Light-Frame Mid-Rise Shear Wall and Diaphragm Design Approaches

Including Use of the Special Design Provisions for Wind and Seismic 2015

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Multi-Story Light-Frame Residential Buildings
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Engineering Challenges

- Diaphragm behavior uncertainty
- Code requirements
- Diaphragm deflection calculations
- Shear wall deflection calculations (including multi-story behavior)
- Determining building drifts
Light-Framed Multi-Story Residential Building Plan
Simplified Floor Plan

- Red: Corridor shear walls
- Green: Party shear walls
SDPWS - 08 (Spid-Wiz)
Diaphragm Rigidity
(SDPWS-08)

- Diaphragms shall be defined as rigid or flexible for the purposes of distributing shear loads and designing for torsional moments.
Terminology (SDPWS-08)

**Diaphragm, Flexible**
- Calculated Flexible Diaphragm Condition
  \[ \Delta_{\text{diaphragm}} > 2 \times \Delta_{\text{shearwall}} \]

**Diaphragm, Rigid**
- Calculated Rigid Diaphragm Condition
  \[ \Delta_{\text{diaphragm}} < 2 \times \Delta_{\text{shearwall}} \]
Cantilevered Diaphragms (SDPWS-08)

- Rigid wood-frame diaphragms shall be permitted to cantilever past the outermost supporting shear wall a distance, $L_c$, of not more than 25ft or 2/3 of the diaphragm width, $W$, whichever is smaller.
Open Front Structures (SDPWS-08)

1. The diaphragm length, L, does not exceed 25ft.
2. The L/W ratio of the diaphragm ... is less than or equal to 1:1 for one-story structures or 0.67:1 for structures over one story in height.
Exception: Where calculations show that diaphragm deflections can be tolerated, the length, L, (normal to the open side) shall be permitted to be increased to an L/W ratio not greater than 1.5:1 when sheathed in conformance with 4.2.7.1 or 4.2.7.3, or not greater than 1:1 when sheathed in conformance with 4.2.7.2.
Open Front Structures Summary (SDPWS-08)

Section 4.2.5.1.1

- Length, L, less than 25 feet
- L/W less than 0.67
- Exception - where calculations show that diaphragm deflections can be tolerated
In buildings of wood frame construction where rotation is provided for, the depth of the diaphragm normal to the open side shall not exceed 25 feet nor two-thirds the diaphragm width, whichever is the smaller depth. Straight sheathing shall not be permitted to resist shears in diaphragms acting in rotation.

**EXCEPTIONS:**
1. One-story, wood-framed structures with the depth normal to the open side not greater than 25 feet, may have a depth equal to the width.
2. Where calculations show that diaphragm deflections can be tolerated, the depth normal to the open end may be increased to a depth to width ratio not greater than $1\frac{1}{2}:1$ for diagonal sheathing or $2:1$ for special diagonal sheathed or plywood diaphragms.
Coordination with ASCE 7-10

ASCE 7-10 terminology (12.3.1)
- “modeled as semi-rigid”
- “idealized as flexible”
- “idealized as rigid”

Torsional irregularity (Table 12.3-1)
- Applicable only when diaphragms are rigid or semi-rigid

Inherent/Accidental torsion requirements (12.8.4.1, 12.8.4.2, 12.8.4.3)
- Applicable for diaphragms that are not flexible
Section 12.3.1 Diaphragm Flexibility

Unless a diaphragm can be idealized as either flexible or rigid, the structural analysis shall explicitly include consideration of the stiffness of the diaphragm (i.e. semi-rigid modeling assumption)
ASCE 7-10 Semi-rigid Diaphragm

- Apparently preferred by ASCE 7-10, but difficult to calculate for wood panel construction due to non-linear load-deformation relationship.
ASCE 7-10 Flexible Diaphragm

ASCE 7 Section 12.3.1.1
Idealization of flexible diaphragm

- Toppings < 1 ½ inches thick
- Each line of vertical elements satisfy drift requirements
  (seldom checked accurately in current practice)

ASCE 7 Section 12.3.1.3
Calculated Flexible Diaphragm Condition

- $\Delta_{\text{diaphragm}} > 2 \times \Delta_{\text{shearwall}}$
Section 12.3.1.2 Rigid Diaphragm Condition

- Diaphragms of concrete slabs or concrete-filled metal deck.
Confusing diaphragm verbiage - implies that a flexible diaphragm can work in torsion

Diaphragm verbiage not consistent with ASCE 7-10

Distinction between cantilever diaphragms and open front structures is not clear

No definition of how to demonstrate that diaphragm deflection can be tolerated when exceeding 25 ft.
AWC WDSC

- Wood Design Standards Committee Wind and Seismic Task Group (WSTC) on Rigid Diaphragms
- Formed in early 2012, under American Wood Council’s WSTC
WSTC TG5

- WSTC Task Group 5 (1 of 5 special Task Groups)
  Developed to propose revisions to diaphragm flexibility and open front structure provisions

- WSTC Task Group 5 members included:
  Rawn Nelson, Doug Hohbach, Tom VanDorpe, Dick Hemmen, Gary Mochizuki, Doug Thompson, Marc Press, Jim Mahaney, Randy Shackelford
WSTC TG5

- To address open front structures and cantilever diaphragms
- Update provisions in SDPWS not well suited to complex wood buildings
- Clarify confusion in practice regarding the basis and application of provisions
Diaphragm Rigidity (SDPWS-15)

4.2.5 Horizontal Distribution of Shear

The distribution of shear to vertical resisting elements shall be based on an analysis where the diaphragm is modeled as semi-rigid, idealized as flexible, or idealized as rigid. When a diaphragm is idealized as flexible, the diaphragm shear forces shall be distributed to the vertical resisting elements based on tributary area. When a diaphragm is idealized as rigid, the diaphragm shear forces shall be distributed based on the relative lateral stiffnesses of the vertical-resisting elements of the story below. It shall be permitted to idealize a diaphragm as rigid when the computed maximum in-plane deflection of the diaphragm itself under lateral load is less than or equal to two times the average deflection of adjoining vertical elements of the lateral force-resisting system of the associated story under equivalent tributary lateral load.

When a diaphragm is not idealized as rigid or flexible, the diaphragm shear forces shall be distributed to the vertical resisting elements using a semi-rigid diaphragm analysis based on the relative stiffnesses of the diaphragm and the vertical resisting elements accounting for both shear and flexural deformations. In lieu of using a semi-rigid diaphragm analysis for distribution of story shear forces, it shall be permitted to use an enveloped analysis whereby distribution of horizontal diaphragm shear to each vertical resisting element is the larger of the shear forces resulting from analyses where the diaphragm is idealized as flexible and the diaphragm is idealized as rigid.

Shear Distribution assumptions:
- Modeled as semi-rigid
- Idealized as flexible
- Idealized as rigid

Calculated rigid condition:
- Definition removed but idealized as rigid permitted where $\Delta D < 2\Delta SW$

Semi-rigid diaphragm analysis

Envelope procedure added:
- permitted in lieu of semi-rigid analysis
Provisions re-organized to provide more logical flow of information.

Limited to diagonally sheathed and wood structural panel diaphragms (no change).

Aspect ratio limits (no change). More restrictive limits invoked for torsionally irregular structures.

Required: i) check of story drift at each edge regardless of whether structure is torsionally irregular, ii) semirigid modeling or idealized as rigid diaphragm assumption.

Cantilevered diaphragm length limited to 35' - replaces 25' which could be exceeded where deflections can be tolerated.

Exclude small cantilevered conditions, 6ft, from open front provisions. Torsionally irregular requirements of 4.2.5.1 still apply.

Allow small one story structures to assume rigid diaphragm.
Open Front Structures

SDPWS-08
Figures

SDPWS-15
Figures
Open Front Structures (SDPWS-15)

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

- The L’/W’ ratio ... is not greater than 1.5:1
- Maximum story drift at each edge of the structure shall not exceed the ASCE 7 allowable story drift (including torsion and accidental torsion)
- L’ does not exceed 35 feet
For open front structures one story in height, where L’ is not more than 25ft and L’/W’ is less than or equal to 1:1, the cantilevered diaphragm defined by L’ x W’ ... shall be permitted to be idealized as rigid for purposes of distribution of shear forces through torsion.

(Drift need not be calculated)
Exception: Wood frame diaphragms in open front structures in which the diaphragm edge cantilevers no more than six feet beyond the nearest line of vertical elements of the lateral force-resisting system need not comply with Section 4.2.5.2.

(Drift need not be calculated)
Torsional Irregularity

4.2.5.1 Torsional Irregularity: Structures with wood-frame diaphragms modeled as semi-rigid or idealized as rigid shall be considered as torsionally irregular under seismic load when the maximum story drift, computed from seismic design forces including accidental torsion, at one end of the structure is more than 1.2 times the average of the story drifts at the two ends of the structure. Where a torsional irregularity exists in structures assigned to Seismic Design Category B, C, D, E, or F, diaphragms shall meet all of the following requirements:

1. The diaphragm conforms to 4.2.7.1, 4.2.7.2, or 4.2.7.3.
2. The L/W ratio is not greater than 1.5:1 when sheathed in conformance with 4.2.7.1 or not greater than 1:1 when sheathed in conformance with 4.2.7.2 or 4.2.7.3.
3. The maximum story drift at each edge of the structure shall not exceed the ASCE 7 allowable story drift when subject to seismic design forces including torsion, and accidental torsion.

Trigger special provisions for diaphragms that are:
- modeled as semi-rigid
- idealized as rigid

Clarify applicability to SDC B-F.

Where torsionally irregular, check story drift at each edge.
Torsional Irregularity (SDPWS-15)

2. The L/W ratio is not greater than 1.5:1 when sheathed in conformance with 4.2.7.1 or not greater than 1:1 when sheathed in conformance with 4.2.7.2 or 4.2.7.3.

3. The maximum story drift at each edge of the structure shall not exceed the ASCE 7 allowable story drift when subject to seismic design forces including torsion, and accidental torsion.
12.3.3.4 Increase in forces Due to Irregularities for Seismic Design Categories D through F.

... design forces...shall be increased 25 percent for connections of diaphragms to vertical elements and to collectors and their connections to the vertical elements of the seismic force-resisting system.
AWC WDSC

Summary of Reasons for Change

- Coordinate with diaphragm rigidity terms in ASCE 7-10
- Clarification to permit more uniform application of provisions to open front structures
- Provide more rational hierarchy of diaphragm requirements within SDPWS - baseline requirements for torsionally irregular structures with increased requirements for open front structures
SDPWS
SDPWS and IBC

- 2015 SDPWS is referenced in 2015 IBC
SDPWS-15 Changes Summary

- Open front structures require drift calculations
- 35’ prescriptive limit for cantilevered diaphragms
- Enveloped analysis allowed in lieu of semi-rigid analysis
- Rigid diaphragm may be idealized based on calculations
- Lots of clarifications
SDPWS-15 Changes Summary

Not a change, but important

- If diaphragm is idealized as flexible, required to calculate drift at each line of vertical elements (already in ASCE 7-10)
Multi-Story Light-Frame Residential Buildings
Simplified Floor Plan

- Corridor shear walls
- Party shear walls
Diaphragm Aspect Ratio

Shear walls

Diaphragm aspect ratio
Diaphragm Aspect Ratio

- Shear walls
- Diaphragm aspect ratio
Rigid Diaphragm

- $\Delta D / \Delta SW = 0.6$ (Transverse Party walls)
- $\Delta D / \Delta SW = 1.3$ (Longitudinal Corridor/Ext. walls)
Flexible Diaphragm Analysis

- Need lateral force resisting elements on all sides of structure
- Required to calculate drift at each line of resistance
Flexible Diaphragm Concerns

- Underestimates forces distributed to the corridor walls (long walls)
- Overestimates forces distributed to the exterior walls (short walls)
- May result in under design of diaphragm shears (i.e. no blocking)
- Computation of building drift problematic
Rigid Diaphragm Analysis

- More accurately distribute lateral forces to corridor and party walls
- Facilitates calculation of building drift
- Contribution of non-full height shear walls are more accurately incorporated
- Straightforward to build three dimensional computer model for analysis
- Usually results in requirement of blocked diaphragm
FINDINGS

- Better building performance will result when seismic forces are resisted locally rather than being redistributed to other portions of the structure.

- Special design attention is needed for transverse walls resisting torsion.

- Reduce torsional response by providing additional capacity and stiffness in transverse and slender elements.
Calculating Building Drift

- Deformation of multi-story shear walls.
- Deformation of cantilevered diaphragm
Shear Wall Deformation

- SDPWS Section 4.3.2
- $\Delta_s = \frac{8\nu h^3}{EAb} + \frac{\nu h}{1000G_a} + \frac{h\Delta_a}{b}$
Shear Wall Deformation

Double-sided w/ finishes

Strength Capacity
(defines linear behavior)
$$\Delta s = \frac{8\nu h^3}{EAb} + \frac{\nu h}{1000G_a} + \frac{h\Delta_a}{b}$$
Multi-Story Shear Wall Deformation

\[ \Delta s = \frac{8\nu h^3}{E A b} + \frac{\nu h}{1000 G_a} + \frac{h \Delta a}{b} \]
Multi-Story Shear Wall Lengths

\[ \Delta s = \frac{8 \nu h^3}{E A b} + \frac{\nu h}{1000 G_a} + \frac{h \Delta_a}{b} \]

H/L = 2, L = 15ft min.

H = 30ft
Multi-Story Shear Wall Deformation
Three-Dimensional Modeling
Benefits of Three-Dimensional Modeling

- Facilitates shear distribution utilizing rigid diaphragms and multi-story shear wall behavior
- Approximates building drifts
- Distribute direct and torsional shear forces
- Approximates stiffness of non-full height shear walls
Multi-Story Shear Wall Deformation

\[ \Delta_T = \Sigma (Vh_i^2)(3L_T-h_i)/6EI_T \]
Typical Floor Plan
3D Model - Plan View
3D Model - Plan View

Assumptions:
- Plywood Type
- Plywood Thickness
- Nailing Pattern
- Chord Size
- Hold Down

Group 1
Group 2
Group 3
Shear Wall Deformation

Deflection (inches)

Force (plf)

Double-sided w/ finishes

Strength Capacity (defines linear behavior)

Double-sided 20'
Idealized Double-sided 20'

Chord Slip

0.00 0.10 0.20 0.30 0.40 0.50 0.60 0.70
3D Model - Isometric View

Roof
4th flr.
3rd flr.
2nd flr.
1st flr.
3D model - Isometric View
3D Model - Isometric View

Assumptions
- Plywood Type ✓
- Plywood Thickness ✓
- Nailing Pattern ✓
- Chord Size ✓
- Hold Down ✓
$\Delta_{Tot} = \Delta_b + \Delta_\theta + \Delta_{Diaph}$
SDPWS -15 Practical Implications

Calculate building drift

Consider multi-story shear wall behavior

Consider diaphragm rigidity to model 3-dimensionally

Diaphragm will generally need to be blocked
Typical Floor Plan
Shear wall information

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Shear wall calculation
Shear wall input

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Stiffness

\[ \Delta_s = \frac{8\nu h^3}{EA b} + \frac{\nu h}{1000G_a} + \frac{h\Delta_a}{b} \]

\[ \Delta_T = \Sigma (Vh_i^2)(3L_T-h_i)/6EI_T \]
3D Model - Isometric View

Roof
4th flr.
3rd flr.
2nd flr.
1st flr.
SEAOC Resources

- SEAOC Seismic Design Manual
- SEAOC Seismology Light Frame Subcommittee
Non-Typical Floor Plan

Non-uniform distribution of lateral force resisting elements
Non-Typical Floor Plan

Non-uniform distribution of lateral force resisting elements

Seismic joint required
Non-Typical Floor Plan

Uniform distribution of similar stiffness lateral force resisting elements
3D model - Isometric View
3D model - Isometric View
Light-Frame Mid-Rise Shear Wall and Diaphragm Design Approaches