Numerical prediction of the in-plane cyclic behavior of reinforced concrete shear walls

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Overview

• Introduction
• Numerical models
• Objective- sensitivity to geometry and material parameters
• Results
• Conclusions
**Introduction**

Reinforced concrete (RC) structural walls provide lateral stiffness and strength in medium to tall buildings.

Performance of few RC shear walls in recent earthquakes raised concerns.

- Splices within plastic hinge length
- Thin wall boundaries
- Low longitudinal reinforcement ratio

Need for code improvements?

Need for good analytical tools!

• Need to simulate wall response and anticipate failure mode, thus exercise the numerical tools response sensitivity geometry and material properties.
Numerical Models

1. **Micro** (membrane Models)
2. **Meso-scale** (fiber and membrane Models)
3. **Macro** (Beam Column, Multiple Spring, Truss, TVLEM, MVLEM Models)
4. **Shell elements** (MCTF, Vecchio et al., 1986)

**Cyclic Shear-Flexure Interaction Model for RC Walls in OpenSees:**

**SFI-MVLEM:** 2D fiber based macroscopic model

- Coupling of axial and shear response at the panel level.
- Model formulation based on fixed strut angle model (FSAM) + shear resisting mechanism along concrete cracks

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**RC Shear Wall Model**

Validation

Experimental Data

## Sensitivity study

### Wall specimen considered

<table>
<thead>
<tr>
<th>Wall</th>
<th>AR</th>
<th>( \frac{b}{L} )</th>
<th>( \rho_{\text{be},l} ) [%]</th>
<th>( \rho_{\text{web},v} ) [%]</th>
<th>N/A ( f'_c ) [%]</th>
<th>( f'_c ) [MPa]-[ksi]</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>WSH1</td>
<td>2.28</td>
<td>0.10</td>
<td>1.32</td>
<td>0.30 – 0.25</td>
<td>5.1</td>
<td>45.0 - 6.5</td>
<td>Lowest ductility prop of reinf.</td>
</tr>
<tr>
<td>WSH2</td>
<td>2.28</td>
<td>0.10</td>
<td>1.32</td>
<td>0.30 – 0.25</td>
<td>5.7</td>
<td>40.5 - 5.9</td>
<td>Improved ductility WSH1</td>
</tr>
<tr>
<td>WSH3</td>
<td>2.28</td>
<td>0.13</td>
<td>1.54</td>
<td>0.54 – 0.25</td>
<td>5.8</td>
<td>39.2 – 5.7</td>
<td>Model ductile wall</td>
</tr>
<tr>
<td>WSH4</td>
<td>2.28</td>
<td>0.00</td>
<td>1.54</td>
<td>0.54 – 0.25</td>
<td>5.7</td>
<td>40.9 – 5.9</td>
<td>WSH3 without ties (limited ductility)</td>
</tr>
<tr>
<td>WSH5</td>
<td>2.28</td>
<td>0.13</td>
<td>0.67</td>
<td>0.27 – 0.25</td>
<td>12.8</td>
<td>38.3 – 5.6</td>
<td>Half reinf. of WSH3, but same moment capacity</td>
</tr>
<tr>
<td>WSH6</td>
<td>2.26</td>
<td>0.19</td>
<td>1.54</td>
<td>0.54 – 0.25</td>
<td>10.8</td>
<td>45.6 – 6.6</td>
<td>Reinf. as WSH3, large moment capacity</td>
</tr>
<tr>
<td>UCSD2</td>
<td>2.00</td>
<td>0.19</td>
<td>1.95</td>
<td>0.80 – 0.55</td>
<td>7.3</td>
<td>41.5 – 6.0</td>
<td>Full-scale ductile wall (ACI-318). Ordinary reinf. prop.</td>
</tr>
</tbody>
</table>

1: Dazio et al. (2009) - Quasi-static cyclic test and plastic hinge length analysis of RC shear walls.

2: Faraone et al. (2017) - Post-installed anchors behavior in a full scale slender RC shear wall subjected to cyclic lateral loading.
Sensitivity study- wall database

Common features:
- $AR \approx 2$
- Modern code-based design

Variations:
- Range of axial loads
- High and low ductility design

Dazio et al. (2009)- Quasi-static cyclic test and plastic hinge length analysis of RC shear walls.
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Sensitivity study

Geometry - mesh sensitivity

Dowel stiffness

\[ F_d = k_d \Delta_d \]
\[ K_d = \alpha E_{s0} \]
\[ \alpha = \text{from 0 to 0.05} \]

Tangent stiffness upon unloading from tension

Tensile concrete strength

- Hsu: \( f_t = 3.75 \sqrt{f'c} \)
- EC2: \( f_t = 1.5 f'c^{0.67} \)
- ACI: \( f_t = 7.4 \sqrt{f'c} \)
Results - Mesh sensitivity

\[
\text{Error at peaks} = \left( \frac{F_{\text{exp}} - F_{\text{FEM}}}{F_{\text{exp}}} \right) \times 100
\]
Results - Dowel stiffness

Dowel force: $F_d = k_d \Delta_d$  
Dowel stiffness: $K_d = \alpha E_{s0}$

Controlling parameter: $\alpha =$ from 0 to 0.05
Results - Tensile concrete strength

Error in lateral force at peak drift ratio, versus top drift ratio.

Error at peaks = \( \frac{F_{\text{exp}} - F_{\text{FEM}}}{F_{\text{exp}}} \times 100 \)

Tensile concrete strength
- Hsu: baseline
- EC2: \( \approx 70\% \) increase
- ACI: \( \approx 100\% \) increase
Results - Unloading stiffness (from tension)

Drift Ratio [%]

Dissipated energy (area underneath the curve):
- $E_0$: sudden crack closure
- $E_1$: gradual crack closure
- $E_{exp}$: experimental test.

<table>
<thead>
<tr>
<th>Wall</th>
<th>$E_0/E_{exp}$</th>
<th>$E_1/E_{exp}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>WSH1$^1$</td>
<td>0.95</td>
<td>1.09</td>
</tr>
<tr>
<td>WSH2$^1$</td>
<td>1.08</td>
<td>1.21</td>
</tr>
<tr>
<td>WSH3$^1$</td>
<td>1.02</td>
<td>1.13</td>
</tr>
<tr>
<td>WSH4$^1$</td>
<td>1.03</td>
<td>1.19</td>
</tr>
<tr>
<td>WSH5$^1$</td>
<td>0.98</td>
<td>1.15</td>
</tr>
<tr>
<td>WSH6$^1$</td>
<td>1.10</td>
<td>1.22</td>
</tr>
<tr>
<td>UCSD$^2$</td>
<td>0.98</td>
<td>1.02</td>
</tr>
</tbody>
</table>

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2: Faraone et al. (2017)- Post-installed anchors behavior in a full scale slender RC shear wall subjected to cyclic lateral loading.
Conclusions

- **Mesh sensitivity:** Element to wall height ratio of 1/5 produced sufficiently accurate results.

- **Dowel action:** influences the shear estimation. Optimal $a$ value observed to be in the upper limit range (around 0.05).

- **Tensile concrete strength:** 20% variation in the lateral load capacity predictions.

- **Unloading stiffness from tension:** FE models implementing the sudden gap closure estimated the dissipated energy within 10%.

Globally the SFI-MVLEM was shown to reasonably capture the strength gain and post-peak strength reductions observed in the flexural walls considered in these analyses.
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Thank you for your attention