SEISMIC ANALYSIS OF LIGHT-FRAMED MULTI-STORY RESIDENTIAL BUILDINGS

Woodworks March 2009 Seminar

SEISMIC ANALYSIS OF LIGHT-FRAMED MULTI-STORY RESIDENTIAL BUILDINGS

Samuel Shiotani, S.E.
Douglas Hohbach, S.E.
Joaquim Roberts, S.E.

CHALLENGES

• Diaphragm behavior
• ASCE 7-05 & 2007 CBC requirements
• Deformation of multi-story shear walls to determine appropriate distribution of lateral forces and building drift

BUILDING GEOMETRY

TYPICAL FLOOR PLAN

Light framed multi-story residential buildings often have uniformly distributed shear walls of approximately equivalent stiffnesses except
• at exterior
• sometimes at first floor

TYPICAL FEATURE

Corridor shear walls
Party shear walls
Exterior shear walls
DIAPHRAGM ASPECT RATIO

DIAPHRAGM BEHAVIOR

- ASCE 7 Section 12.3.1
  Diaphragm Flexibility
  • Flexible
  • Rigid
  • Semi-rigid

FLEXIBLE DIAPHRAGM CONCERNS

- Underestimates forces distributed to the corridor walls (long walls)
- Overestimates forces distributed to the exterior walls (short walls)
- Computation of building drift problematic

RIGID DIAPHRAGM

- ASCE 7
  \( \frac{\Delta_d}{\Delta_{SW}} = 0.6 < 2 \) (Transverse – Party walls)
  \( \frac{\Delta_d}{\Delta_{SW}} = 1.3 < 2 \) (Longitudinal – Corridor/Ext. walls)
BENEFITS OF RIGID DIAPHRAGM ANALYSIS

• More accurately distribute lateral forces to corridor and party walls
• Approximate building drift
• Build three dimensional computer model for analysis

OPEN FRONT STRUCTURE

Per CBC 2006 Section 2305.2.5 Rigid diaphragms

• Length, L, less than 25 feet
• LW less than 0.67
• Exception – where calculations show that diaphragm deflections can be tolerated

CUREE WOODFRAME PROJECT OPEN FRONT BUILDINGS

FINDINGS

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

CUREE WOODFRAME PROJECT OPEN FRONT BUILDINGS

FINDINGS

• Special design attention is needed for transverse walls resisting torsion.
• Reduce torsional response by providing additional capacity and stiffness in transverse and slender elements.

NORTHRIDGE EARTHQUAKE DAMAGE OPEN FRONT BUILDINGS
1997 Uniform Building Code

- Section 1633 – Detailed Systems Design Requirements
  1633.2.5 Ties and continuity

All parts of a structure shall be interconnected and the connections shall be capable of transmitting the seismic force induced by the parts being connected. As a minimum, any smaller portion of the building shall be tied to the remainder of the building with elements having at least a strength to resist 0.5 $C_{u}I$ times the weight of the smaller portion.

- Section 1633 – Detailed Systems Design Requirements
  1633.2.9 Diaphragms

7. In structures in Seismic Zones 3 and 4 having a plan irregularity of Type 2 in Table 16M, diaphragm chords and drag members shall be designed considering independent movement of the projecting wings of the structure. Each of these diaphragm elements shall be designed for the more severe of the two following assumptions:
   - Motion of the projecting wings in the same direction
   - Motion of the projecting wings in the opposing direction

Exception: This requirement may be deemed satisfied if the procedures of Section 1631, in conjunction with a three-dimensional model have been used to determine the lateral seismic forces for design.
ASCE 7-05

- Section 12.12 – Drift and Deformation
  12.12.3 Building Separation
  
  All portions of the structure shall be designed and constructed to act as an integral unit in resisting seismic forces unless separated structurally by a distance sufficient to avoid damaging contact under total deflection (δ) as determined in Section 12.8.8.

ASCE 7-05

- Diaphragms, Chords and Collectors
  12.10.2 Collector Elements
  
  Collector elements shall be provided that are capable of transferring the seismic forces originating in other portions of the structure to the element providing the resistance to those forces.

ASCE 7-05

- Diaphragms, Chords and Collectors
  12.10.2.1 Collector Elements Requiring Load Combinations with Overstrength
  
  In structures assigned to Seismic Design Category C, D, E, or F, collector elements shall be provided that are capable of transferring the seismic forces originating in other portions of the structure to the element providing the resistance to those forces.

Exception: In structures or portions thereof braced only by light-frame shear walls, collector elements, splices, and connections to resisting elements need only be designed to resist forces in accordance with Section 12.10.1.1.

ASCE 7-05

Table 12.3-1 Horizontal Structural Irregularities

<table>
<thead>
<tr>
<th>Irregularity Type and Description</th>
<th>Reference Section</th>
<th>Seismic Design Category Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>2. Reentrant Corner Irregularity is defined to exist where both plan projections of the structure beyond a reentrant corner are greater than 10% of the plan dimension of the structure in the given direction.</td>
<td>12.3.14 Table 12.4-1</td>
<td>B, C, D, E, and F</td>
</tr>
<tr>
<td>3. Diaphragm Discontinuity Irregularity is defined to exist where there are diaphragms with abrupt discontinuities or variations in stiffness, including those having cutout or open areas greater than 50% of the gross enclosed diaphragm area or changes in effective diaphragm stiffness of more than 50% from one story to the next.</td>
<td>12.3.14 Table 12.4-1</td>
<td>B, C, D, E, and F</td>
</tr>
</tbody>
</table>

ASCE 7-05

- Table 12.3-1
  2. Re-entrant Corner Irregularity
    See 12.3.3.4 and Table 12.6 1br Seismic Categories D, E, and F
  3. Diaphragm Discontinuity Irregularity
    See 12.3.3.4 and Table 12.6 1br Seismic Categories D, E, and F
12.3.3.4 Increase in forces Due to Irregularities for Seismic Design Categories D through F.

For structures assigned to Seismic Design Category D, E or F and having a horizontal structural irregularity of Type 1a, 1b, 2, 3 or 4 or a vertical structural irregularity of Type 4 in Table 12.3-1, the design forces determined from Section 12.8.1 shall be increased 25 percent for connections of diaphragms to vertical elements and to collectors and for connections of collectors to the vertical elements. Collectors and their connections shall be designed for these increased forces unless they are designed for the load combinations with overstrength factor of Section 12.4.3.2, in accordance with Section 12.10.2.1.

Table 12.6-1 Permitted Analytical Procedures

<table>
<thead>
<tr>
<th>Category</th>
<th>Static Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>D, E, F</td>
<td>P, P</td>
</tr>
<tr>
<td>All other structures</td>
<td>NP, P</td>
</tr>
</tbody>
</table>

ASCE 7-05

No seismic joints are required for 3-story or less light frame building.

ASCE 7 apparently assumes that light frame buildings are laterally braced by evenly distributed shear walls of roughly equivalent stiffness.

An analysis incorporating diaphragm rigidity is required for light frame buildings taller than 3-stories to identify potential torsional irregularity.

An analysis incorporating diaphragm rigidity should be used for buildings with non-uniform distribution or stiffness of vertical elements (required by code for mixed systems).
Provide uniform distribution of similar stiffness lateral force resisting elements.

- Use rigid diaphragm analysis
  - (use semi-rigid as necessary at large diaphragm spans or anomalies)

\[ \Delta_s = \frac{8vh^2}{EA_b} + \frac{vh}{G_t} + \frac{0.75h_{e_n}}{b} + \frac{h_{d_a}}{b} \]

CBC Section 2305.3.2

\[ \Delta = 88 \nu + 0.75h_{e_n} + 0.75h_{e_n} + h_{d_a} \]

SHEAR WALL DEFORMATION

Double-sided w/ finishes

Strength Capacity (defines linear behavior)

STACKED SHEAR WALL DEFORMATION

\[ \Delta_1 = \Delta_4 + \Delta_3 + \Delta_2 \]
MULTI-Story Shear Wall Deformation

**SEAOC Seismology (2007)**
- Structures depend on longer shear walls

**SEAOC Blue Book (1999)**
- Aspect ratios > 2:1 cannot be adequately predicted

\( H/L = 2, L = 15 \text{ ft min.} \)

THREE-DIMENSIONAL MODELING

**Continuous**
\[ \Delta_T = \frac{\sum (Vh_i^2)(3L-h_i)/6EI_T}{L^2} \]

**Stacked**
\[ \Delta_T = Vh_i^3/3EI \]

Continuous vs. Stacked Shear Wall Deformation

- Approximate building drift
- Distribute direct and torsional shear forces
- Stiffness of non-full height shear walls incorporated correctly

Benefits of Three-Dimensional Modeling

- \( h_1 \leq 30 \text{ ft} \)
- \( L = 15 \text{ ft min.} \)
Assumptions

Plywood Type
Plywood Thickness
Nailing Pattern
Chord Size
Hold Down

Group 1
Group 2
Group 3

CONCLUSION

The appropriate analysis technique for light-framed multi-story residential buildings is rigid diaphragm analysis incorporating multi-story shear wall deformations via three-dimensional modeling.