Lateral Design Considerations for Mid-Rise Wood Structures

By: R. Terry Malone, PE, SE
Senior Technical Director
Architectural & Engineering Solutions
www.woodworks.org

E-mail: terrym@woodworks.org

This presentation is copyrighted by Woodworks
Mid-rise Codes and Standards

Crescent Terminus building- credit: Richard Lubrant.

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 information for designers to consider to refine their own techniques.
Course Description

Research, full-scale testing and code requirements continue to evolve for mid-rise construction. This presentation will focus on important engineering considerations related to the lateral design of mid-rise* wood buildings. Implementation of a well-considered design requires the understanding of diaphragm and shear wall flexibility and their effects on the horizontal distribution of forces through the structure. In mid-rise, multi-family buildings, corridor only shear walls are becoming very popular as a way to eliminate exterior shear walls. The special design issues this situation creates will be addressed.

*Definition:
A mid-rise building can be described as something between a high-rise and low-rise structure — that is, between four and ten stories with heights ranging between 35 to 75 feet tall.
Learning Objectives

• Design Considerations
  
  Discuss important lateral engineering issues that need to be considered to successfully design a mid-rise structure.

• Diaphragm and Shear Wall Flexibility
  
  Understand the relationship between diaphragm and shear Wall stiffness on the horizontal distribution of shears within a mid-rise structure.

• Tall Shear Walls With Multi-story Effects
  
  Discuss the behavior of shear walls under multi-story effects and the impact on the distribution of shear forces within the structure.

• Overview-Open Front and Non-Open Front Structures
  
  Review key points in the analysis of open front diaphragms and non-open front designs.
• Design Considerations
  • Complete Load Paths
  • Diaphragm Flexibility
  • Tall Shear Walls-Flexibility
  • Horizontal Distribution of Shears
  • Overview-Mid-rise: Exterior shear Walls
  • Overview-Mid-rise: Open Front
Design Considerations

Methods of analysis for open-front or tall shear wall mid-rise structures are currently evolving as more complex building geometries are becoming more prevalent. Building shapes and footprints are driving the design procedures for all lateral resisting systems and materials.

Design requirements:

• IBC1604.4- Analysis:
  o Method of analysis shall take into account equilibrium, general stability, geometric compatibility, and both short- and long term material properties.
  o Shall be based on rational analysis in accordance with well established principals of mechanics. Analysis shall provide complete load paths.

Considerations:

• Make sure that you have complete continuous lateral load paths.
• Address vertical / horizontal irregularities.
• Investigate diaphragm and shear wall flexibility/stiffness.
• Consider the multi-story effects on shear wall stiffness.
• Check the effects of offset diaphragms and shear walls.
• Verify the horizontal distribution of forces within the diaphragm and to the shear walls.
Open Front & Non-open Front
Floor Plan w/ and w/o offsets
Non-open front

- ASCE 7-10 Section 12.3.1.1- (c), Light framed construction, meeting all conditions:
  - Longitudinal-Typically permitted to be idealized as flexible, provided exterior shear walls of adequate stiffness exist. However, diaphragm can be semi-rigid, rigid or open front, even if exterior walls exist.
  - Transverse-Traditionally assumed to be flexible diaphragm.
  - If token or questionable wall stiffness occurs at the exterior wall line, consider using semi-rigid analysis using the envelope method-(conservative), or semi-rigid, or idealize as rigid.

Open Front Structures:

- SDPWS 4.2.5.2 :
  - Loading parallel to open side - Model as semi-rigid, which shall include shear and bending deformation of the diaphragm, or it can be idealized as rigid.
  - Loading perpendicular to open side (Transverse)-traditionally assumed to be flexible.
  - Drift at edges of the structure ≤ the ASCE 7 allowable story drift when subject to seismic design forces including torsion, and accidental torsion (strength, multiplied by Cd). No set drift requirements required for wind (Drift can be tolerated).
Presentation Topics

- Design Considerations
- Complete Load Paths
- Diaphragm Flexibility
- Tall Shear Walls-Flexibility
- Horizontal Distribution of Shears
- Overview-Mid-rise: Open Front
- Overview-Mid-rise: Exterior shear Walls
Analysis: ASCE7-10 Sections:
• 1.3.1.3.1-Design shall be based on a rational analysis
• 12.10.1-At diaphragm discontinuities such as openings and re-entrant corners, the design shall assure that the dissipation or transfer of edge (chord) forces combined with other forces in the diaphragm is within shear and tension capacity of the diaphragm.

ASCE7-10 Section 1.4-Complete load paths are required including members and their splice connections
SDPWS 4.3.5.1
Collectors for shear transfer to individual full-height wall segments shall be provided.

Where offset walls occur in the wall line, the shear walls on each side of the offset should be considered as separate shear walls and should be tied together by force transfer around the offset (in the plane of the diaphragm).

ASCE7-10 Section 1.4-Complete load paths are required including members and their splice connections
Presentation Topics

• Design Considerations
• Complete Load Paths
• **Diaphragm Flexibility**
• Tall Shear Walls-Flexibility
• Horizontal Distribution of Shears
• Overview-Mid-rise: Exterior shear Walls
• Overview-Mid-rise: Open Front
### ASCE7-10 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 lateral force resisting system.

#### 12.3.1.1 - Is any of the following true?

<table>
<thead>
<tr>
<th>1 &amp; 2 family Dwelling</th>
<th>Vertical elements one of the following:</th>
<th>Light framed construction where all of the following are met:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Is diaphragm concrete slab or concrete filled steel deck?</td>
<td>1. Steel braced frames 2. Composite steel and concrete braced frames 3. Concrete, masonry, steel SW or composite concrete and steel shear walls.</td>
<td>1. Topping of concrete or similar material is not placed over wood structural panel diaphragms except for non-structural topping not greater than 1 ½” thick. 2. Each line of vertical elements of the seismic force-resisting system complies with the allowable story drift of Table 12.12-1.</td>
</tr>
</tbody>
</table>

#### Structural analysis must explicitly include consideration of the stiffness of the diaphragm (i.e. semi-rigid modeling), or calculated as rigid in accordance with 2015 IBC Section 1604.4 or ASCE 7-10 Section 12.3.1.3.
ASCE7-10, Section 26.2 Diaphragm Flexibility

Start

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.

No

Wind

ASCE 7-10 Section 27.5.4-Diaphragm flexibility
The structural analysis shall consider the stiffness of diaphragms and vertical elements of the MWFRS.
Presentation Topics

- Design Considerations
- Complete Load Paths
- Diaphragm Flexibility
- Tall Shear Walls-Flexibility
- Horizontal Distribution of Shears
- Overview-Mid-rise: Exterior shear Walls
- Overview-Mid-rise: Open Front
Current Examples of Mid-rise Analysis

Current Examples of Mid-rise Analysis-Traditional Method

• Thompson Method-Woodworks Website
  Webinar 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
Traditional Shear Walls:
- Max. A/R=3.5:1
- Walls assumed to be pinned at top and fixed at the bottom at each floor,
- rigid wall sections and,
- out-of-plane diaphragm stiffness-rigid
- Doesn’t account for multi-story shear wall effects

\[ \Delta_T = \Delta_{sw1} + \Delta_{sw2} + \Delta_{sw3} \]

\[ \Delta_{SW} = \frac{8v_h^3}{EAb} + \frac{vh}{1000G_a} + \frac{h\Delta_a}{b} \]
The equation is judged to be adequate as long as the aspect ratios of the walls are reasonable.

Shear wall deflections are approximated based on this equation and extrapolated for multistory behavior.

Shear walls for this building type have continuous rod tie down systems that are integral to their multistory behavior.

Column elements simplify the model, over shell or plate elements.

Provides a reasonable approximation for shear wall deflection (conservative).

It also captures the flexural deformation of the full height wall.

**Procedure**

- Break the wall up into multi story components
- Calculate the deflection of the wall’s story(s) components
- A column section is used, then back calculated for the required moment of inertia to produce the expected deflection at the top of the multi-story shear wall.
- The sum of those deformations are greater than the traditional multi-story shear wall deflections.
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.

$$\sum M_i H_i^2 + \sum V_i (H^3)/(3EI)_i$$

Floor to floor A/R’s and Stiffness of Shear Walls
Rim joist

Should consider as flexible because it is unknown where rim joist splices will occur.

Platform framed

Semi-balloon framed (Very flexible)

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)

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

Diaphragm out-of-plane

Flexibility

Compression blocking

Platform framed

Should consider as flexible because it is unknown where rim joist splices will occur.
Tall Wall Deflection: \[ \Delta_i = \frac{\sum M_i H_i^2}{2EI_i} + \frac{\sum V_i H_i}{3EI_i} + \frac{V_i H_i}{g_{v,i} v_i} + 0.75H_i e_{n,i} + \frac{H_i}{L_i} d_{a,i} + H_i \sum_{j=1}^{i-1} \left( \frac{M_j H_j}{(EI)_j} + \frac{V_j H_j^2}{2(ET)_j} \right) + H_i \sum_{j=1}^{i-1} \frac{d_{a,j}}{L_j} \]

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

Deflection-Bending + Rotation translates to top

Deflection-Wall rotation translates to top
Presentation Topics

- Design Considerations
- Complete Load Paths
- Diaphragm Flexibility
- Tall Shear Walls-Flexibility
- **Horizontal Distribution of Shears**
  - Overview-Mid-rise: Exterior shear Walls
  - Overview-Mid-rise: Open Front
Distribution of shear to vertical resisting elements shall be based on:

- 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.
Exterior shear walls

Rigid support or Partial support

Rigid or spring Support ??

Seismic Loads

Wind Loads as applicable

Unit with Exterior Wall

Unit without Exterior Wall

Flexible
Semi-rigid
Rigid

Semi-rigid
Rigid

Flexible
Semi-rigid
Rigid

Full support (SW rigid)

Partial support (Decreasing SW stiffness)

Condition A

Condition B

Condition C

Corridor only SW

Varying Degrees of Stiffness Effects of Exterior Walls
Multi-story Effects of Tall Shear Walls

Note that possible changes in diaphragm flexibility can occur from floor to floor: non-open front (flexible) vs. non-open front/open front (rigid or semi-rigid).
Presentation Topics

- Design Considerations
- Complete Load Paths
- Diaphragm Flexibility
- Tall Shear Walls-Flexibility
- Horizontal Distribution of Shears
- Overview-Mid-rise: Exterior shear Walls
- Overview-Mid-rise: Open Front

The following information is from an on-going example calculation and 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.
Case Study - Non-Open Front Floor Plan With Offsets

- Flexible analysis
- Rigid analysis
- Semi-rigid (Envelope)

- ASCE 7-10 Section 12.3.1.1- (c), Light framed construction, meeting all conditions:
  - All Light framed construction
  - Non-structural concrete topping ≤ 1 ½”
  - Each element of the seismic line of vertical force-resisting system complies with the allowable story drift of Table 12.12-1
  - Longitudinal—Allowed to be idealized as flexible, provided exterior shear walls exist and is in compliance with ASCE 7-10 Section 12.3.1.1 (c). If calculations show that the story drift at a line of lateral force resistance exceeds the allowable limit, flexible diaphragm behavior cannot be used.
Automatic Tensioning Systems/Devises

- Restraints are required at roof and each floor level to get best results
- Software programs are available for design
- Must be installed per manufacturers recommendations

 ATS isolator nut take-up device and bearing plate
Coupler
Semi-balloon framing
Steel rod
Platform framing

Number and size of studs as required by design
Anchorage into foundation as required by calculation and per manufacturers recommendations

Overturning Resistance
Determination of Non-Open Front Diaphragm Flexibility

Sym. C.L.

Tall or narrow SW

Seismic

Displ. \( \Delta_{sw \ ext} \) From Tall wall calc.

Shear Deflection per USDA Research Note FPL-0210

Positive moment

Bending Stiffness = \( A \frac{d^2}{2} \)

Moderately stiff. support

Check exterior SW stiffness effects

Computer Model

Bending

Check Total deflection-Diaphragm flexibility

\( \Delta_{sw \ corr.} \)

\( \Delta_1 \)

\( \Delta_2 \)

\( \Delta_3 \)

\( \Delta_4 \)

\( \Delta_{SW\, \text{aver.}} \)

\( \Delta_{Diaph} \)

\( \Delta_{SW\, \text{ext}} \) From Tall wall calc.

Corridor

Ext. SW

Sym. C.L.

\( \Delta \)

Full depth \( \sum K_{\text{diaph.}} \)

Torsion + acc. torsion

Seismic

Shear Deflection

Nail slip deflection

\( \Delta_{SW\, \text{ext}} \) From Tall wall calc.

\( \Delta_{sw \ ext} \) From Tall wall calc.
Bending increases at start of offset.

Roof Plot - Longitudinal Loads - A/R\(^*\)=1.5:1 (8’ wall)

*Aspect ratios Floor to Floor
Determine Diaphragm and TD Nailing, and Chord Forces

Longitudinal Loading
Drift by semi-rigid or rigid analysis only (Open front)

Spring support
If Shear walls

Same as

Collectors

Collectors

ASCE 7-10 12.8.6
Story drift check (Non-open front)

Check Story Drift - 3D model or 2D plane Grid

W1

or

W2

= +

Drift by semi-rigid or rigid analysis only (Open front)
Story Drift Check Longitudinal + Torsion (8’ ext. walls)

Notice curvature (bending) of offset sections

ASCE 7-10 12.8.6 Story drift check (Non-open front)

Significant shear distributed to corridor walls (cantilever action)

Maximum drift (open front)
Presentation Topics

• Design Considerations
• Complete Load Paths
• Diaphragm Flexibility
• Tall Shear Walls-Flexibility
• Horizontal Distribution of Shears
• Mid-rise: Exterior shear Walls

• Overview-Mid-rise: Open Front

The following information is from an on-going example calculation and 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.
Relevant 2015 SPDWS 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

Figure 4A Examples of Open Front Structures
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.
**Case Study - Open Front Floor Plan With Offsets**

- Rigid analysis
- Semi-rigid (Envelope)

![Diagram of a floor plan with annotations](image)

- **Open Front**
  - Corridor walls typical
  - Shear panels are required over corridor walls

- **Non-Open Front**
  - Shear panels are required over corridor walls

- **Typical Unit**
  - Transverse shear walls typical
  - No exterior shear walls typical

**Annotations:**
- SW1, SW2, SW3, SW4, SW5
- 1.33, 1.67
- 11.5', 23', 27', 35'
- 6', 35', 76'
- 26' typ.
Check drift at edges (extreme corners) including torsion plus accidental torsion (Deflection-strength level x Cd.)

- Seismic-meet ASCE7 drift
- Wind-deflections can be tolerated.
Final Diaphragm (Total) Deflections

Verify Diaphragm Flexibility:
- If flexible, add blocking
- If still flexible, decrease nail spacing to stiffen up

Check for diaphragm flexibility

Seismic
Reference Materials

• 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-The Analysis of Irregular Shaped Diaphragms (paper). Complete Example with narrative and calculations.

Method of Analysis and Webinar References

Offset Diaphragms

Offset Shear Walls

Diaphragms Openings

Example Results

FTAO Shear Walls

Mid-rise Design Considerations

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

This concludes Woodworks Webinar on:
Lateral Design Considerations for Mid-rise Structures