Simplified Modeling of Non-Rectangular RC Structural Walls

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Outline

• Introduction
• Simplified Modeling Procedure
  – Load vs. Deflection Relationship
  – Prediction of Damage States
• Validation
• Summary & Recommendations

Specimen NTW1

• 4 stories
• Continuous reinforcement over height
• Reinforcement concentrated in boundary elements
• Confinement spacing relaxed from ACI 318-02 (consistent with ACI 318-11)
Specimen NTW2

- 2 stories
- Lap splices above first floor level
- Uniformly distributed longitudinal steel in flange
- Expanded confined region

Deformations of Interest

- Shear
- Flexure
- Strain
- Penetration

Existing Modeling Tools

- Simplified Models
  - FEMA 356/ASCE 41 Supplement 1
  - Hines Bridge Pier Model
- Other Models
  - Waugh & Aaletti OpenSees Wall Model
  - Other finite-element-based approaches

Applied displacements

Performance Level

<table>
<thead>
<tr>
<th>Immediate Occupancy</th>
<th>Life Safety</th>
<th>Collapse Prevention</th>
</tr>
</thead>
<tbody>
<tr>
<td>Damage State &amp; Needed Repair</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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- Recommendations
Desired Capabilities of Procedure

- Appropriate for general design use
- More precise than FEMA 356/ASCE 41 Supp. 1
- Applicable to any flexural wall geometry (i.e. rectangular or flanged, height, length)
- Not sensitive to particular detailing (i.e. distributed or concentrated reinforcement, splices, confinement)
- Applicable to any loading direction, orthogonal or skew
- Transparent procedure, additional terms can be incorporated

F-S-SP Integration Model

- Based on flexural sectional analysis

  - Flexural Component
    - Integrate M-\(\phi\) twice
  - Shear Component
    - Calculated from cracked shear stiffness & flexural stiffness
  - Strain Penetration Component
    - Calculated from longitudinal strains at base

Flexural Component of Deformation

- Section analysis calculates M-\(\phi\) relationship
- Integrate twice over height of specimen to get P-\(\Delta\) for flexural deformations
- Assumes plane sections remain plane
  - Neglects shear lag in flanged walls
  - Neglects tension shifting
- Challenges with post-peak behavior

Effectiveness of Model

- Observed relationship between shear deformation and flexural damage

Shear Demands and Shear Deformation

- Interstory shear displacement, shear failure - web direction
- Load vs. displacement graph
- Uncracked stiffness
Proposed Method

- $\Delta v = C^* \theta$ or $\gamma = C^* \psi$
- Use cracked shear stiffness & flexural stiffness at yield to define proportional relationship

\[ K_s = \frac{\rho E_b d}{1 + 4n_p} \] for 45° cracks

- $C = \frac{M}{z}$, $z$ = shear span

Effectiveness of Model

Proposed Method

- Assume constant bond length & strain gradient

\[ \delta = \frac{\delta_{p}}{d-c} \]

Strain Penetration

- Assume plane sections remain plane
- Assume behavior in tension and compression similar

\[ \theta = \frac{\delta_{p}}{d-c} \]

Prediction of Damage Levels

<table>
<thead>
<tr>
<th>Damage Performance Level</th>
<th>Local EDP</th>
<th>Threshold Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Negligible</td>
<td>Steel tensile strain</td>
<td>$\varepsilon_s &lt; 0.003$</td>
</tr>
<tr>
<td>Immediate Occupancy</td>
<td>Steel tensile strain</td>
<td>$\varepsilon_s &lt; 0.003$</td>
</tr>
<tr>
<td>Minimal</td>
<td>Core concrete compressive strain</td>
<td>$&gt;0.003 \varepsilon_c$, or $0.003$</td>
</tr>
<tr>
<td>Moderate</td>
<td>Core concrete compressive strain</td>
<td>$&gt;0.003 \varepsilon_c$, or $0.003$</td>
</tr>
<tr>
<td>Significant Collapses</td>
<td>Placement of section</td>
<td>FEMA 356, ATC 58-2, etc.</td>
</tr>
</tbody>
</table>

FEMA 356, ATC 58-2, etc.

Berry, Lehman, & Lowes (2008)
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Model Validation

- Comparison to NTW1 & NTW2
- Comparison to results of 6 tests reported in literature
- Comparison to FEMA 356/ASCE 41 Supplement 1 & Hines models
- All validation based on reported as-built material properties
  - In general
    - Moment capacity predicted within 5% in all cases
    - Displacement capacity typ. underpredicted 5 to 40%

Sections Used for Validation

- Johnson (2 walls) \( h/l = 2.7 \)
- Wallace \( h/l = 3.0 \)
- Sittipunt & Wood \( h/l = 3.0 \)
- Hines (2 piers) \( h/l = 2.6 \)

Comparison to FEMA 356/ASCE 41 Supp. 1

Evaluation of Proposed Model

- NTW1 Flange Direction
  - Load capacity within 3%
  - Underestimates drift capacity
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Summary of Model

• Takes advantage of relative ease of modeling flexure
• Applicable to more generalized cases than existing simplified tools
• More accurate than existing simplified tools
• Provides framework for predicting damage levels
• Validated using results of tests with aspect ratios of 2.5 to 3.0
• Does not track damage due to prior load history

Possible Modifications to F-S-SP Integration Model

• Calibration of threshold strains for damage prediction using larger data set
• Incorporate shear lag effects
• Add “artificial” plastic hinge length to represent tension shifting
• Improve prediction of post-peak behavior
• Refine shear crack angle prediction
• Refine strain penetration model

Questions?

Measured vs. Predicted Curvature

Potential Implications of Neglecting Tension Shifting
Variation in Crack Angle

- General relationships can be established for crack angle; reliable prediction is difficult

Pure Shear

Shear + Axial Compression

Shear + Axial Tension

Lap Splices

Outside Plastic Hinge Region

- Splices in 2nd story did not slip during testing

Rectangular wall with lap splices at base

Lap Splices

Outside Plastic Hinge Region

- Splices in 2nd story did not slip during testing
- Lap splices did interrupt yielding
- Neglecting splice increases flexibility ~1-2%
- Use a 2nd model with double steel for lap region

Effectiveness of Flexural Model with Lap Splices

Evaluation of Proposed Model

NTW2 Web Direction

- Load capacity within 0.5%
- Underestimates drift capacity

NTW2 Flange Direction

- Load capacity within 3%
- Underestimates drift capacity
Hines Bridge Pier Model

- Modeling of bridge piers based on sectional analysis
- Limited to cantilevers loaded at tip
- Results only at tip
- Assumes relationship between flexure and shear/strain penetration
- Includes tension shifting term

Comparison to Hines Model

Key Contributions
Performance Based Engineering

- Developed simplified pushover model appropriate for routine design use
- Model separates contributions of flexure, shear, and strain penetration
- Established thresholds linking significant damage levels to local strains

Shear and Flexure Interaction

- Previous researchers have reported a linear relationship between deformation components at tip of specimen

Comparision of Bar Slip Models

Evaluation of Proposed Model
NTW1 Web Direction

- Load capacity within 2%
- Overestimates drift capacity (exceptional case)
FEMA 356 model

- Modeling of flexure-controlled walls based on elastic flexural stiffness, yield moment, prescribed inelastic drift capacity
- Thought to be very conservative

\[ \text{Load} - P_y \]

\[ \Delta y/h \]

\[ \Delta \text{Drift}=\Delta y/h \]

40\%P_y

Estimating $\delta_{\text{slip}}$

- Bar "slip" is found by integrating strain over anchorage length
- Simplified procedure
  - Assume bond length constant regardless of applied bar stress
  - Assume strain gradient constant over anchorage length

More detailed model (i.e., Lowes & Altoontash)

Simplified model

Shear and Flexure Interaction

- Profile of shear deformation similar to profile of rotation over height
- $\gamma=C^\phi$ or $\Delta_\gamma=C^\theta_f$

Performance-Based Design

- Statistically-based expectation of seismic events
- Multiple design options
- Model of Structure
- Performance expectation for each design option
- Cost analysis over entire building life
- Recommendation to building owner