Seismic Performance Assessment and Retrofit of Non-Ductile RC Frames with Infill Walls

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Masonry-Infilled RC Frames

- Complicated structural systems.
- Additional complexity introduced for older construction, where shear failures are expected in concrete columns.
- Mixed performance in past earthquakes.

Collaborative research project to develop understanding of behavior, modeling techniques and retrofit schemes for masonry-infilled frames.
Cyclic Behavior of Infilled Frames

Single-Story, single-bay, non-ductile reinforced concrete frames, infilled with solid brick masonry panel, tested at CU Boulder by Willam et al.

\[
\frac{W}{2} = 156\text{kN}
\]

Lateral displacement

8 #5 bars
#2 @ 26.5mm stirrups

Lateral displacement

8 #5 bars
#2 @ 26.5mm stirrups
Cyclic Behavior of Infilled Frames
Modeling Scheme

- **Plane stress smeared cracking continuum elements** to describe distributed cracking & crushing.

- **Interface elements** to describe strongly localized cracks as well as mortar joint cracking-sliding.
Modeling Approach – RC Columns

Cracks are modeled in discrete and smeared fashion.

Triangular smeared crack element

Interface element to model discrete cracks

Stavridis and Shing, 2010
Modeling Approach – Infill Panels

Anticipated cracking pattern mainly runs through the mortar joints, with some brick splitting cracks.

- Quadrilateral smeared crack elements (each elem. = half brick)
- Interface (for bed joints)
- Interface (for head joints)
- Interface (for possible splitting cracks)

*Stavridis and Shing, 2010*
Smeared Crack Element

Originally formulated by Lotfi and Shing (1992)

**Uncracked material:** Failure surface combines Von Mises criterion with a tension cutoff criterion.

\[
\sigma = f + f' \left( \varepsilon - \varepsilon_{1p} \right) \left[ 1 - \exp \left( -\frac{m}{\sigma_{p} - \sigma_{2e} - \sigma_{2e}} \left( \varepsilon_{p} - \varepsilon_{2p} \right) \right) \right]
\]

Failure surface of uncracked material

Nonlinear isotropic hardening-softening law for effective strength
Cracked material: Orthotropic stress-strain law:
Interface Element

Local coordinate system

\[ \tau^2 - \mu^2(\sigma - s)^2 - 2r(\sigma - s) = 0 \]

\( \mu, r, s \): strength parameters

Displacement vector:

\[ d = d^{\text{el}} + d^{\text{pl}} + d^{\text{g}} \]

\( d^{\text{el}}, d^{\text{pl}}, d^{\text{g}} \): elastic, plastic, geometric

Yield surface (Lotfi and Shing 1994)
Interface Element

Koutromanos and Shing (2010)

Tensile Stress vs. Normal Crack Opening

Loading-unloading

Reloading

Tensile Stress (MPa)

Normal Displacement (µm)

Experiment

Analysis

0 20 40 60 80 100 120

0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5

σ

d_n1 d_n2 d_n

σ

d_n1 d_n2 d_n
Interface Element

Test on mortar joint by Mehrabi and Shing (1994)

100-psi Normal Compression

Axial Compression

Joint Dilatation & Compaction
Verification – Quasi-static Tests

[Graphs showing experimental and analytical results for drift ratio (%).]
Verification – Quasi-static Tests
Prototype 3-story Building

R/C frame with solid brick infill panels, representing design practice in California in the 1920s.
Base Acceleration Time Histories

Gilroy 3 000 Record, 1989
Loma Prieta Earthquake

El Centro NS Record, 1940
Imperial Valley Earthquake
## Motion Sequence

<table>
<thead>
<tr>
<th>Trial</th>
<th>Motion</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Gilroy 40%</td>
</tr>
<tr>
<td>2</td>
<td>Gilroy 67%</td>
</tr>
<tr>
<td>3</td>
<td>Gilroy 67b%</td>
</tr>
<tr>
<td>4</td>
<td>Gilroy 83%</td>
</tr>
<tr>
<td>5</td>
<td>Gilroy 91%</td>
</tr>
<tr>
<td>6</td>
<td>Gilroy 100%</td>
</tr>
<tr>
<td>7</td>
<td>Gilroy 120%</td>
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<tr>
<td>8</td>
<td>El Centro 250%</td>
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*Stavridis et al, 2010*
# Specimen Damage

## Bottom Story Response

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<tbody>
<tr>
<td>G40</td>
<td>0.01%</td>
<td>None</td>
</tr>
<tr>
<td>G67</td>
<td>0.10%</td>
<td>Slight</td>
</tr>
<tr>
<td>G67b</td>
<td>0.12%</td>
<td>Slight</td>
</tr>
<tr>
<td>G83</td>
<td>0.28%</td>
<td>Moderate</td>
</tr>
<tr>
<td>G91</td>
<td>0.40%</td>
<td>Moderate</td>
</tr>
<tr>
<td>G100</td>
<td>0.55%</td>
<td>Important</td>
</tr>
<tr>
<td>G120</td>
<td>1.06%</td>
<td>Severe</td>
</tr>
<tr>
<td>E250</td>
<td>-</td>
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After G67 ( = DE level)
Specimen Damage

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After G91 ( = MCE level)
Specimen Damage

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After G120
Final Test - Collapse

El Centro 250% Motion
Verification – Shake Table Test 1

- Response is examined for a sequence of 5 motions: Gilroy 67% (twice), 83%, 91%, 100%, 120%.
- Initial stiffness-proportional Rayleigh damping:
Bottom Story Drift Time Histories

G67 Motion
- Drift ratio (%)
- Time (sec)
- Experiment
- Analysis

G67b Motion
- Drift ratio (%)
- Time (sec)
- Experiment
- Analysis

G83 Motion
- Drift ratio (%)
- Time (sec)
- Experiment
- Analysis

G91 Motion
- Drift ratio (%)
- Time (sec)
- Experiment
- Analysis

G100 Motion
- Drift ratio (%)
- Time (sec)
- Experiment
- Analysis

G120 Motion
- Drift ratio (%)
- Time (sec)
- Experiment
- Analysis
Cracking Pattern

Experiment

Analysis

After G91
Cracking Pattern

Experiment

After G100

Analysis
Cracking Pattern

Experiment

After G120

Analysis
Shake Table Test 2

Panel with ECC retrofit
Application of ECC Retrofit

- Dowels
- Anchors (1’ x 1’ grid)
- Unbonded dowels (with grease)
Application of ECC Retrofit
ECC Retrofit Behavior

1/5 scale specimens tested quasi-statically at Stanford University by Kyriakides and Billington.
Damage at Specimen

Frame/panel separation
Second Story Strengthening

Epoxy injections at major cracks

GFRP overlay (by Fyfe Co.)

1 layer of Tyfo BC

1 layer of Tyfo SEH-51A System, Oriented Horizontally

1 layer of Tyfo SEH-51A System, Oriented Vertically
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</tr>
<tr>
<td>7</td>
<td>Gilroy 150%</td>
</tr>
<tr>
<td>8</td>
<td>El Centro 150%</td>
</tr>
<tr>
<td>9</td>
<td>El Centro 200%</td>
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Effectiveness of 2nd Story Repair

Before FRP Retrofit

After FRP Retrofit
Bottom Story Response

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<td>Slight</td>
</tr>
<tr>
<td>G67</td>
<td>0.15%</td>
<td>Slight</td>
</tr>
<tr>
<td>G83</td>
<td>0.17%</td>
<td>Slight</td>
</tr>
<tr>
<td>G91</td>
<td>0.19%</td>
<td>Slight</td>
</tr>
<tr>
<td>G100</td>
<td>0.24%</td>
<td>Slight</td>
</tr>
<tr>
<td>G120</td>
<td>0.34%</td>
<td>Moderate</td>
</tr>
<tr>
<td>G150</td>
<td>0.65%</td>
<td>Severe</td>
</tr>
<tr>
<td>E150</td>
<td>0.52%</td>
<td>Severe</td>
</tr>
<tr>
<td>E200</td>
<td>0.67%</td>
<td>Severe</td>
</tr>
</tbody>
</table>

\(^1\)Damage due to previous motions
Final Damage

- Failure of top ECC/frame shear dowel connection
- Joint failure
- Signs of delamination
Shear/sliding Crack at Bottom Story

Failure of shear dowels
Conclusions

• Infills can significantly increase the lateral strength of a non-ductile frame, thus improving seismic performance.
• Retrofit using ECC overlay increased the resistance of the infilled frame, however it may not always be possible to increase ductility.
• Repair based on epoxy injection/GFRP is fast and efficiently restores the strength of an infill panel.
Conclusions

• The proposed analysis methodology offers satisfactory agreement with recorded data in terms of global response quantities and failure mechanism.

• Further numerical investigation of system performance for different configurations is feasible.
Acknowledgements

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- Johnson Western Gunite Company.
- Fyfe Co. (Scott Arnold).
Thank you

• Questions?