Nonlinear Analysis of Reinforced Masonry Shear Walls with ASCE 41

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Reinforced Masonry Wall Systems

NIST GCR 14-917-31
Seismic Design of Special Reinforced Masonry Shear Walls
A Guide for Practicing Engineers
Nonlinear Behavior of RM Walls

Flexure-Dominated Behavior

Shear-Dominated Behavior

Flexure-Dominated Behavior

Damage includes:
- Toe crushing
- Vertical bar buckling
- Vertical bar fracture
- Lap splice failure

Strength and ductility depend on:
- Amount of vertical steel
- Amount of axial compressive load
- Effective aspect ratio ($h_{eff}/l_w$ or $M/Vd$)

Wall tested by Sherman (2011)

Relatively gentle
ASCE 41-13 – Flexure-Dominated Walls

Deformation-Controlled In-Plane RM Walls

For cantilever walls, \[ k = \frac{1}{h \frac{h}{f}+\frac{h}{I}} \]

Axial Stress \( \frac{f_a}{f_n} \)

1/Aspect Ratio \( \frac{l_a}{l_n} \)

Reinforcement Index \( \rho_n \frac{f_{y_n}}{f_n} \)

Acceptable Drift Ratio 1/\( \mu_p \)

Table 11.7: Modelling Parameters and Acceptance Criteria for Nonlinear Procedures—Reinforced Masonry In-Plane Walls

Wall Components Controlled by Flexure

Damage involves:
- Diagonal cracking
- Masonry crushing
- Horizontal bar fracture /anchorage failure

Strength and ductility depend on:
- Amount of horizontal steel
- Amount of vertical steel
- Amount of axial compressive load
- Presence/absence of wall flanges

Severe load drop

Wall tested by Ahmadi (2011)
For cantilever walls,

\[
k = \frac{1}{h^3 (0.5 I_a)} + \frac{h}{3 E_a I_a G_w}
\]

TMS 402:

\[
Q_f = (V_{cm} + V_{cm}) \cdot \gamma_f
\]

\[
V_{cm} = \left[ 4.0 - 1.75 \left( \frac{M}{V_{cm}} \right) \right] A_{w} \sqrt{\gamma_{cm}} + 0.25 P
\]

\[
V_{cm} = 0.5 \frac{A_{w}}{f_{ck}} d
\]

### Comparison with Experimental Data

**Flexure-Dominated Wall**

**Shear-Dominated Wall**

ASCE 7-13 pushover curves:

- Too stiff
- Too brittle
Proposed Changes

Chapter 9 Reinforced Masonry Walls

Flexure-Dominated RM Walls

Experimental Data + Rational Analysis

\[ Q_s = 0.8Q_{\text{nom}} \]

\[ Q_c = 0.5Q_{\text{nom}} \]

\[ Q_{\text{cr}} = 0.75Q_{\text{nom}} \]

\[ k = \frac{1}{h^2} \left( \frac{1}{h} \right) \frac{\Delta}{\Delta_{\text{cr}}} \]

\[ L_c = 0.15L \]

Considering cracking based on wall test data

Cantilever Wall for Example
Envelope Determined by Moment-Curvature Analysis

Cantilever Wall for Example:

$$\Delta_m = \Delta_{mf} + \Delta_{mv}$$  Flexure + Shear

$$\Delta_{mf} = \frac{M_{max}}{EI_m} h + \left( \phi_m - \frac{M_{max}}{EI_m} \right) L_p \left( h - \frac{L_p}{2} \right)$$

$$\Delta_m = \frac{Q_{max}}{0.20A_G}$$

Same for $\Delta_{mv}$ and $\Delta_v$

$$L_p = 0.20h_{eff}$$

Material Models

Masonry

Steel

Accounts for
- Buckling
- Low-cycle fatigue

$$\alpha = \frac{f_b}{f_{m,0}}$$

$$\beta = \frac{P}{f_{m,0}A_s}$$
Nondimensionalized Moment-Curvature Relation for a Rectangular Wall Section

Function of:
\[ \alpha = \frac{f_y}{f_m} \rho_v \]
\[ \beta = \frac{P}{f_m A_n} \]
\[ \sigma_m / f'_m = \varepsilon \] relation
\[ \sigma / f_y = \varepsilon \] relation

Nondimensionalized M-\(\phi\) Values for Fully Grouted Rectangular Wall Sections under Cyclic Loading

<table>
<thead>
<tr>
<th>Reinforcement (a = (f_y f_m) / P)</th>
<th>Axial Compression Ratio (\beta = P/(f_m A_n))</th>
<th>(\phi L_n)</th>
<th>(\phi L_m)</th>
<th>(\phi L_s)</th>
<th>(M/(f_m A_n L_s))</th>
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<td>0.0238</td>
<td>0.0350</td>
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Comparison with Test Data

Axial Load = 0
\( h/l_w = 1 \)

\( \rho_v = 0.33\% \)
\( h/l_w = 2 \)

Axial Load = 0
Axial Load Ratio = 6.25%

\( \rho_v = 0.16\% \)

\( h/l_w = 3 \)

Axial Load Ratio = 5%
\( \rho_v = 0.72\% \)
\( h/l_w = 4.5 \)

Lap-splice failure not well represented

- Too ductile for a slender wall
- Need to impose 4% Drift Limit
Comparison with 32 Wall Tests

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<th>Calculated/Experimental</th>
<th>$Q_{\max}$</th>
<th>$\Delta_\gamma$</th>
<th>$\Delta_m$</th>
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Cyclic Analyses

Beam-Column Element in OpenSEES

Hysteretic Material Model for Steel
Monotonic vs. Cyclic Loading

\[ \alpha = \frac{f_y}{f_{y,c}} \]

\[ \beta = \frac{P}{f_{w}A_a} \]

Lateral Force (kips) vs. Lateral Drift Ratio (%)

Lap Splices at Base of Walls

Slender wall w/ extensive toe crushing leading to loss of two extreme vertical bars
Shear-Dominated Fully Grouted Walls

Based on Experimental Data

For cantilever walls,

\[ k = \frac{1}{h^3} + \frac{1}{h} \left( 3E_0 I_e + 0.35A_f G_e \right) \]

\[ L_e = 0.15l \]

TMS 402:

\[ Q_{\text{max}} = V_a = V_{\text{as}} + V_{\text{al}} \]

\[ V_{\text{as}} = 4.0 - 1.75 \frac{M}{V_L} A_h \sqrt{f_{\text{as}}} + 0.25P \]

\[ V_{\text{al}} = 0.5 \frac{A_h}{S} f_{\text{al}} \]

Comparison with Test Data

16 Wall Tests

2% ultimate drift limit is a bit more than that indicated by wall component tests
2-Story RM Building Tested on Shaking Table

Wall system appeared to be more ductile than wall components.

Maximum Local Drift Ratio of Piers:
- 3.8% in positive direction
- 2.3% in the negative direction

Additional displacement capability contributed by:
- Wall flange
- Out-of-plane walls

Shear-Dominated Partially Grouted Walls

Based on Experimental Data

For cantilever walls,
\[
k = \frac{1}{h} \left( \frac{E_h I_e}{3E_g I_s} + \frac{0.35 A_g}{h} \right)
\]
\[I_e = 0.15I\]

TMS 402:
\[
Q_{\text{max}} = V_u = (V_{\text{es}} + V_{\text{en}}) \times 0.75
\]
\[
V_{\text{es}} = 4.0 - 1.75 \frac{M}{W_{\text{eq}}} A \sqrt{f_{\text{e}}} + 0.25P
\]
\[
V_{\text{en}} = 0.5 \frac{A_e}{s} f_{\text{d}} d_e
\]
\[Q_e = V_{\text{en}} \times 0.75\]
Wall System Analysis

Special attention:
- Ability of beam-column elements to model shear behavior is limited.
- One may add a nonlinear shear spring to a beam element.
- Predefined shear behavior will not account for the variation of axial loads induced by lateral forces.
- Behavior of partially grouted walls can be complicated resembling an infilled frame.

This concludes The American Institute of Architects Continuing Education Systems Course

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