued. They will make a difference.

Send to: terrym@woodworks.org

R. Terry Malone, P.E., S.E.
Senior Technical Director
WoodWorks.org

Contact Information:
terrym@woodworks.org
928-775-9119

Thank You

Disclaimer:
The information in this publication, including, without limitation, references to information contained in other publications or made available by other sources (collectively “information”) should not be used or relied upon for any application without competent professional examination and verification of its accuracy, suitability, code compliance and applicability by a licensed engineer, architect or other professional. This example has been developed for informational purposes only. It is not intended to serve as recommendations or as the only method of analysis available. Neither the Wood Products Council nor its employees, consultants, nor any other individuals or entities who contributed to the information make any warranty, representative or guarantee, expressed or implied, that the information is suitable for any general or particular use, that it is compliant with applicable law, codes or ordinances, or that it is free from infringement of any patent(s), nor do they assume any legal liability or responsibility for the use, application of and/or reference to the information. Anyone making use of the information in any manner assumes all liability arising from such use.