LATERAL INSTABILITY OF DUCTILE STRUCTURAL WALLS: STATE-OF-THE-ART

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Buckling of a portion of a wall section out-of-plane, as a result of in-plane actions.

(Paulay and Priestley 1993)
Earthquake Observations

2010 Chile earthquake
(Wallace 2012)

2011 Christchurch
(Elwood 2013)
Lab Observations: PCA Wall Experiments (Oesterle et al. 1976)

Specimen R2 (Oesterle et al. 1976)
Lab Observations: EERC Wall Experiments (Vallenas et al. 1979)

Specimen 3 (Vallenas et al. 1979)
Code Provisions to control Global Instability: NZS3101

Minimum thickness for walls with axial force levels greater than $0.05f'_cA_g$

$$b_m = \frac{\alpha_r k_m \beta (A_r + 2)L_w}{1700\sqrt{\xi}}$$

$\alpha_r=1.0$ for doubly reinforced walls and $1.25$ for singly reinforced walls; and
$\beta = 5$ for limited ductile plastic regions
$\beta = 7$ for ductile plastic regions
$A_r =$ aspect ratio of wall ($h_w/L_w$)
$k_m = 1.0$, unless it can be shown that for long walls:

$$k_m = \frac{L_n}{(0.25 + 0.055A_r)L_w} < 1.0 \quad \xi = 0.3 - \frac{\rho f_y}{2.5f'_c} > 0.1$$

The buckling length is assumed to be equal to the theoretical length of the plastic hinge, considered as
$$l_p = (0.25 + 0.055A_r)L_w.$$
Basis of Code Provisions

Paulay & Priestley (1993)

\[ \xi = \frac{\varepsilon_{sm}}{8\beta} \left( \frac{l_o}{b} \right)^2 \]

Stability criterion

\[ \xi \leq 0.5(1 + 2.35m - \sqrt{5.53m^2 + 4.70m}) \]

\[ l_o = l_p = 0.2l_w + 0.044h_w \]

Where

\( l_w = \) horizontal length of the wall section
\( h_w = \) full height of the cantilever wall
Analytical Studies on Out-of-Plane Instability

Chai and Elayer (1999)

\[ \varepsilon_{sm} = \frac{\pi^2}{2} \left( \frac{b}{l_o} \right)^2 \xi + 3\varepsilon_y \]

Stability criterion

\[ \xi \leq 0.5(1 + 2.35m - \sqrt{5.53m^2 + 4.70m}) \]

\[ l_o = l_p = 0.2l_w + 0.044h_w \]
Numerical Simulation

✓ Curved shell element in DIANA

- Dashti et al. (2014)
- Parra (2016)
- Scolari (2017)
- Rosso et al. (2017)
- Daza Rodríguez (2018)
### Verification of the model; different failure modes


<table>
<thead>
<tr>
<th>Specimen</th>
<th>Length, $L_w$ mm</th>
<th>Height, $H_w$ mm</th>
<th>Thickness, $t_w$ mm</th>
<th>Section Aspect Ratio, $L_w/t_w$</th>
<th>Slenderness, $H_w/t_w$</th>
<th>Shear-span Ratio, $M/(V L_w)$</th>
<th>Axial Load, kN$[(n = N/(f'c A_c)]$</th>
<th>Failure mechanism</th>
</tr>
</thead>
<tbody>
<tr>
<td>SW11 (Lefas et al. 1990)</td>
<td>750</td>
<td>750</td>
<td>70</td>
<td>10.7</td>
<td>10.7</td>
<td>1.0</td>
<td>0 [0.0]</td>
<td>Shear</td>
</tr>
<tr>
<td>SW12 (Lefas et al. 1990)</td>
<td>750</td>
<td>750</td>
<td>70</td>
<td>10.7</td>
<td>10.7</td>
<td>1.0</td>
<td>230 [0.1]</td>
<td>Shear</td>
</tr>
<tr>
<td>S5 (Vallenas et al. 1979)</td>
<td>2412</td>
<td>3009</td>
<td>114</td>
<td>21.2</td>
<td>26.4</td>
<td>1.6</td>
<td>598 [0.06]</td>
<td>Flexure - Shear</td>
</tr>
<tr>
<td>PW4 (Birely 2013)</td>
<td>3048</td>
<td>3658</td>
<td>152.4</td>
<td>20.0</td>
<td>24.0</td>
<td>2.0</td>
<td>1601 [0.12]</td>
<td>Flexure - Bar buckling</td>
</tr>
<tr>
<td>R2 (Oesterle 1976)</td>
<td>1905</td>
<td>4572</td>
<td>101.6</td>
<td>18.8</td>
<td>45.0</td>
<td>2.4</td>
<td>0 [0]</td>
<td>Flexure - Out of plane instability</td>
</tr>
<tr>
<td>RW2 (Thomsen IV and Wallace 1995)</td>
<td>1219</td>
<td>3660</td>
<td>102</td>
<td>12.0</td>
<td>35.9</td>
<td>3.0</td>
<td>533 [0.1]</td>
<td>Flexure</td>
</tr>
</tbody>
</table>
Bar buckling can not be captured PW4 (Birely 2013)

<table>
<thead>
<tr>
<th>Overall Drift (%)</th>
<th>-1.62</th>
<th>-1.08</th>
<th>-0.54</th>
<th>0</th>
<th>0.54</th>
<th>1.08</th>
<th>1.62</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Base Shear (kN)</th>
<th>-1200</th>
<th>-800</th>
<th>-400</th>
<th>0</th>
<th>400</th>
<th>800</th>
<th>1200</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Top Displacement (mm)</th>
<th>-60</th>
<th>-40</th>
<th>-20</th>
<th>0</th>
<th>20</th>
<th>40</th>
<th>60</th>
</tr>
</thead>
</table>

**TEST**

- Out-of-plane deformation
- Bar buckling, Concrete crushing

**ANALYSIS**

Out-of-plane instability
Verification of the model; out-of-plane instability


Specimen3 (Beattie 2004)
Verification of the model; out-of-plane instability

Verification of the model; blind prediction

Failure mechanism & controlling parameters

$\varepsilon < \varepsilon_{\text{critical}}$

$\varepsilon > \varepsilon_{\text{critical}}$
Failure mechanism & controlling parameters

- Wall thickness
- Axial load
- Wall length
Experimental Studies

Boundary zone testing

Chai and Elayer (1999)
Acevedo et al. (2010)
Creagh et al. (2010)
Chrysanidis and Tegos (2012)
Shea et al. (2013)
Hilson et al. (2014)
Welt et al. (2016)
Taleb et al. (2016)
Rosso et al. (2017)
Haro et al. (2018)
Experimental Studies
Wall unit testing

Experimental Studies
Wall unit testing  Dashti et al. (2017, 2018)
Test Matrix

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specimen</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><strong>RWB</strong> (Benchmark specimen)</td>
</tr>
<tr>
<td><strong>Wall thickness</strong></td>
<td><strong>RWT</strong> (Thickness increased)</td>
</tr>
<tr>
<td><strong>Wall length</strong></td>
<td><strong>RWL</strong> (Length decreased)</td>
</tr>
<tr>
<td><strong>Axial load</strong></td>
<td><strong>RWA</strong> (Axial load decreased)</td>
</tr>
</tbody>
</table>
Experimental Response

- **A**: Initiation of out-of-plane deformation
- **B**: Bar fracture
- **C**: Bar buckling
- **D**: Instability

Graphs showing the response of different specimens:

- **RWB** (Benchmark specimen)
- **RWT** (8.0% increase in thickness)
- **RWL** (20% decrease in length)
Out-of-plane deformation

Bar fracture & Bar buckling

Instability

Local instability (secondary failure)
RWB & RWT

Global instability (main failure)
RWL
Out-of-Plane Instability as a Secondary Failure Mode
Specimen RWL: West Boundary
Out-of-plane Deformation & Recovery

A: Initiation of out-of-plane deformation
B: Out-of-plane instability
Specimen RWL: West Boundary Out-of-plane Instability
Global instability (main failure)

The experimental observations were in line with:

- The mechanism predicted by the **numerical model**
- Observations of past **benchmark research (boundary zone test)**
- The **assumptions made in the analytical models** available in the literature.
Research Findings

Stages of out-of-plane deformation response:

1) **Minimal or no** out-of-plane deformation

2) Development & **complete** recovery
   \[ \varepsilon_{sm} = 0.014 \text{ (about } 6\varepsilon_y \text{ for the tested specimen)} \]

3) Development & **partial recovery** (some residual out-of-plane deformation)
   \[ \varepsilon_{sm} = 0.017 \text{ (about } 7.2\varepsilon_y \text{ for the tested specimen)} \]

4) Development & **steady increase** resulting in out-of-plane instability of the wall
   \[ \varepsilon_{sm} = 0.023 \text{ (about } 10\varepsilon_y \text{ for the tested specimen)} \]
Research Findings

The progression of these stages depends on:

▪ Wall thickness, which governs the possibility of timely crack closure in the inner face of the out-of-plane displacement profile

▪ Any parameter controlling development of residual strain in longitudinal reinforcement, such as:
  
  i) axial load,
  
  ii) wall length,
  
  iii) cyclic loading protocol
Conclusions

- To address out-of-plane instability of rectangular walls, analytical, numerical and experimental studies have been conducted on full wall units as well as concrete columns that represent wall boundary zones.

- Out-of-plane instability of ductile structural walls under concentric in-plane cyclic loading was numerically simulated for the first time by Dashti et al. (2014).

- Based on an experimental study on out-of-plane response of doubly reinforced walls, the out-of-plane instability of rectangular walls under in-plane loading was classified as global and local (secondary) modes of failure.

- The characteristics of the global out-of-plane instability observed in this study (Dashti et al. 2017) are more in line with those of the analytical and numerical predictions as well as post-earthquake observations.
Thank you
Test matrix based on the identified parameters

**REINFORCEMENT SCHEDULE**

<table>
<thead>
<tr>
<th>Mark</th>
<th>Reinforcement</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>D12@75</td>
</tr>
<tr>
<td>B</td>
<td>D10@210</td>
</tr>
<tr>
<td>C</td>
<td>D10@150</td>
</tr>
<tr>
<td>D</td>
<td>R6@55 Ties1</td>
</tr>
<tr>
<td>E</td>
<td>R6@55 Ties2</td>
</tr>
</tbody>
</table>

**REINFORCEMENT SCHEDULE**

<table>
<thead>
<tr>
<th>Mark</th>
<th>Reinforcement</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>D16@80</td>
</tr>
<tr>
<td>B</td>
<td>D12@150</td>
</tr>
<tr>
<td>C</td>
<td>D10@150</td>
</tr>
<tr>
<td>D</td>
<td>R6@60 Ties1</td>
</tr>
<tr>
<td>E</td>
<td>R6@60 Ties2</td>
</tr>
</tbody>
</table>