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

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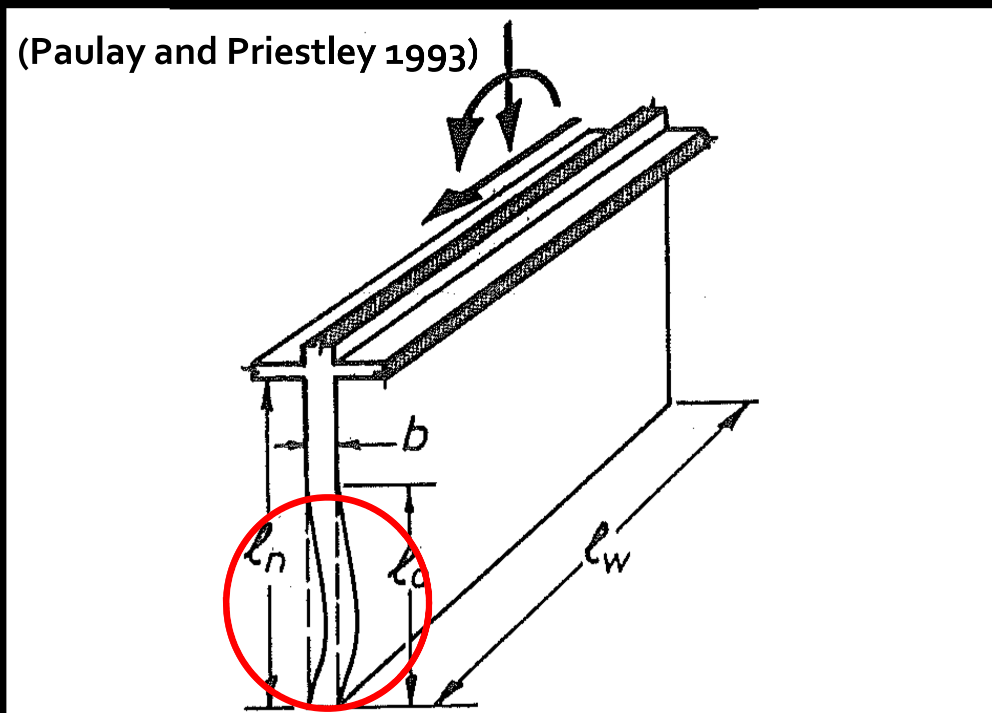
Introduction



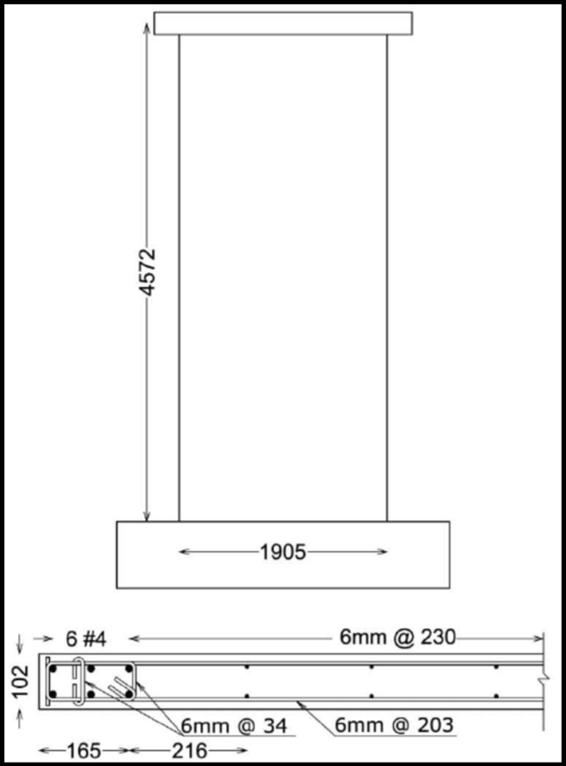
Buckling of a portion of a wall section out-of-plane, as a result of in-plane actions

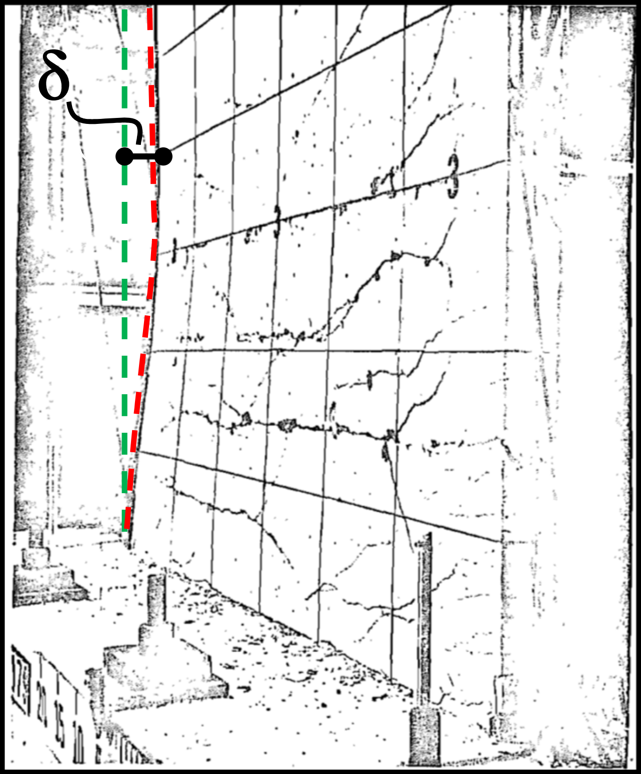
Earthquake Observations

2010 Chile earthquake
(Wallace 2012)

2011 Christchurch
(Elwood 2013)

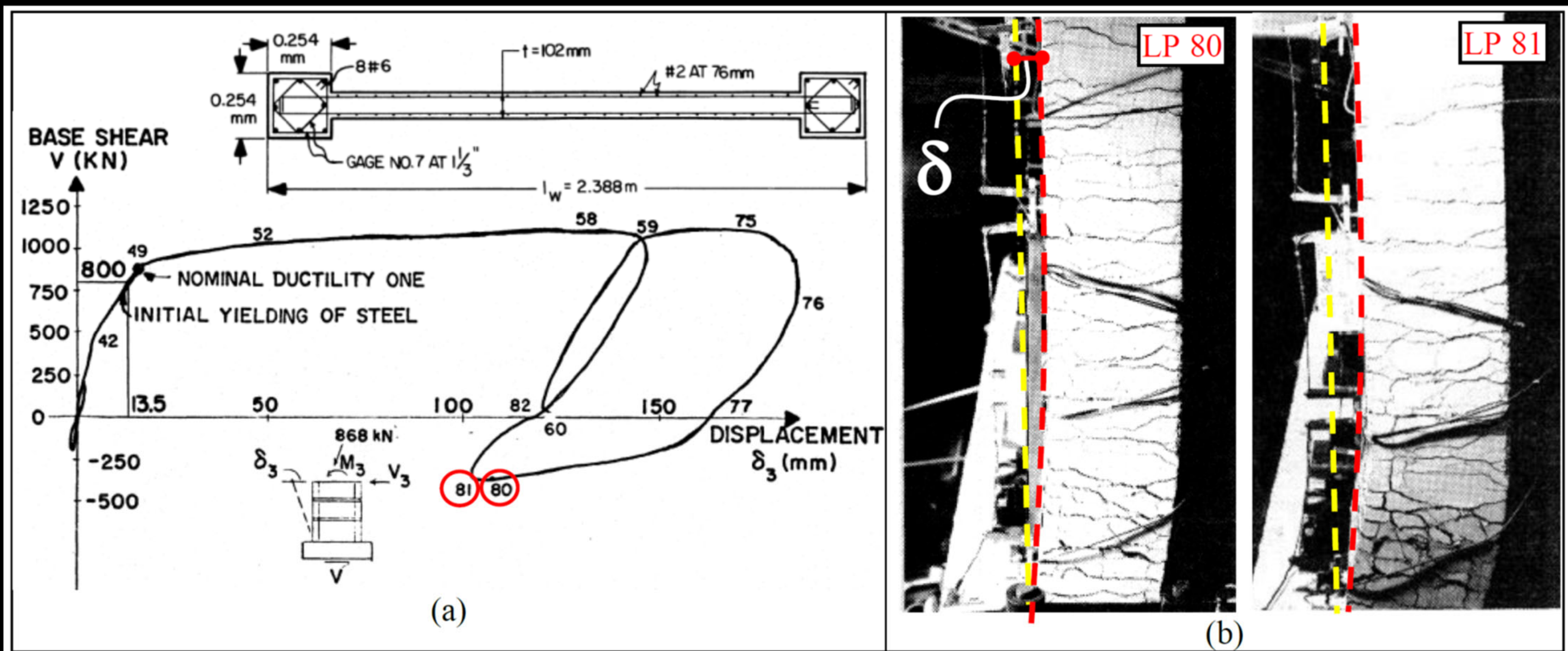
Lab Observations: PCA Wall Experiments (Oesterle et al. 1976)





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 $0.05f'_c A_g$

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

α_r=1.0 for doubly reinforced walls and 1.25 for singly reinforced walls; and
β = 5 for limited ductile plastic regions
β = 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:

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

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)

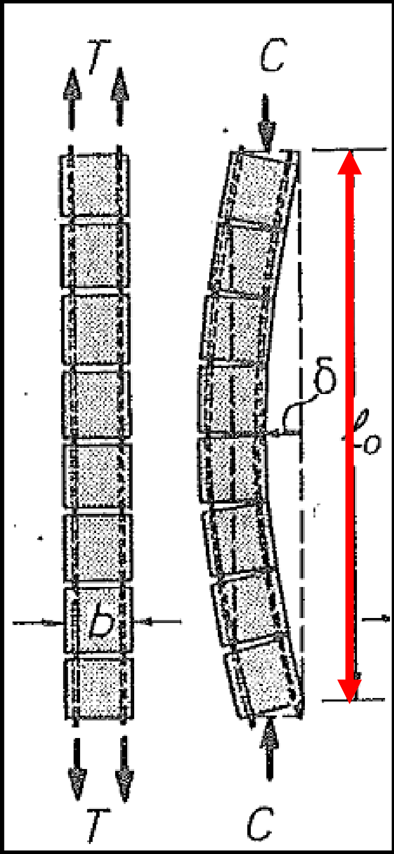
$$\xi = \frac{\varepsilon_{sm}}{8\beta}\left(\frac{l_o}{b}\right)^2$$

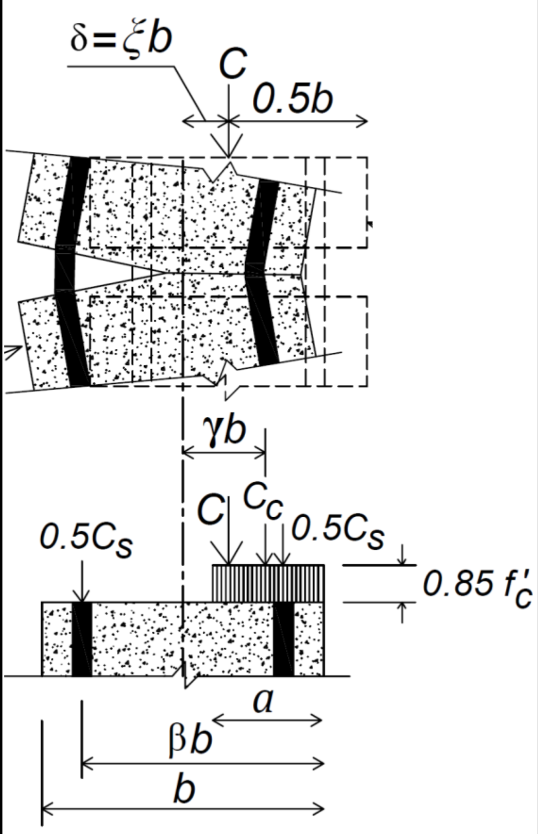
Stability criterion

$$\xi \le 0.5\left(1 + 2.35m - \sqrt{5.53m^2 + 4.70m}\right)$$

$$\mathbf{l_o = l_p = 0.2}\boldsymbol{l_w} \mathbf{+ 0.044}\boldsymbol{h_w}$$

Where
l_w= horizontal length of the wall section
h_w= full height of the cantilever wall





Analytical Studies on Out-of-Plane Instability

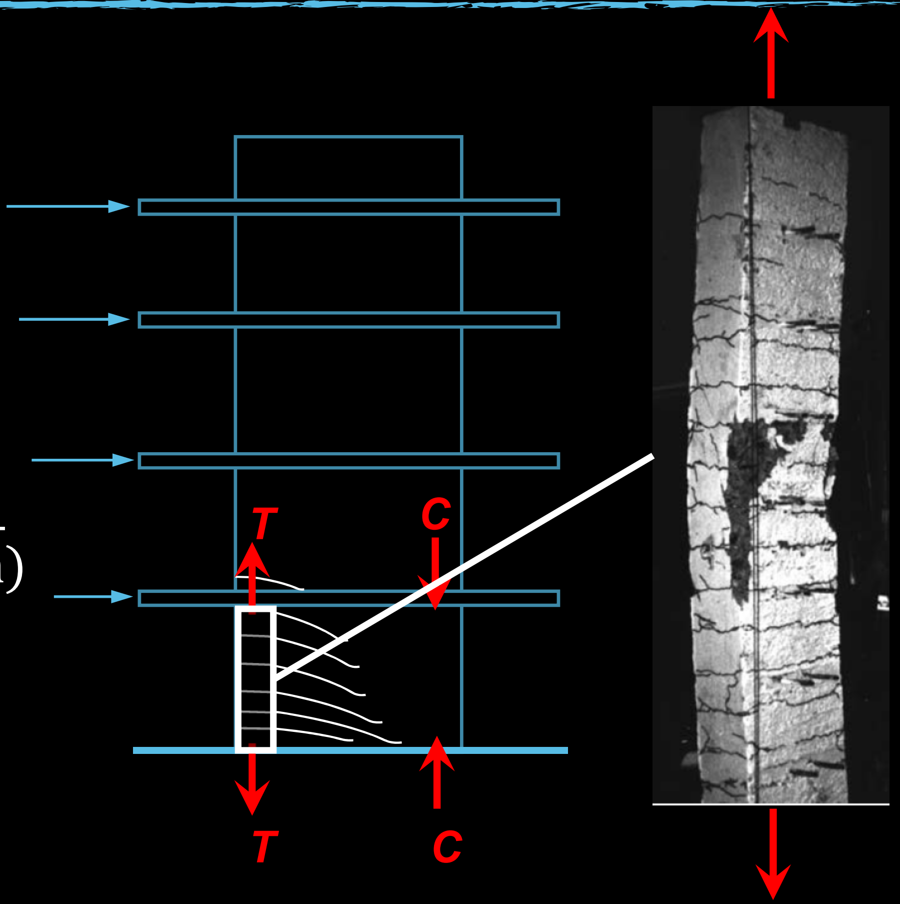
Chai and Elayer (1999)

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

Stability criterion

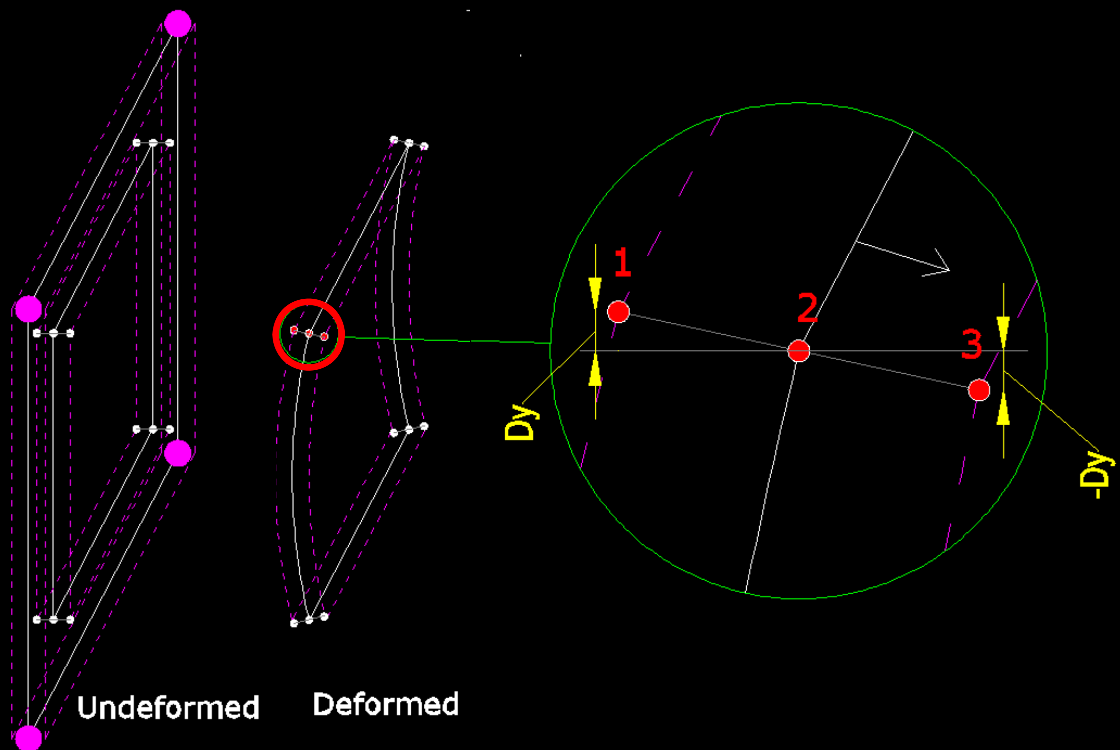
$$\xi \leq 0.5\left(1 + 2.35m - \sqrt{5.53m^2 + 4.70m}\right)$$

$$\mathbf{l_o = l_p = 0.2}\boldsymbol{l_w} \mathbf{+ 0.044}\boldsymbol{h_w}$$



Numerical Simulation

✓ Curved shell element in DIANA



Dashti et al. (2014)

Parra (2016)

Scolari (2017)

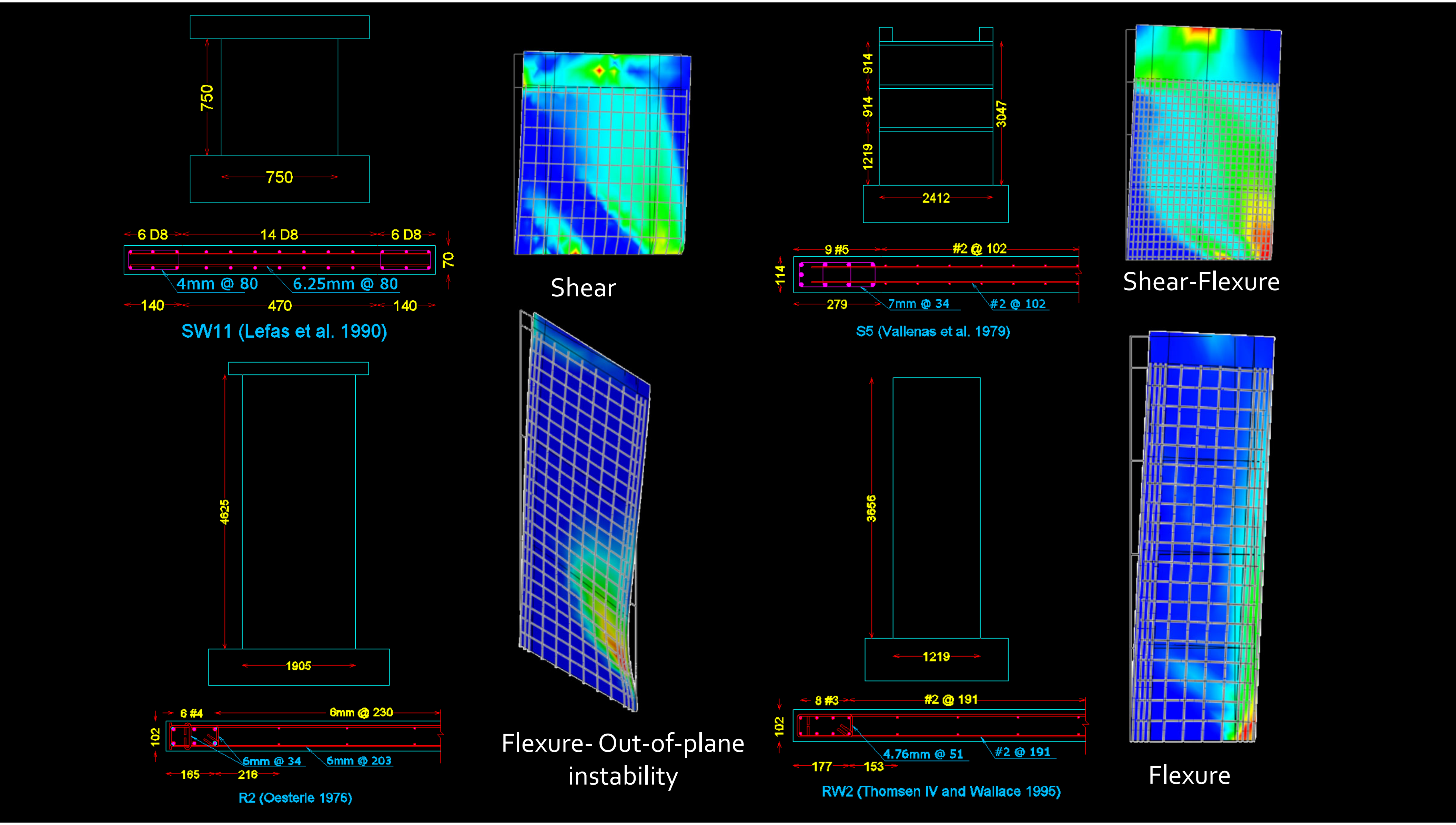
Rosso et al. (2017)

Daza Rodríguez (2018)

Verification of the model; different failure modes

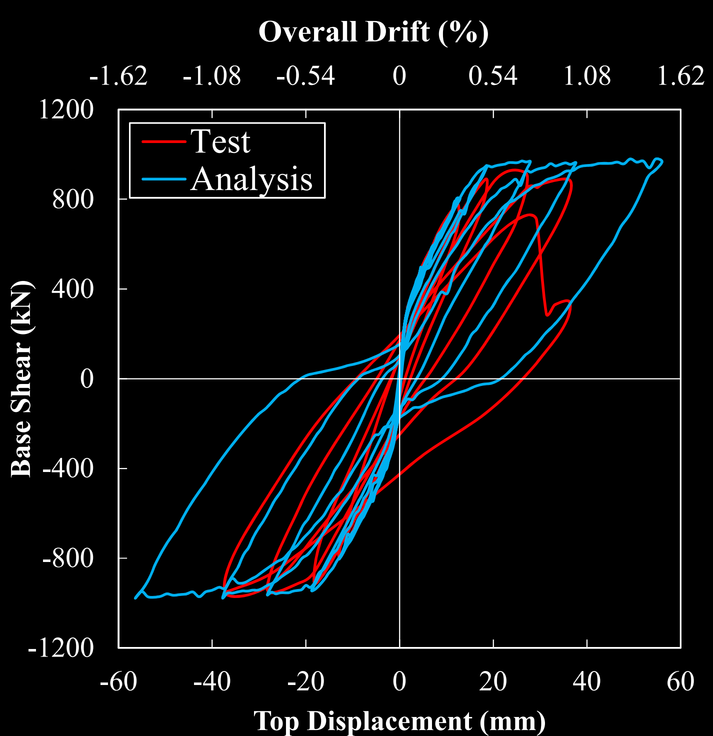
Dashti, F., R. P. Dhakal and S. Pampanin (2017). "Numerical Modelling of Rectangular Reinforced Concrete Structural Walls." *Journal of structural engineering* 143 (6). DOI: 10.1061/(ASCE)ST.1943-541X.0001729

Specimen	Length, L_w, mm	Height, H_w, mm	Thickness, t_w, mm	Section Aspect Ratio, L_w/t_w	Slenderness, H_w/t_w	Shear-span Ratio, $M/(VL_w)$	Axial Load, kN[(n = N/(f'cAc)]	Failure mechanism
SW11 (Lefas et al. 1990)	750	750	70	10.7	10.7	1.0	0 [0.0]	Shear
SW12 (Lefas et al. 1990)	750	750	70	10.7	10.7	1.0	230 [0.1]	Shear
S5 (Vallenas et al. 1979)	2412	3009	114	21.2	26.4	1.6	598 [0.06]	Flexure - Shear
PW4 (Birely 2013)	3048	3658	152.4	20.0	24.0	2.0	1601 [0.12]	Flexure - Bar buckling
R2 (Oesterle 1976)	1905	4572	101.6	18.8	45.0	2.4	0 [0]	Flexure - Out of plane instability
RW2 (Thomsen IV and Wallace 1995)	1219	3660	102	12.0	35.9	3.0	533 [0.1]	Flexure



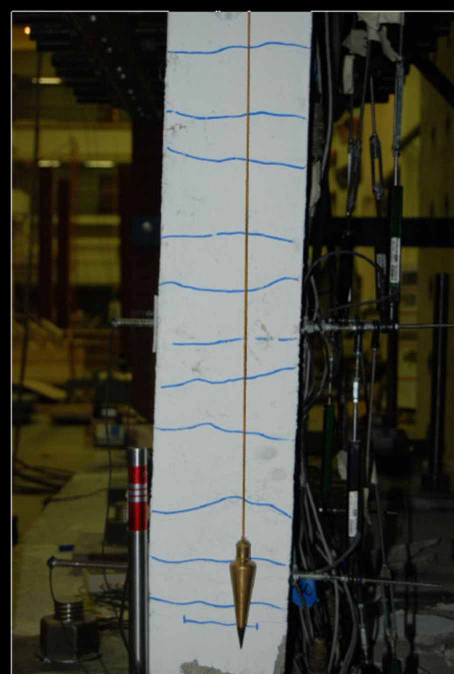
750
750
6 D8
14 D8
6 D8
70
4mm @ 80
6.25mm @ 80
140
470
140
SW11 (Lefas et al. 1990)
Shear
914
914
1219
3047
2412
9 #5
#2 @ 102
114
279
7mm @ 34
#2 @ 102
S5 (Vallenas et al. 1979)
Shear-Flexure
4625
1905
6 #4
6mm @ 230
102
6mm @ 34
6mm @ 203
165
216
R2 (Oesterle 1976)
Flexure- Out-of-plane instability
3656
1219
8 #3
#2 @ 191
102
4.76mm @ 51
#2 @ 191
177
153
RW2 (Thomsen IV and Wallace 1995)
Flexure

Bar buckling can not be captured
PW4 (Birely 2013)



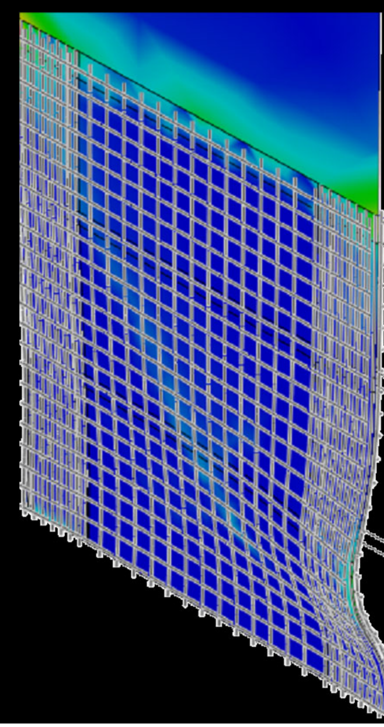
TEST

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



ANALYSIS

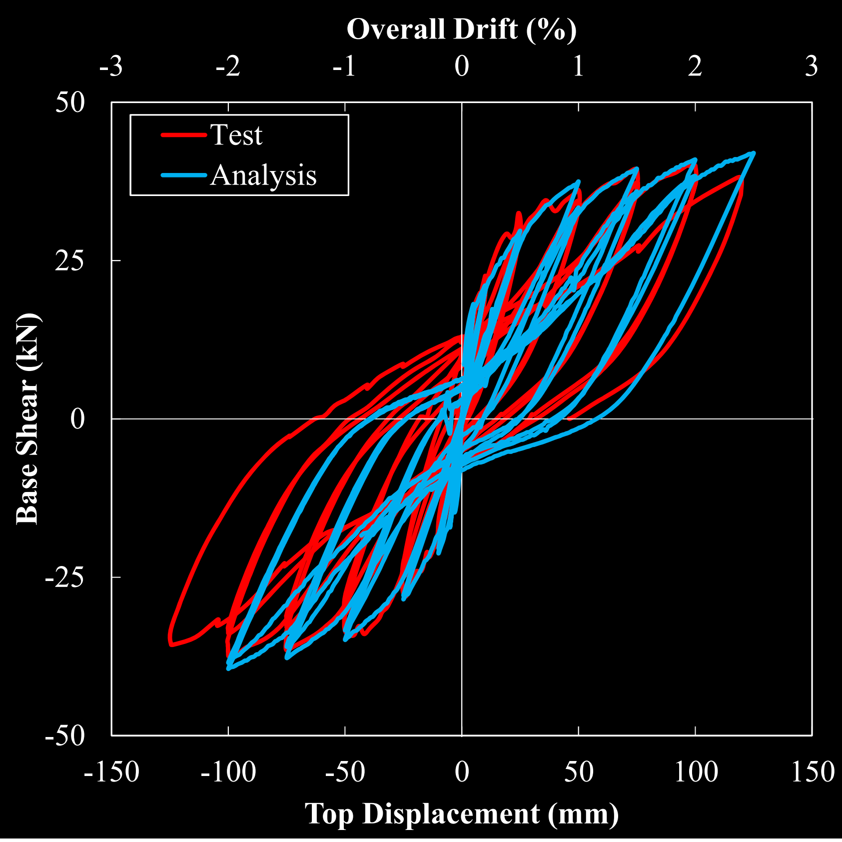
Out-of-plane instability

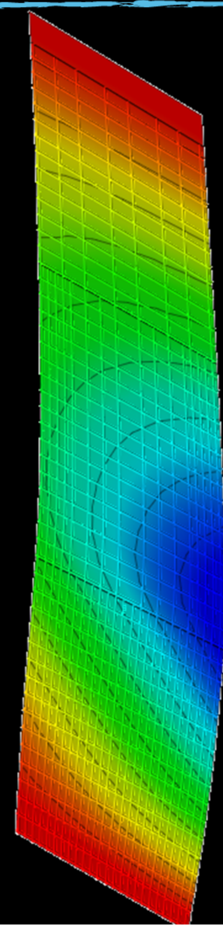


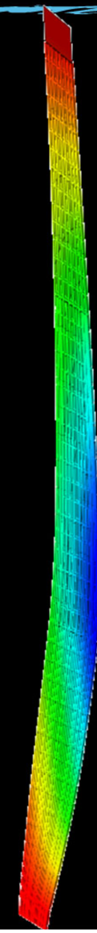
Verification of the model; out-of-plane instability

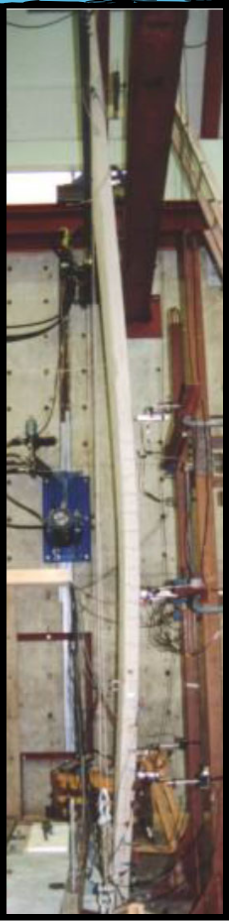
F. Dashti, R.P. Dhakal, S. Pampanin (2017) "Validation of a Numerical Model for Prediction of Out-of-plane Instability in Ductile Structural Walls under Concentric In-plane Cyclic Loading " *Journal of Structural Engineering*, DOI 10.1061/(ASCE)ST.1943-541X.0002013

Specimen3 (Beattie 2004)





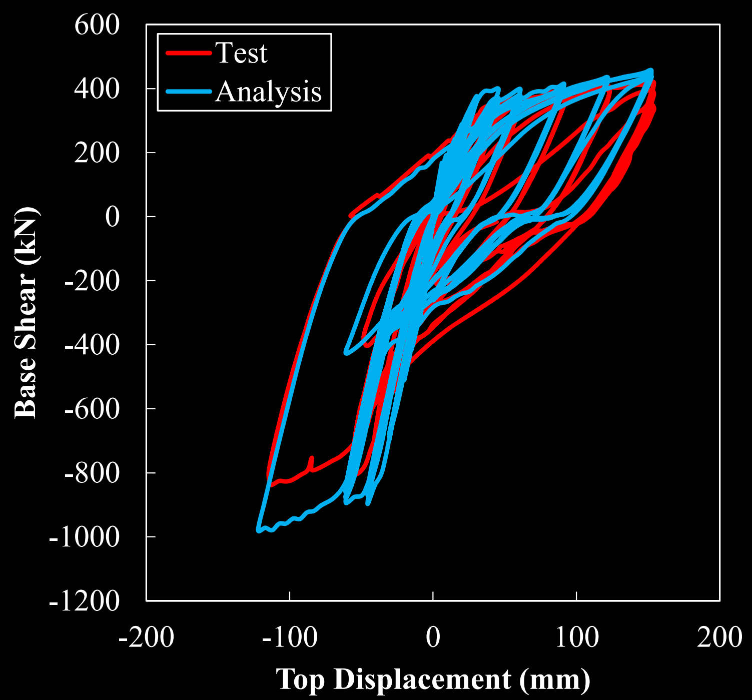


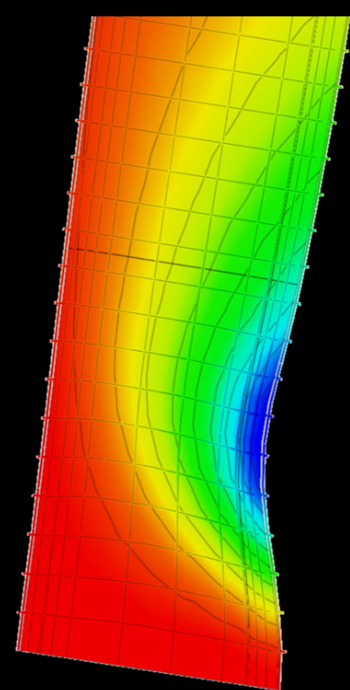


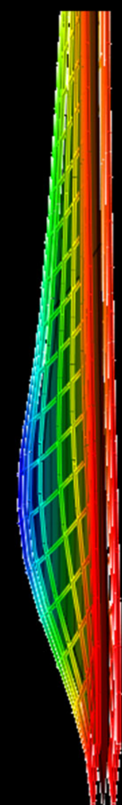
Verification of the model; out-of-plane instability

F. Dashti, R.P. Dhakal, S. Pampanin (2017) “Validation of a Numerical Model for Prediction of Out-of-plane Instability in Ductile Structural Walls under Concentric In-plane Cyclic Loading " *Journal of Structural Engineering*, DOI 10.1061/(ASCE)ST.1943-541X.0002013

RWN (Johnson 2010)

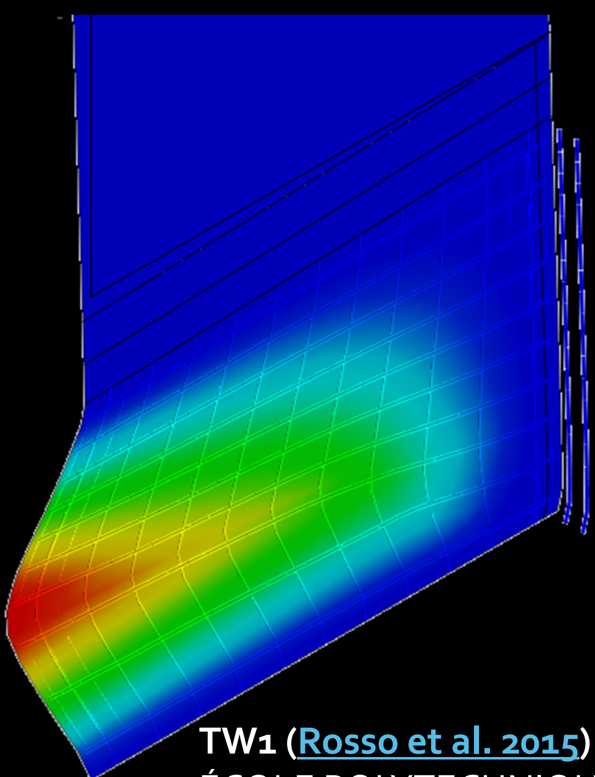


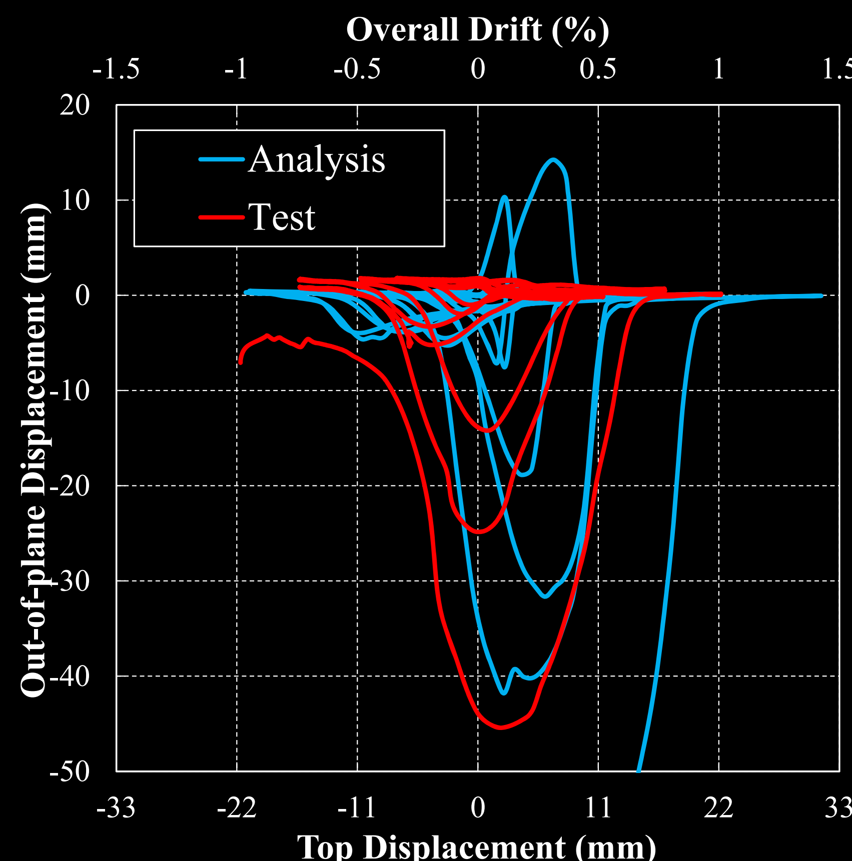




Verification of the model; blind prediction

F. Dashti, R.P. Dhakal, S. Pampanin (2017) “Blind prediction of in-plane and out-of-plane responses for a thin singly reinforced concrete flanged wall" *Bulletin of Earthquake Engineering*, DOI 10.1007/s10518-017-0211-x

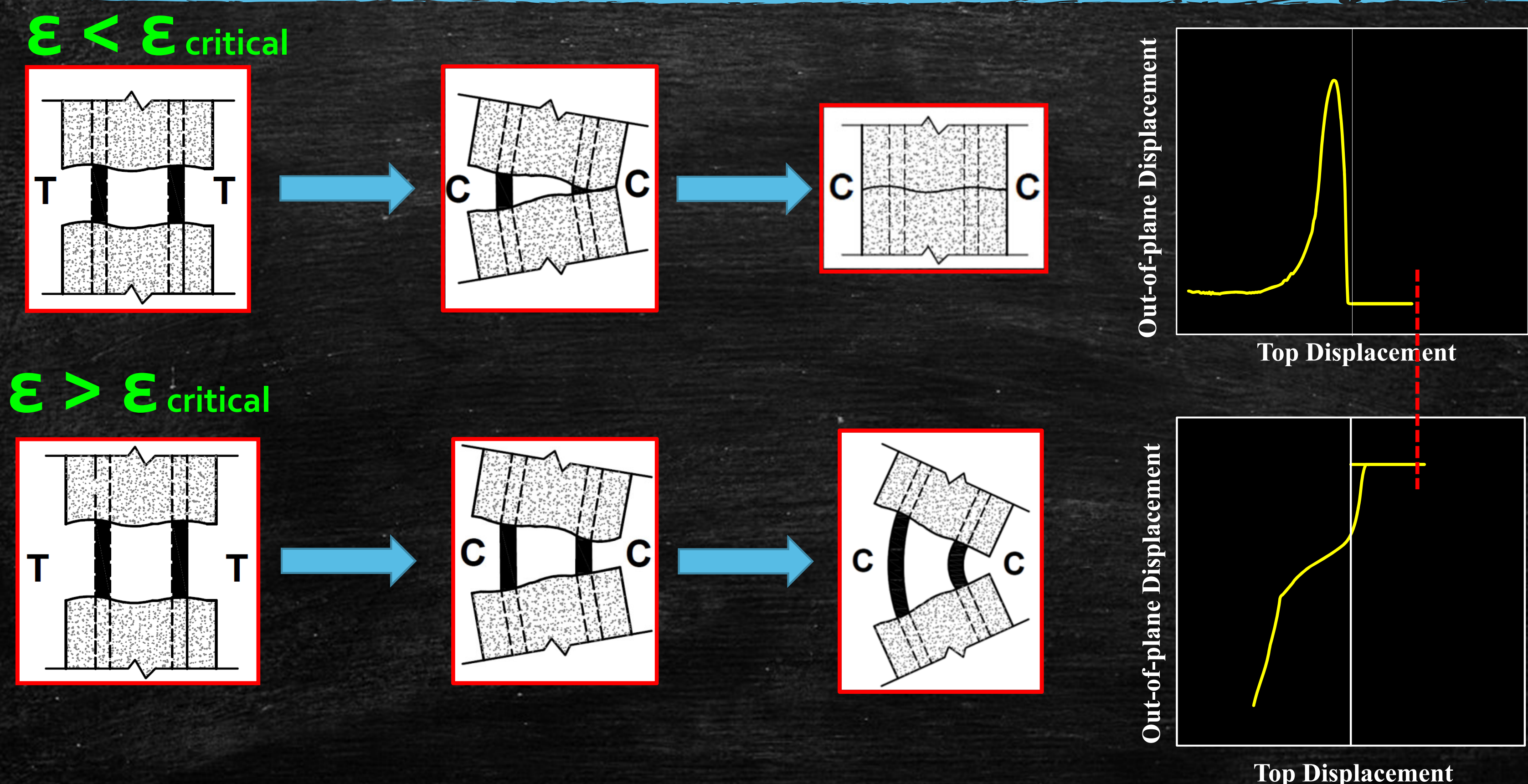




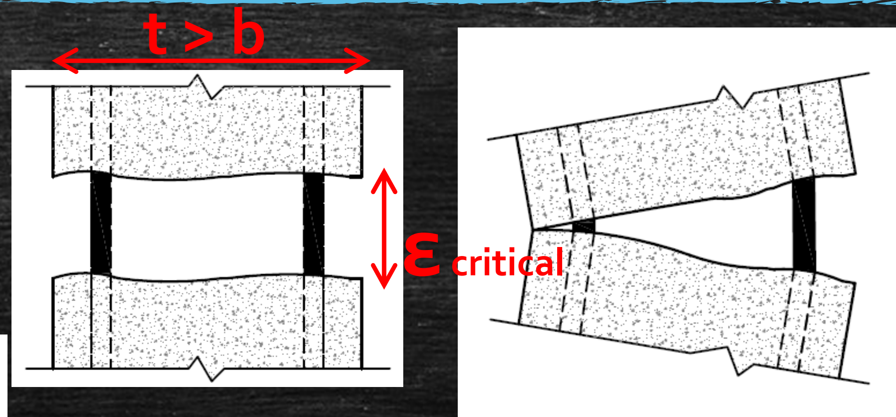
TW1 (Rosso et al. 2015)

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE (EPFL)

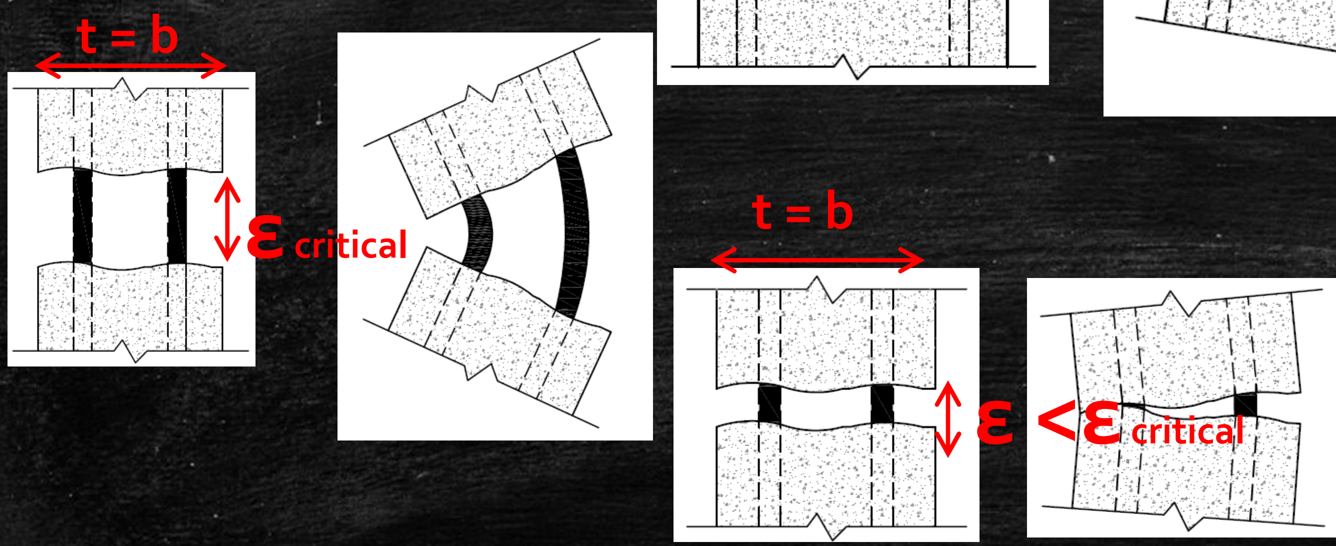
Failure mechanism & controlling parameters



Failure mechanism & controlling parameters



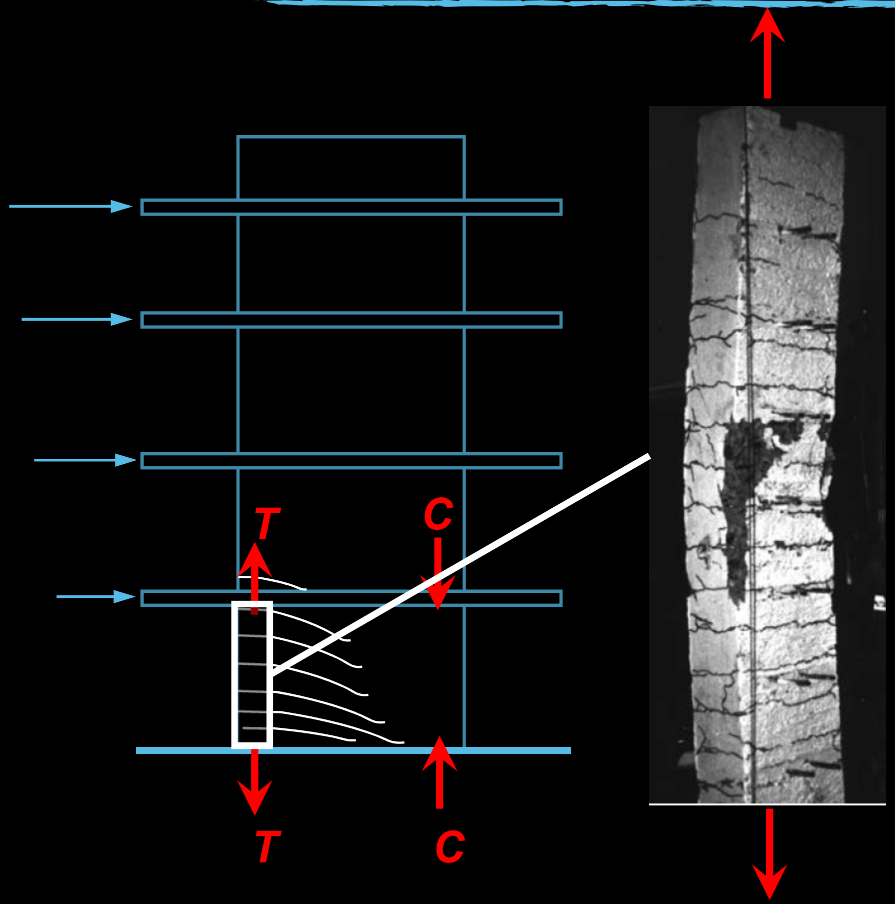
- ✓ Wall thickness



- ✓ Axial load
- ✓ Wall length

Experimental Studies

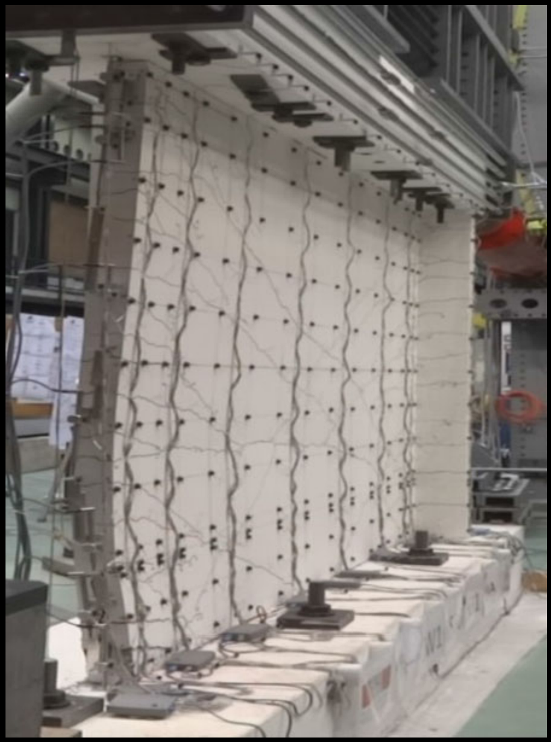
Boundary zone testing



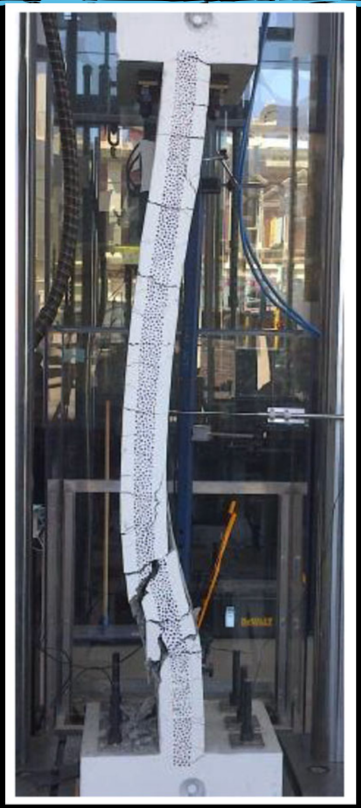
Chai and Elayer (1999)
Acevedo et al. (2010)
Creagh et al. (2010)
Chrysanidis and Tegos (2012)
Shea et al. (2013)
Hilson et al. (2014)
Welt et al. (2016)
Taleb et al. (2016)
Rosso et al. (2017)
Haro et al. (2018)

Experimental Studies

Wall unit testing



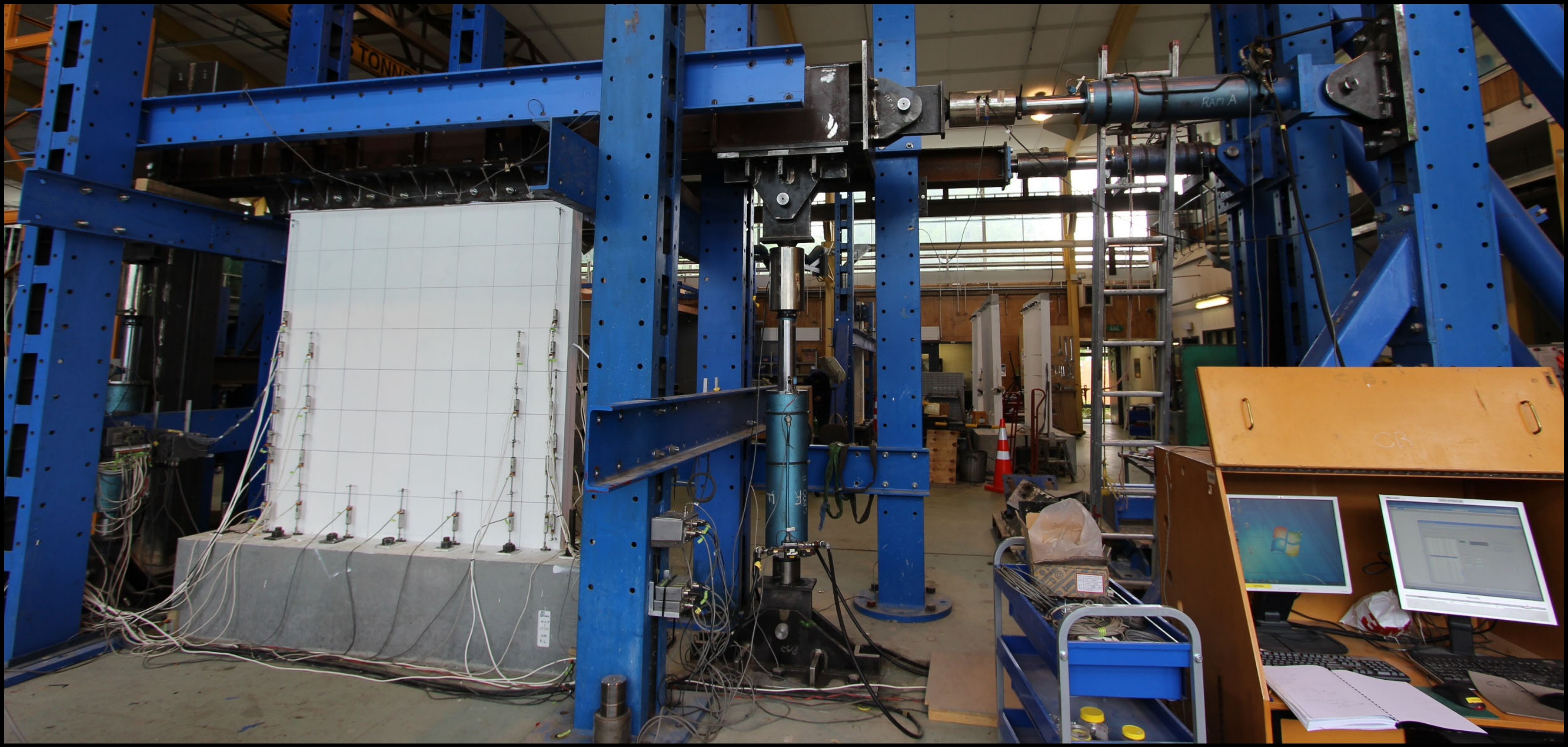
Rosso et al. (2015)



Menegon et al. (2015)

Experimental Studies

Wall unit testing Dashti et al. (2017, 2018)

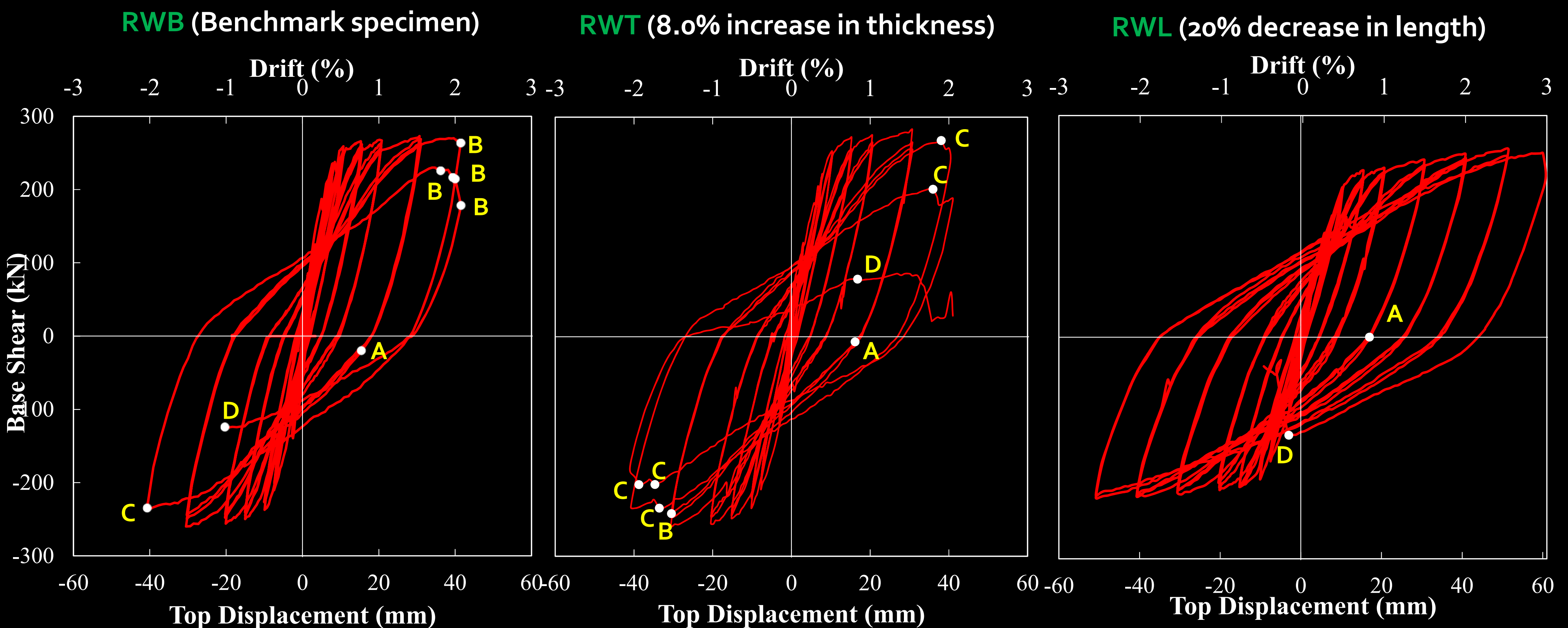


Test Matrix

Parameter	Specimen
	RWB (Benchmark specimen)
Wall thickness	RWT (Thickness increased)
Wall length	RWL (Length decreased)
Axial load	RWA (Axial load decreased)

Experimental Response

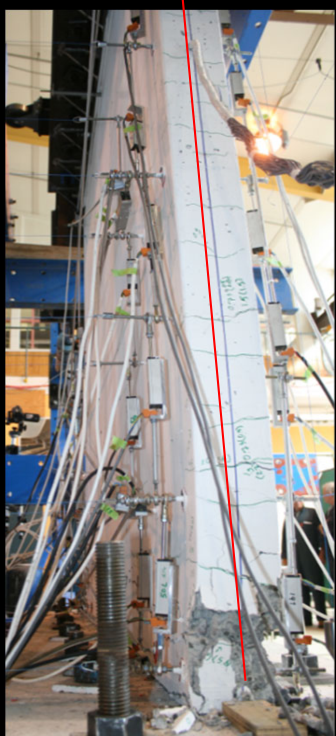
A: Initiation of out-of-plane deformation
B: Bar fracture
C: Bar buckling
D: Instability



Local instability (secondary failure)
RWB & RWT

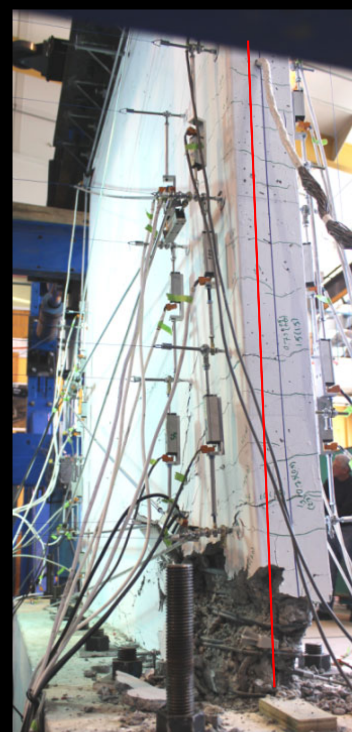
Global instability (main failure)
RWL

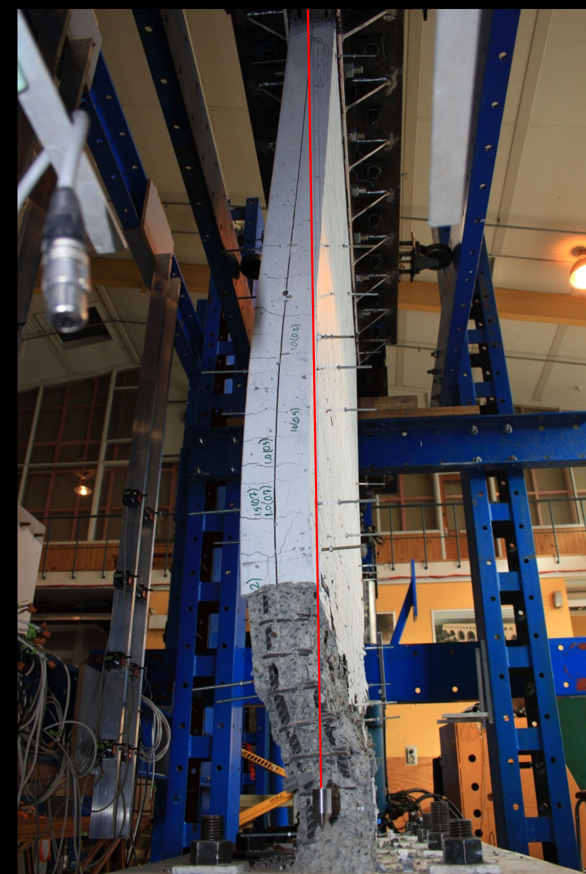
Out-of-plane deformation



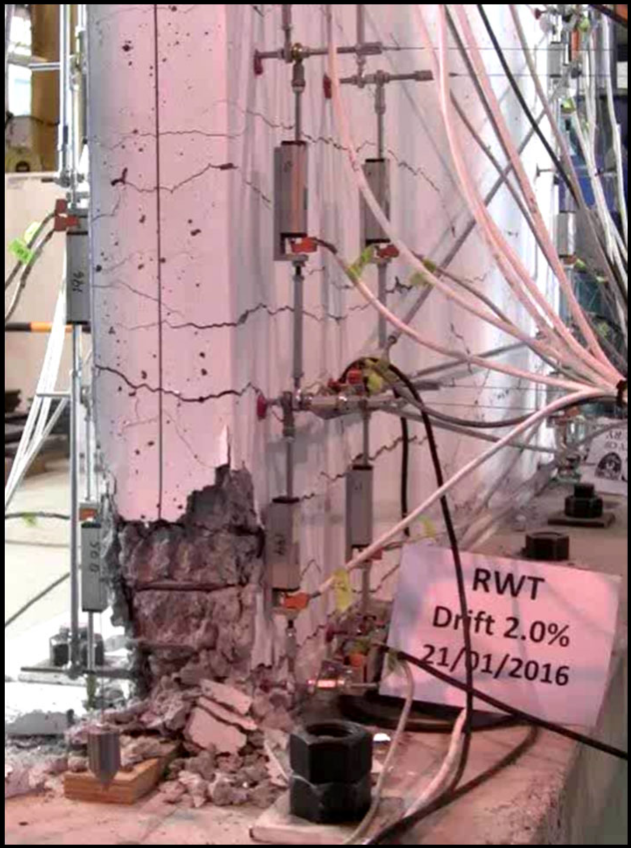
Bar fracture & Bar buckling

Instability

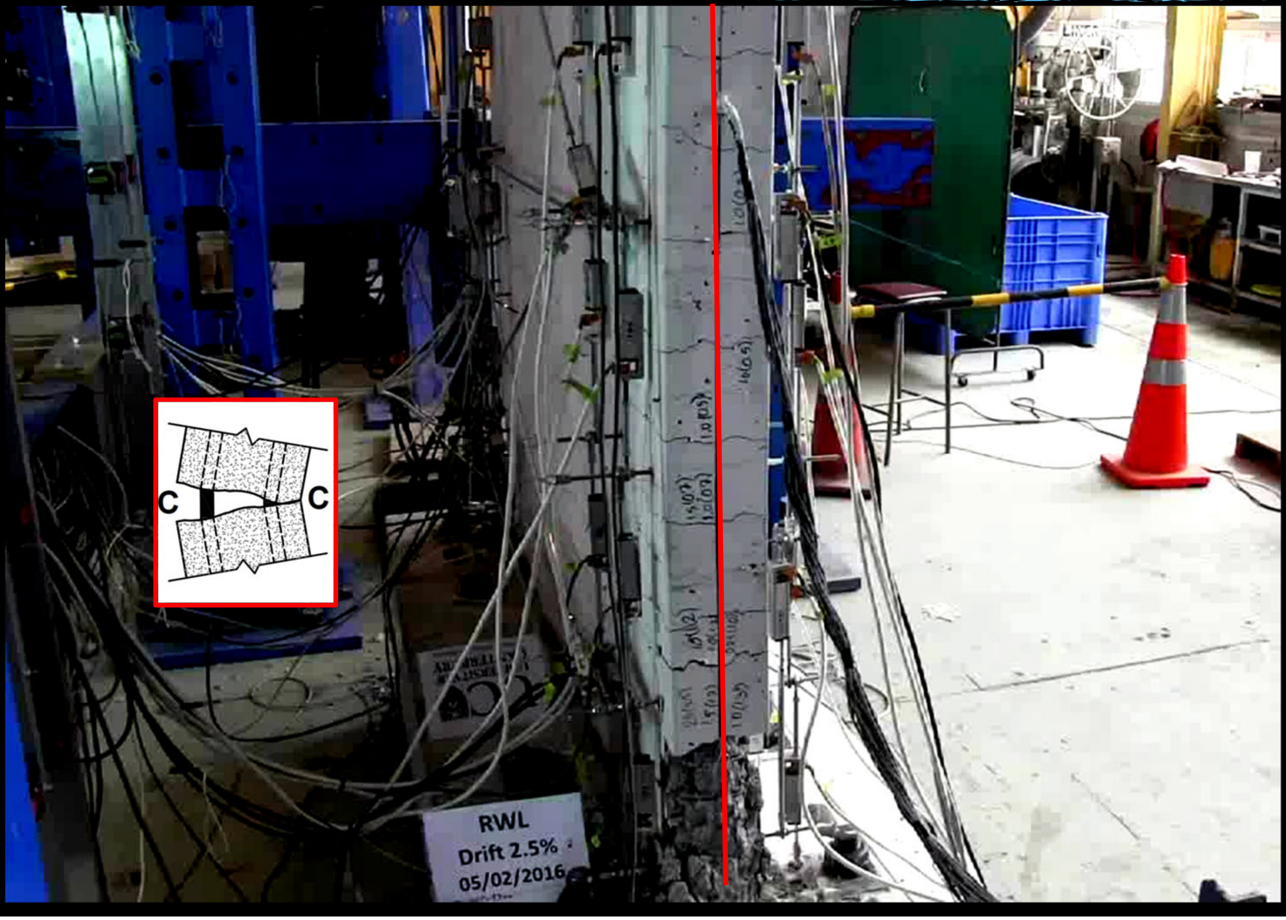


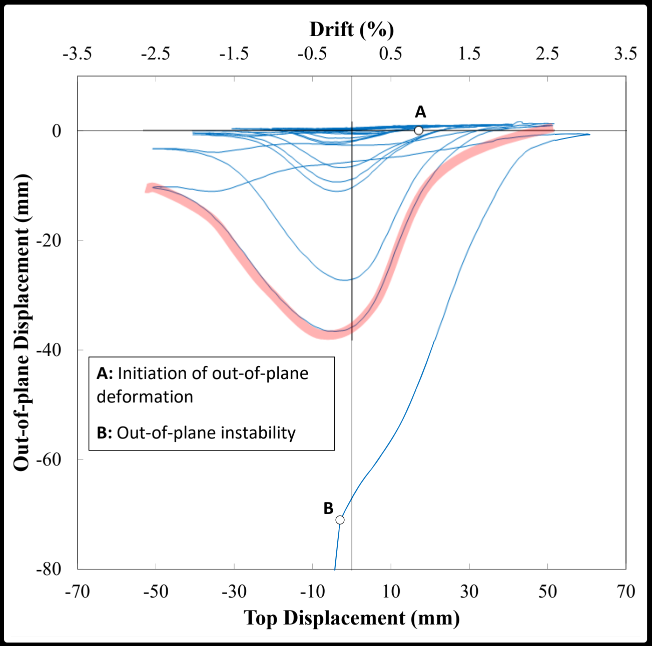


Out-of-Plane Instability as a Secondary Failure Mode

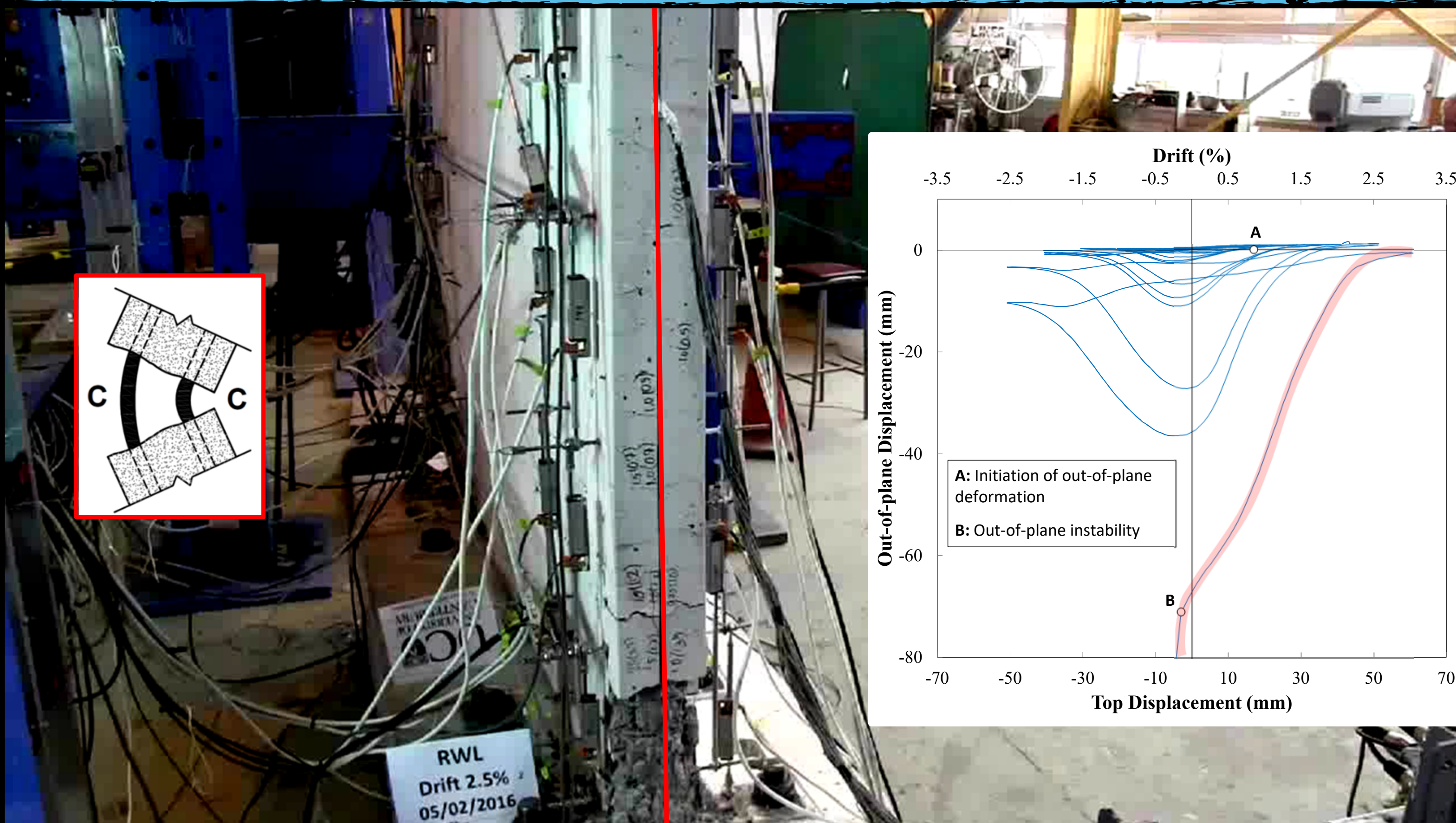


Specimen RWL: West Boundary
Out-of-plane Deformation & Recovery





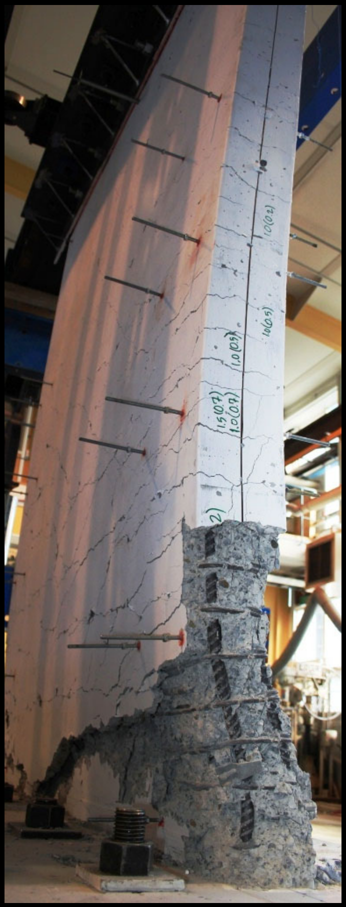
Specimen RWL: West Boundary
Out-of-plane Instability



Global instability (main failure)

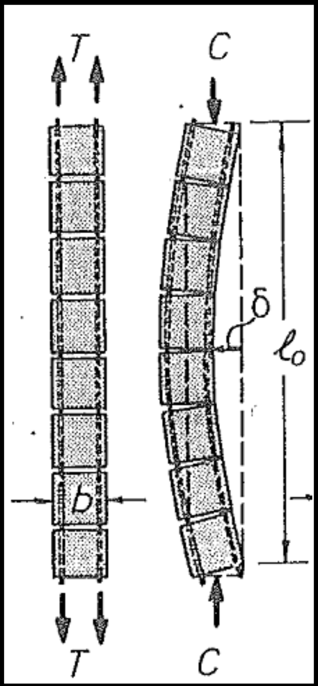
The experimental observations were in line with:

- 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.

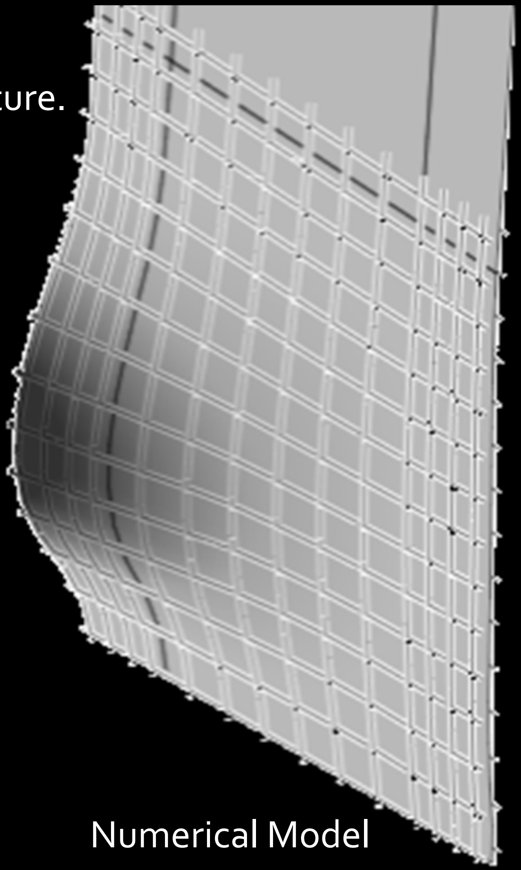


Specimen RWL

2011 Christchurch (Elwood 2013)



Paulay & Priestley (1993)



Numerical Model

Research Findings

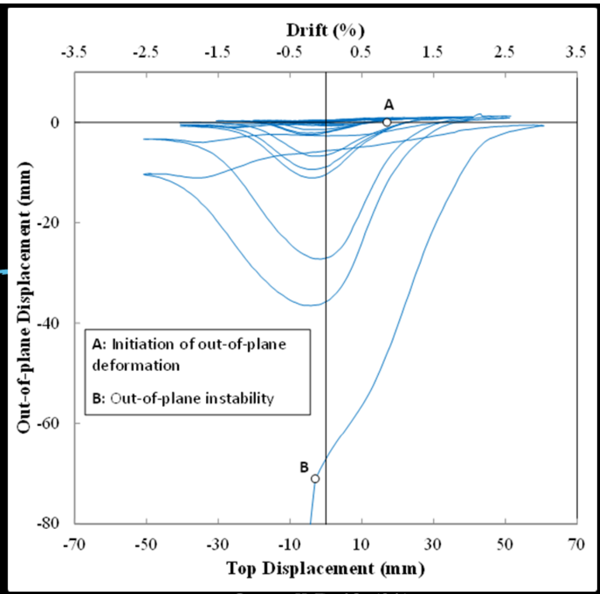
Stages of out-of-plane deformation response:

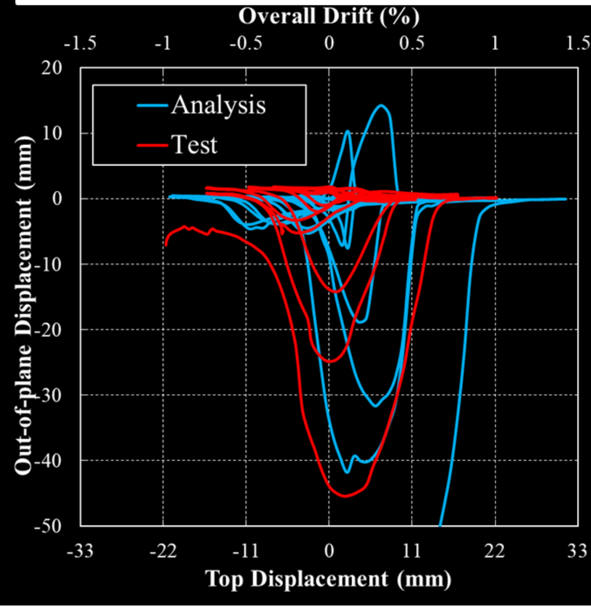
1) **Minimal or no** out-of-plane deformation

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

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

4) Development & **steady increase** resulting in out-of-plane instability of the wall
$\varepsilon_{sm} = 0.023$ (about $\mathbf{10\varepsilon_y}$ 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

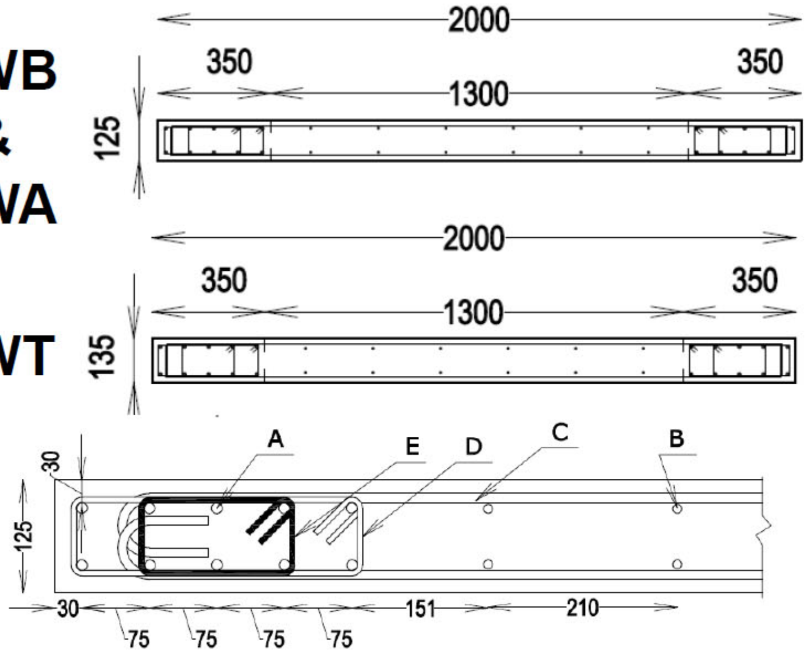
Conclusions

- 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

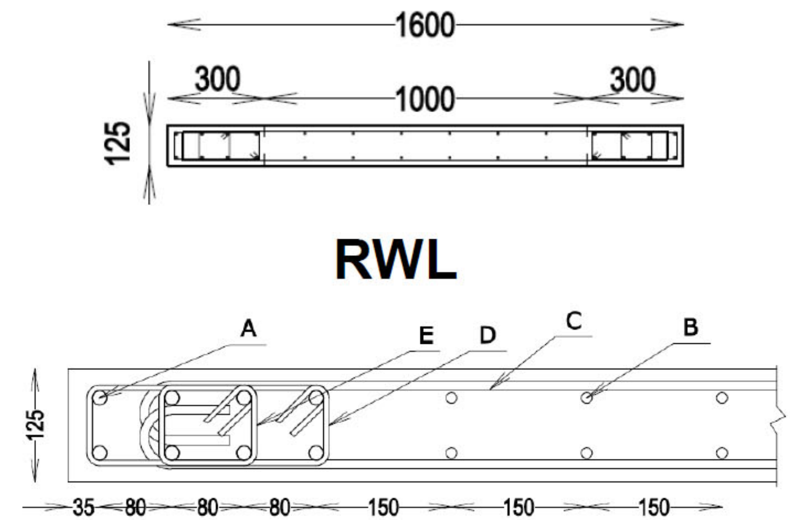
RWB & RWA

RWT



REINFORCEMENT SCHEDULE	
Mark	Reinforcement
A	D12@75
B	D10@210
C	D10@150
D	R6@55 Ties1
E	R6@55 Ties2

RWL



REINFORCEMENT SCHEDULE	
Mark	Reinforcement
A	D16@80
B	D12@150
C	D10@150
D	R6@60 Ties1
E	R6@60 Ties2