Seismic Retrofit of Non-Ductile Reinforced Concrete Frames Using Infill Walls as Rocking Spines

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Motivation (1/2)

Infill Walls

- As “non-structural” elements
  - significant effects on functionality
  - failure compromise life-safety
- As structural elements, they change
  - Dynamic properties
  - Seismic demand forces
  - Overall structural behavior
- **Problem**: Predict seismic response, e.g.
  - Tendency to form a soft story
  - Shear failure of columns
  - In-plane/out-of-plane interaction
  - Level of demand and capacity forces
  - Distribution & redistribution of forces upon damage
Motivation (2/2)

Recall what Prof. Krawinkler said this morning!

In-plane/out-of-plane interaction of infills,
2009 Abruzzo earthquake, Italy

In-plane/out-of-plane interaction of infills,
2008 Wenchuan earthquake, China

L’Aquila Town (Lower story)
2009 Abruzzo earthquake, Italy

L’Aquila Town (Crack pattern)
2009 Abruzzo earthquake, Italy
Objectives

1. Making a positive use of the presence of infill walls by overcoming the detrimental effects of infill walls

2. Developing a practical and economical retrofit solution of non-ductile RC frames with URM infill walls
Overview of Proposed Retrofit (1/2)

Example:
Mesh reinforcement, added concrete layer to the infill, and infill/beam connectors
Overview of Proposed Retrofit (2/2)

Basic idea
1. Enhance arching action for out-of-plane resistance
2. Increase the force in the diagonal compression strut
3. Greater tension force in the column
4. Let the foundation lift

\[ T = F_s \sin \theta \]

Compression-only springs, restrained in the other translational & rotations DOFs
Previous Works (1/10)

Modeling URM Infill Walls: FE Modeling of Bare Frame

- Compared with PSD test results
  - Input: Experiment command displacement
  - Output: compared with measured frame resistance

Level Duzce 7, Pseudo-dynamic time-history
Previous Works (2/10)
Modeling Infill Walls: FE Modeling of Infilled Frame

- Compared with PSD test results
  - Input: Experiment command displacement
  - Output: compared with measured frame resistance

![Graph showing resisting force over time](image)

- Level Duzce 7, Pseudo-dynamic time-history
Previous Works (3/10)
Modeling Infill Walls: FE Modeling of Test Structure

- FE model of shake table test structure
  - Beam and columns
    - 3-node, 18 dof beam elements
    - 8 elements per column, 5 elements per beam
    - 5 section per element
    - 35 integration points at each section
    - Total strain rotating crack
      - Compression: parabolic
      - Tension: linear softening
  - Embedded reinforcement

- URM wall
  - Curved shell element
  - Total strain rotating crack
    - Compression: EPP
    - Tension: linear brittle

- Interface elements
  - Compression: Stiff
  - Discrete cracking in tension
  - No shear capacity
Previous Works (4/10)

Modeling Infill Walls: FE Results of Test Structure

- Comparison between FE nonlinear time-history analysis and shaking table results

Partial roof displacement and base shear comparisons
Previous Works (5/10)
Combined In-Plane and Out-of-Plane

- Verification of the model
  - In-plane
  - Out-of-plane
Previous Works (6/10)

In-Plane/Out-of-Plane Interaction

- Loading
  - Constant out-of-plane pressure
  - In-plane pushover

- Idealized interaction curve

- More practical (convex) curve

\[
P_H = -0.943 P_N^2 + 3.96 P_N^2 + -12.0 P_N + 109
\]

\[
\text{FEM results - Best fit}
\]

\[
\text{FEM results}
\]

\[
\text{Hashemi and Mosalam FEM Model}
\]

\[
\text{3 / 2 Power Curve}
\]
Previous Works (7/10)

1. Acceleration corresponding to diaphragm-wall connection failure
2. After connection failure, compare kinetic energy with potential energy → wall fails when kinetic energy is higher

\[
a_{\text{con}} = \frac{F_{\text{friction}}}{m_w/2} = \left(\frac{P\mu_s}{W_w/2}\right)g
\]

\[
KE_w = \frac{1}{24} \frac{W_w}{g} \left[(V_t - V_b)^2 + (V_t + V_b)^2\right]
\]

\[
PE_{f,\text{lb}} = \frac{W_w}{2} \left[\frac{P}{W_w} \left(0.9 \frac{3}{4} \frac{t_w}{h_s} + \mu_k t_w\right) + 0.45 \frac{t_w^2}{h_s}\right]
\]

\[
PE_{f,\text{lab}} = \frac{W_w}{2} \left[0.45 \frac{t_w^2}{h_s}\right]
\]

Calculation of PE

Calculation of KE
Previous Works (8/10)

Rocking and Uplift of Foundations


• The building designed with a base shear coefficient of 0.1 experienced very minor damage in San Fernando earthquake, where the PGA was estimated to be 0.7g ~ 1.3g

• Based on the simulations, nonlinear soil structure interaction & partial uplift was determined to be amongst the factors reducing the damage
Previous Works (9/10)

Rocking and Uplift of Foundations

Midorikawa et al. (2003) FEM Analyses on Seismic Responses of Rocking Structural Systems with Yielding Base Plates

The Idea

Finite Element Model

Mode shapes and periods

Good match with the test results
Previous Works (10/10a)
Tests of Infill Wall Retrofit with Mesh Reinforcement


Cyclic quasi-static 1/3 scale tests of 1 bay, 2 story as-built & strengthened frames
Previous Works (10/10b)

Tests of Infill Wall Retrofit with Mesh Reinforcement


Cyclic quasi-static 1/3 scale tests of 1 bay, 2 story as-built & strengthened frames
Employed Analytical Tools (1/5)

*IP-OOP Interaction For Infill Walls (Kadysiewski and Mosalam, PEER 2008/102, 2009) and (Hashemi and Mosalam, PEER 2007/100, 2007)*

Each infill panel is modeled using diagonal members composed of two beam-column elements, joined at the midpoint node with a lumped mass in the out-of-plane (OOP) direction.

The fiber discretization of beam column elements reflects the in-plane (IP) & out-of-plane (OOP) stiffness & IP/OOP strength interaction.
Employed Analytical Tools (2/5)

**IP-OOP Interaction For Infill Walls**

1. Elastic stiffness & unidirectional strength of the infill based on FEMA 356
2. The strength interaction relationship is taken as a 3/2-power model

\[
\left( \frac{P_N}{P_{N0}} \right)^\frac{3}{2} + \left( \frac{P_H}{P_{H0}} \right)^\frac{3}{2} \leq 1.0
\]

- \( P_N \): OOP capacity with IP force
- \( P_{N0} \): OOP capacity without IP force
- \( P_H \): IP capacity with OOP force
- \( P_{H0} \): IP capacity without OOP force

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*Hashemi and Mosalam, PEER 2007/100, 2007*
Employed Analytical Tools (3/5)

Direct Element Removal (Talaat and Mosalam, PEER 2007/10, 2008)

Before

\[ \text{Mass} = m \]
\[ \text{Time} = t \]

\[ M_{C2}, F_{C2} \]
\[ M_{B1}, F_{B1} \]

\[ M_{C1}, F_{C1} \]

\[ ma, I_\alpha \]

Dynamic Equilibrium

After

\[ \text{Mass} = m' \]
\[ \text{Time} = t' = t + \Delta t \]

\[ M'_{C2}, F'_{C2} \]
\[ M'_{B1}, F'_{B1} \]

\[ M'_{B2}, F'_{B2} \]

\[ m'a', I'_\alpha' \]

\[ a' >> a \]
\[ \alpha' >> \alpha \]

removed element releases internal forces

Restored Dynamic Equilibrium
Employed Analytical Tools (4/5)

Direct Element Removal

Start from main code

Check for dangling nodes, floating elements, and element loads and masses

Remove dangling nodes
Remove floating elements
Delete element/node loads
Remove element
Update nodal masses

Identify nodal kinetics at separation

Update structural model, time step, and solution parameters

Identify location, compute force, duration, and mass redistribution

End back to main code

Italicized text executed outside of OpenSees

Intact structure

Nodal load

Dangling node

Dashed elements have been removed during analysis

Floating element

Distributed load

time = 0 sec
1. The FEMA 356 “collapse prevention” (CP) level is considered for IP & OOP unidirectional deformations of the infill panel.
2. For convenience, $3/2$-power relationship is used for deformation interaction.

IP deformation is the relative horizontal displacement between the top and bottom nodes of the diagonal member.

OOP deformation is the OOP displacement of the middle node with respect to the chord connecting the top and bottom nodes.
Analysis Example (1/10)

9 story, 5 bay frame (similar to Bombiya Arcade Building, Pakistan)

Bay width = 120 in
Story height = 140 in
f’_c = 3 ksi, f_y = 60 ksi
Infill walls at all bays and stories
f_{me} = 1 ksi, E_m = 500 ksi
f_{vie} = 0.05 ksi, t_{inf} = 6 in
Analysis Example (2/10)

Exterior column section
- 8"
- 6 #7 long. bars
- Stirrups #3@5"
- $M_n = 171$ kip-ft
- $V_n = 71$ kip

Interior column section
- 12"
- 12 #7 long. bars
- Stirrups #3@5"
- $M_n = 417$ kip-ft
- $V_n = 105$ kip

Beam section
- 8"
- 4 #7
- Stirrups #3@5"
- $M_n (-ive) = 277$ kip-ft
- $M_n (+ive) = 155$ kip-ft
- 2 #7

90° hooks for stirrups → confinement factor $K=1.1$ for concrete
Analysis Example (3/10)

Strengthening – Infill walls at the first and last bays strengthened with wire mesh reinforcement and added concrete layers.

#3@6” as mesh reinforcement, 4” thick concrete on each side.
Analysis Example (4/10)

Modeling

- **OpenSees**

- Force-based beam-column element (**nonlinearBeamColumn**) for beams and columns with **five integration points**

- **Concrete02** for concrete, necessary parameters obtained by using the stress–strain model of **Mander** et al.

- **Steel02 without isotropic hardening** for reinforcement

- **Nonlinear shear springs** at the top and bottom of **columns**

- **Beamwithhinges** for infill walls with **OOP mass at the center node**

- **Infill cross-section modeled** according to [Kadsyiewski & Mosalam, 2009]

- **Removal of infill** considering **IP and OOP interaction**

- At the base, **compression-only springs in the vertical direction**

- **OOP translational elastic springs** at the story levels to represent the frames in transverse direction

- **Stiffness of OOP springs** selected for $T_{\text{long}} = T_{\text{transv}}$
Analysis Example (5/10)

Unretrofitted case under KB_kobj (lateral & transverse components)

\[ T_1 = 0.98 \text{ sec} \rightarrow \text{scaling ground motion such that } S_a(T_1)=1.4g \]
Analysis Example (6/10)

Retrofitted case under KB_kobj (lateral & transverse components)

$T_1 = 0.93$ sec but scaling ground motion as for unretrofitted case
Analysis Example (7/10)

Retrofitted case: Displaced shape at the time of maximum uplift
Analysis Example (8/10)

Maximum Interstory Drifts

Interstory Drift Ratio

Story #

As-built
Retrofitted
Analysis Example (9/10)

Failure of the ground story, first bay infill in the as-built case

![Graph showing displacement history and failure curve.](image-url)
Analysis Example (10/10)

Analysis did not converge for the as-built case because of excessive frame deformation in the OOP direction.
On-Going Work...

1. 3D modeling and bi-directional ground shaking

2. Fragility analyses for unretrofitted and retrofitted cases for frames with 3, 6, 9, and 12 stories
Thank You All!
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Questions? Comments?