Nonlinear Analysis of Reinforced Masonry Shear Walls with ASCE 41

November 4, 2017

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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

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
Deformation-Controlled In-Plane RM Walls

For cantilever walls,

\[
k = \frac{1}{3E_a(0.5l_v)A_G_a + h}
\]

Shear-Dominated Behavior

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
For cantilever walls,
\[
k = \frac{1}{h^3 + \frac{h}{3E_m(0.5I_s)}}
\]

TMS 402:
\[
Q_f = (V_{ma} + V_{ma}) \cdot \gamma_f
\]
\[
V_{ma} = \left[4.0 - 1.75 \frac{M}{W} \right] A \sqrt{f_{ma} + 0.25p}
\]
\[
V_{ud} = 0.5 \frac{A}{s} f_y d_y
\]

Comparison with Experimental Data

ASCE 7-13 pushover curves:
- Too stiff
- Too brittle
Proposed Changes

NIST GCR 17-917-45

Recommended Modeling Parameters and Acceptance Criteria for Nonlinear Analysis in Support of Seismic Evaluation, Retrofit, and Design

Chapter 9 Reinforced Masonry Walls

Flexure-Dominated RM Walls

Experimental Data + Rational Analysis

$Q = \frac{1}{h \Delta A \Delta y}$

Considering cracking based on wall test data

$Q_x = 0.8Q_{\text{max}}$
Envelope Determined by Moment-Curvature Analysis

Moment-Curvature Relation

Cantilever Wall for Example:
\[ \Delta_m = \Delta_{pm} + \Delta_{mm} \]
\[ \Delta_{pm} = \frac{M_{pm}}{EJ} \left( \frac{h}{3} + \frac{\phi_p - M_{max}}{EJ} \right) L_p \left( h - \frac{L_p}{2} \right) \]
\[ \Delta_{mm} = \frac{Q_{max}}{0.20A_iG_v} \]
Same for \( \Delta_{c1} \) and \( \Delta_c \)

\( L_p = 0.20h_{eff} \)

Material Models

Masonry

Steel

Function of \( \alpha \) and \( \beta \)

\( \alpha = \frac{f}{f_{tm}} \rho_{s} \)

\( \beta = \frac{P}{f_{tm} A_v} \)

Accounts for
- Buckling
- Low-cycle fatigue
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

\[ \sigma_s / f_s = \varepsilon \]  relation

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

<table>
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<th>Reinforcement ( a = (f_y f_m^2) / P )</th>
<th>Axial Compression Ratio ( \beta = P / (f_m A_n) )</th>
<th>( \phi L_y )</th>
<th>( \phi A_n )</th>
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Comparison with Test Data

Axial Load = 0

\( \rho_v = 0.33\% \)

\( h/l_w = 1 \)

\( \rho_v = 0.33\% \)

\( h/l_w = 2 \)

Axial Load Ratio = 6.25%

Axial Load Ratio = 5%

Lap-splice failure not well represented

- Too ductile for a slender wall
- Need to impose 4% Drift Limit

\( \rho_v = 0.72\% \)

\( h/l_w = 3 \)

\( \rho_v = 0.72\% \)

\( h/l_w = 4.5 \)
Comparison with 32 Wall Tests

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

Beam-Column Element in OpenSEES

Hysteretic Material Model for Steel
Monotonic vs. Cyclic Loading

\[ \alpha = \frac{f_y}{f_{yw}} \rho_c \]

\[ \beta = \frac{P}{f_{yw} A_y} \]

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,

\[ k = \frac{1}{h^3} \left( \frac{1}{h} + \frac{3E_s I_s}{0.35A_h G_m} \right) \]

\[ L_e = 0.15l \]

TMS 402:

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

\[ V_{as} = 4.0 - 1.75 \frac{M}{V_{ls}} A_s \left[ f_{m} - f_{y} \right] + 0.25P \]

\[ V_{es} = 0.5 \frac{A_s}{f_{y}} \]

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

For cantilever walls, 

\[ k = \frac{1}{\frac{k'}{h} + \frac{0.35A_g}{E_I}} \]

\[ I_r = 0.15I \]

TMS 402:

\[ Q_{\text{max}} = V_a = (V_{\text{sw}} + V_{\text{sw}}) \times 0.75 \]

\[ V_{\text{sw}} = 4.0 - 1.75 \frac{M}{V_{\text{sw}}} A_s \sqrt{f_n} + 0.25P \]

\[ V_{\alpha} = 0.5A_s f_n d_v \]
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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