UC San Diego

Recent Research Efforts to Understand the Seismic Behavior of Anchorage in Cracked Concrete

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HILTI

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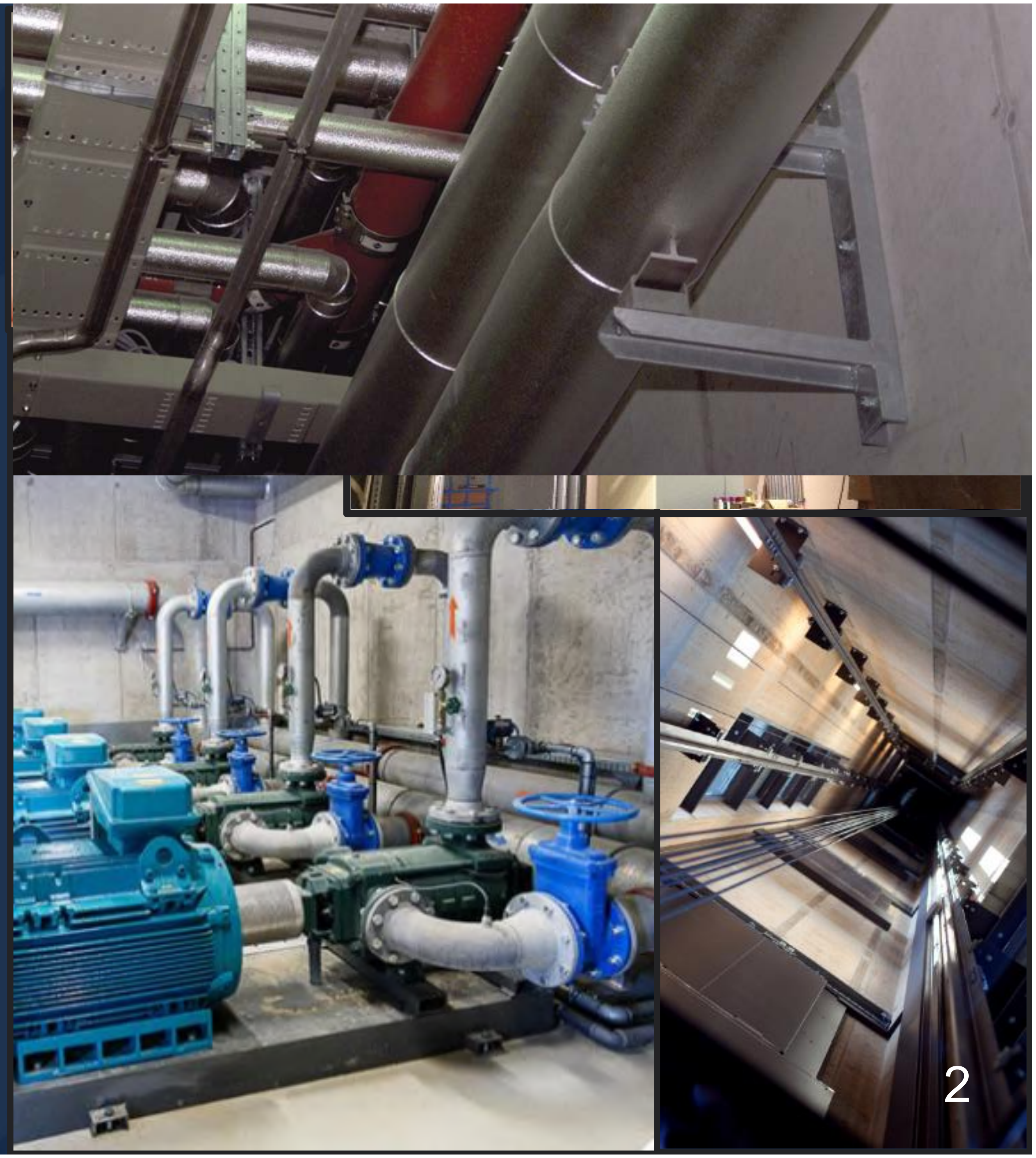
INTRODUCTION

Post-installed metal anchors connect nonstructural components and systems (NCS) to concrete structures (walls/ceilings/floor/slabs)

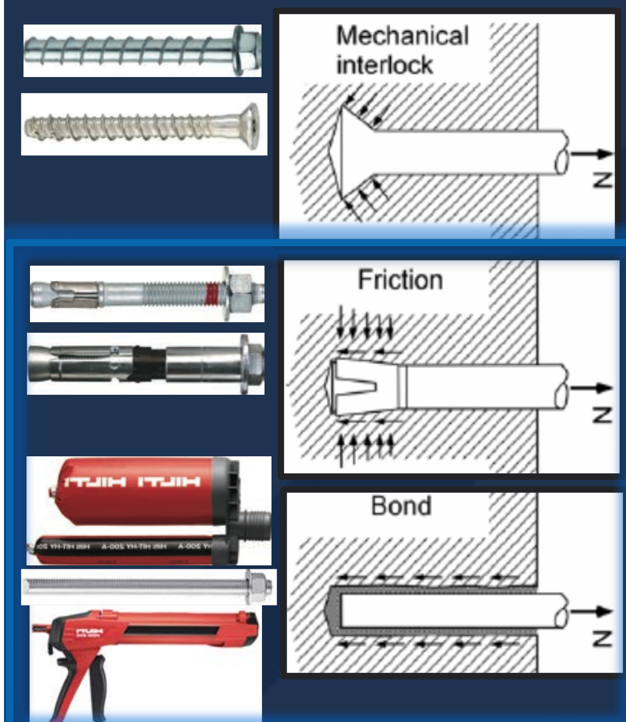
- Nuclear power plants
- Mechanical/electrical rooms
- Elevator shafts

~60% of these applications requires horizontal installation!

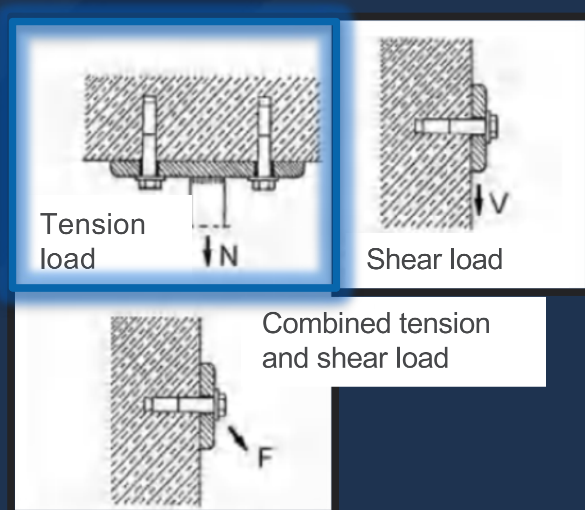


INTRODUCTION

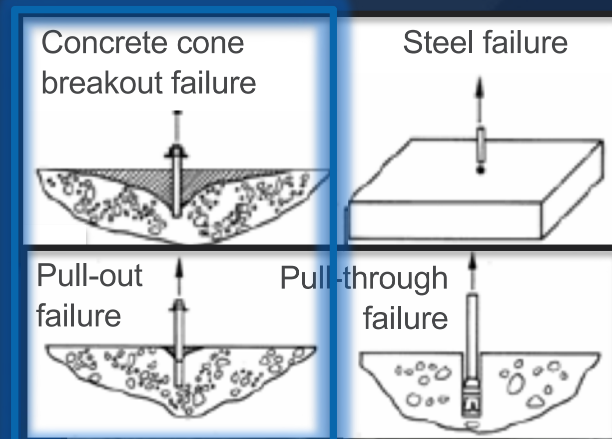
Different anchoring mechanisms:

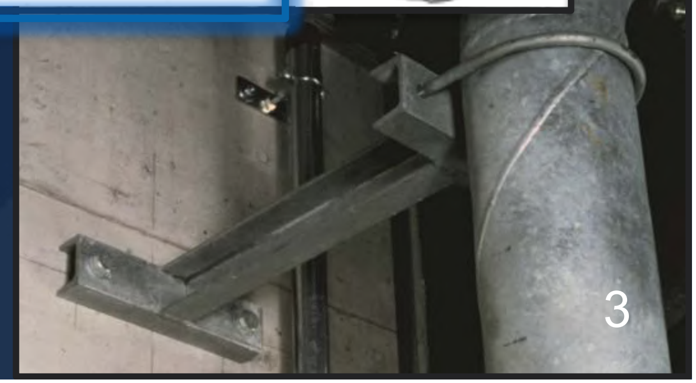


Different static and dynamic actions:



Typical failure modes for anchors loaded in tension:

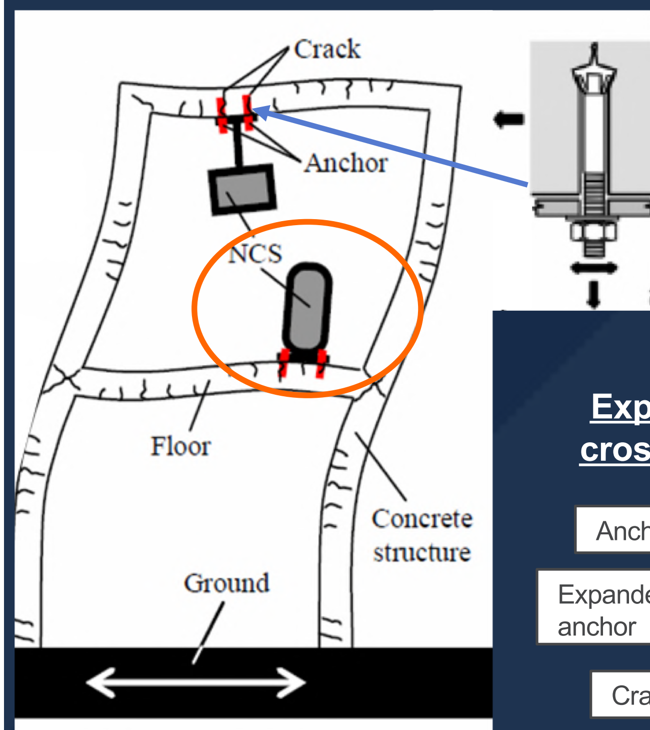


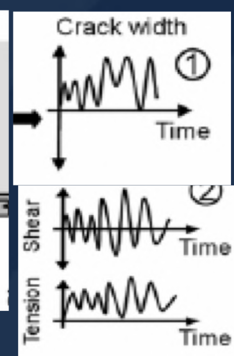


Figures from "Behavior and Testing of Fastenings to Concrete for Use in Seismic Applications", Hoehler, 2006 and "Anchorage in concrete construction", Eligehausen et al., 2006

INTRODUCTION

During an earthquake, anchors are subjected to **cracks that are cycling opened/closed**, in addition to the loading history from **earthquake induced inertial forces** on the structure.



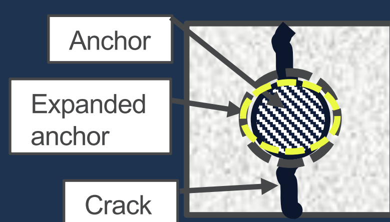


"Seismic displacement behavior of anchors connecting nonstructural components to cyclic cracked concrete", Mahrenholtz et al., 2014

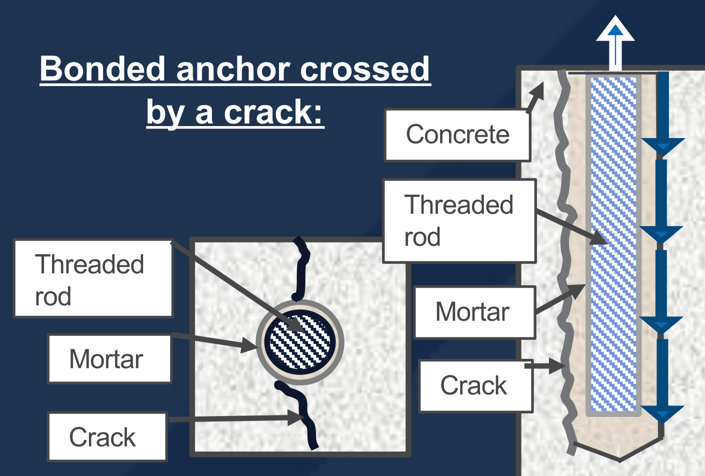
Cracks affect anchors performance:

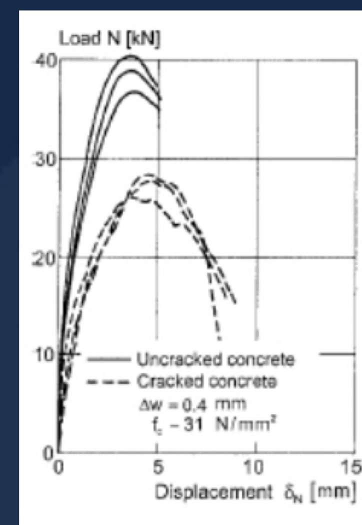
- enlarge installation hole bigger
- change the **stress concentration**
- compromise anchors strength

Expansion anchor crossed by a crack:



Bonded anchor crossed by a crack:





Eligehausen et al. 2006

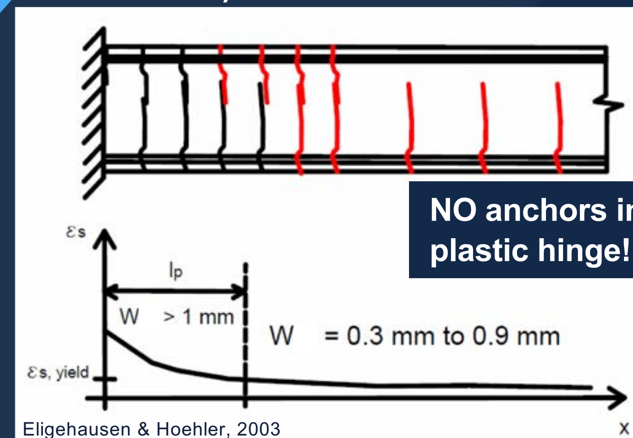
MOTIVATION

European anchor qualification procedures

Table 1.1 Minimum recommended performance categories for anchors under seismic actions

Seismicity		Importance Class acc. to EN 1998-1:2004, 4.2.5			
	$a_g \cdot S$ [2)]	I	II	III	IV
Very low[1)]	$a_g \cdot S \leq 0{,}05\ g$	ETAG 001 Part 1 to Part 5			
Low[1)]	$0{,}05\ g < a_g \cdot S \leq 0{,}1\ g$	C1	C1 [3)] or C2 [4)]		C2
	$a_g \cdot S > 0{,}1\ g$	C1	C2		

Crack widths in frame-type structures (max crack width at yield of reinforcement W = 0.8 *mm*).



NO anchors inside plastic hinge!

Cracking and damage → Response Modification Coefficient R ≈ capacity to dissipate energy through inelastic actions

ASCE 7-16 Tab. 12.2-1: R factors

A. BEARING WALL SYSTEMS	R
1. Special RC shear walls	5
2. Ordinary RC shear walls	4
C. MOMENT-RESISTING FRAME SYSTEMS	**R**
5. Special reinforced concrete moment frames	8
6. Intermediate reinforced concrete moment frames	5
7. Ordinary reinforced concrete moment frames	3

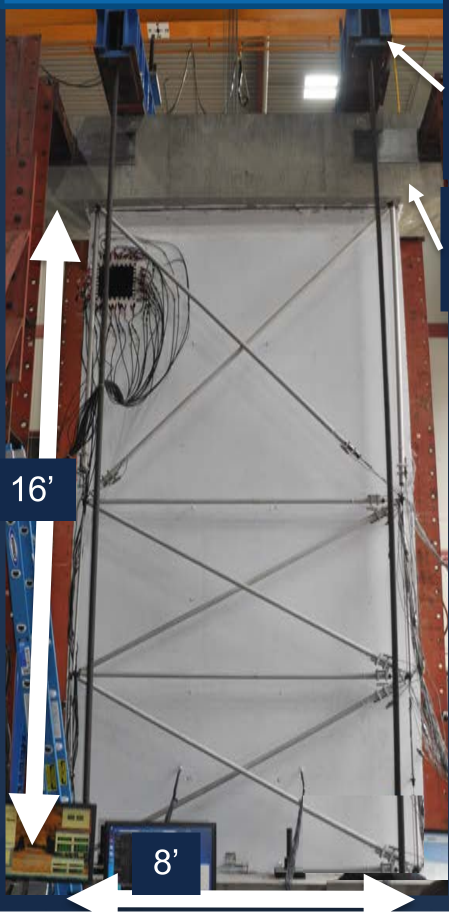
How will anchors perform when installed in other types of structural components, which have different R-factors and expected damage patterns?

UC SAN DIEGO TEST PROGRAM

R = 5

… shear walls behavior depends on aspect ratio (AR = h_w / l_w)

AR=2 full-scale specimen



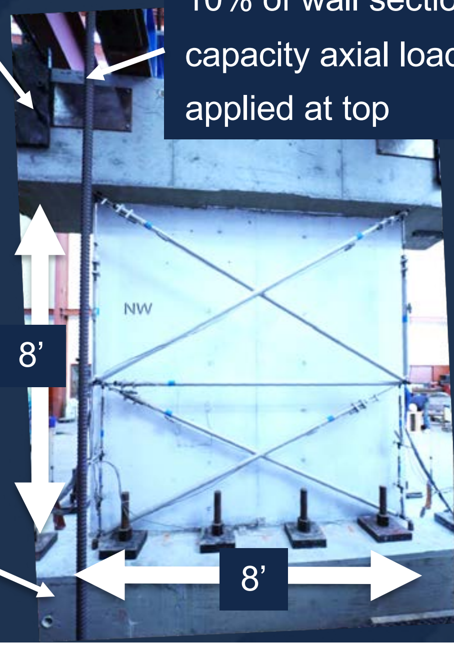
10% of wall section capacity axial load applied at top

Free rotation at the top

Fixed at the base

2 identical AR=1 full-scale specimens

10% of wall section capacity axial load applied at top



0% of wall section capacity axial load applied at top

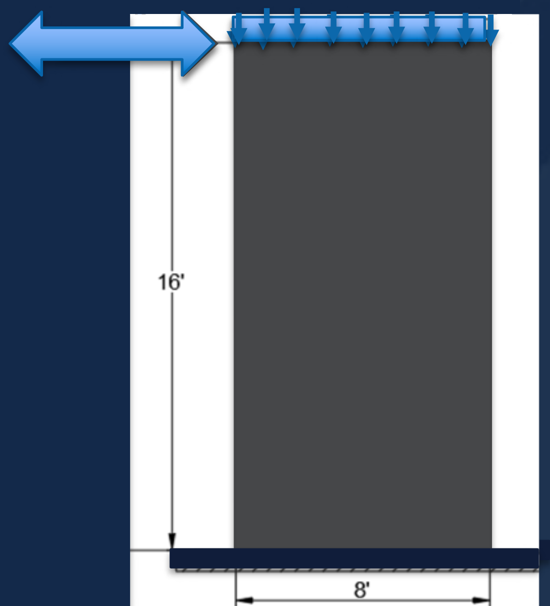
WALL DESIGN

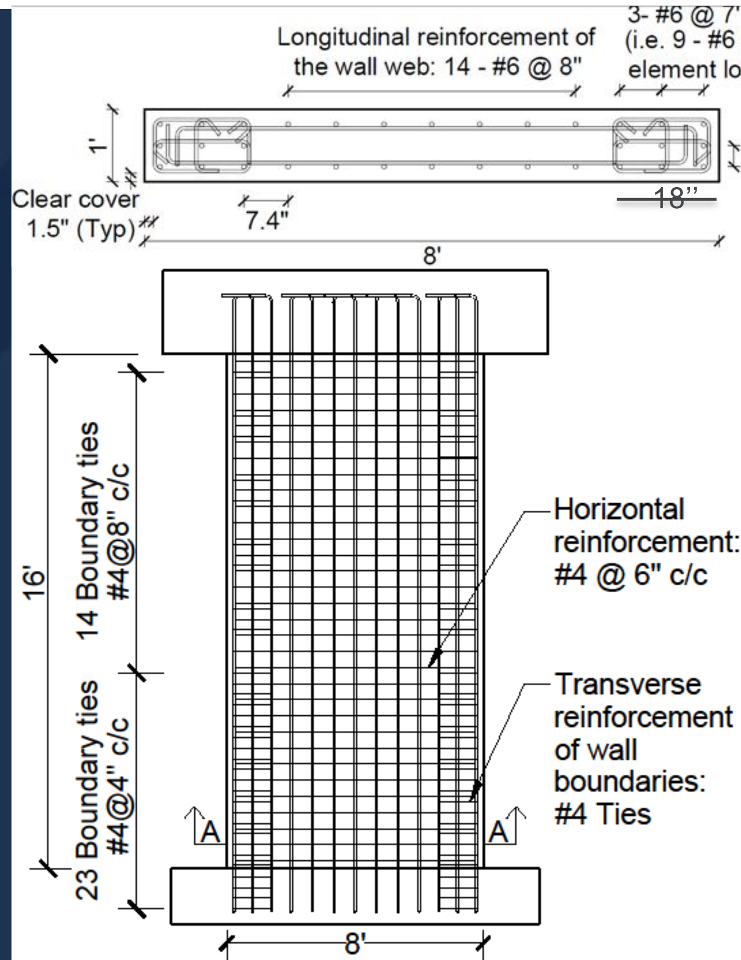
SLENDER WALL

Assumption:

- The resultant of a triangular load distribution is at about 2/3 of the height. The model wall will be 16' height.

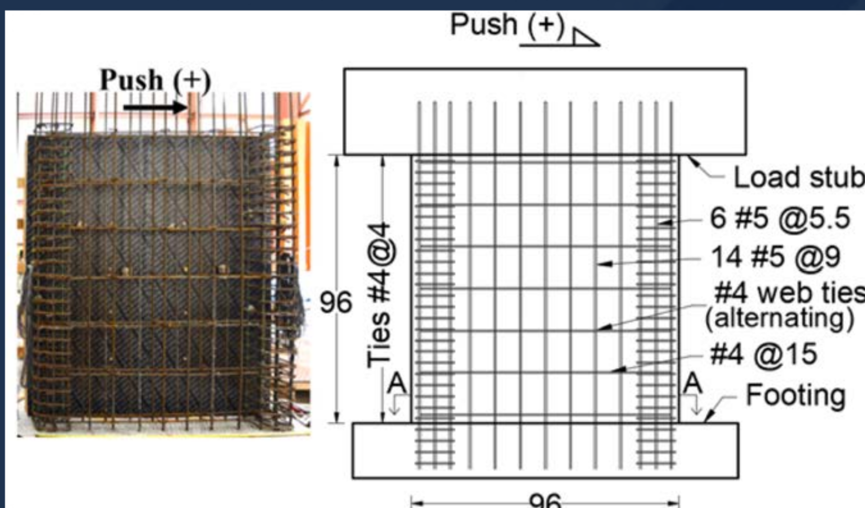
Wall model to test

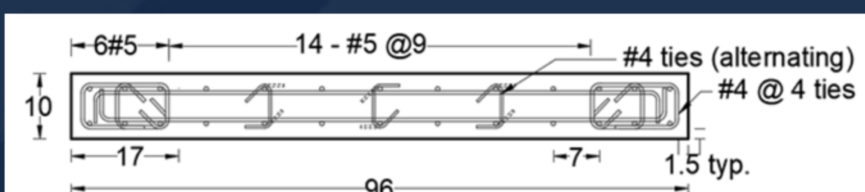


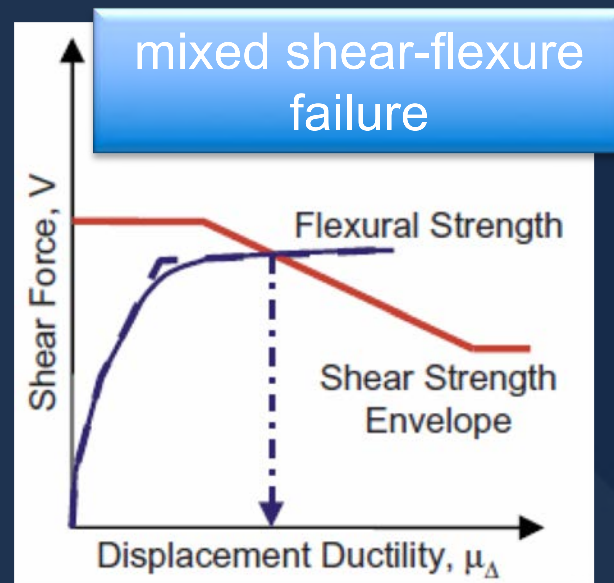


WALL DESIGN

SQUAT WALLS DESIGN

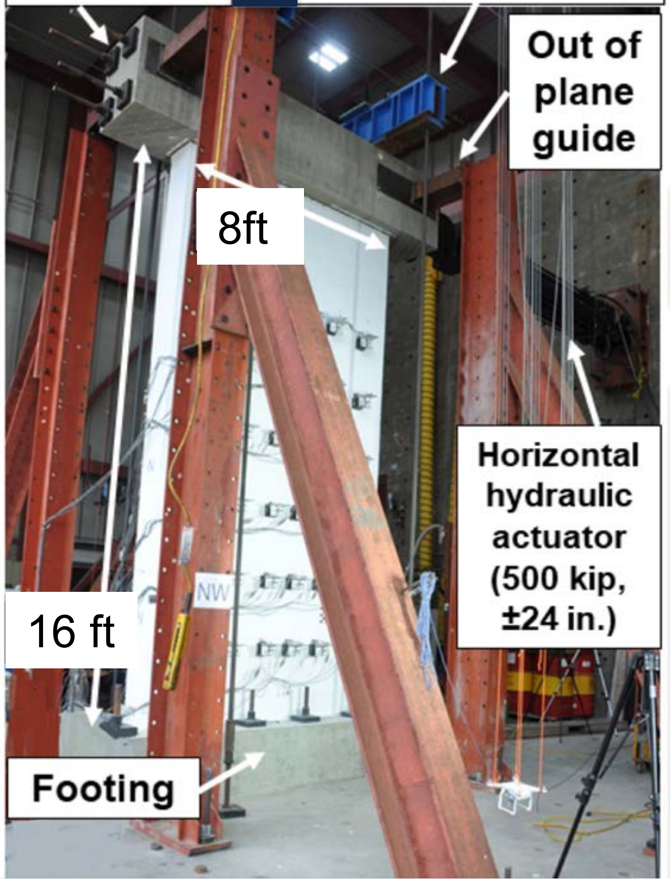




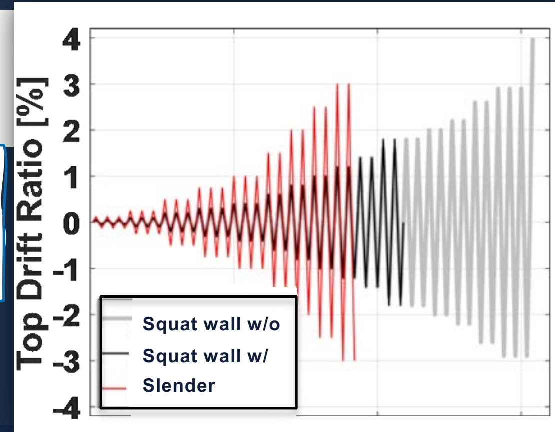


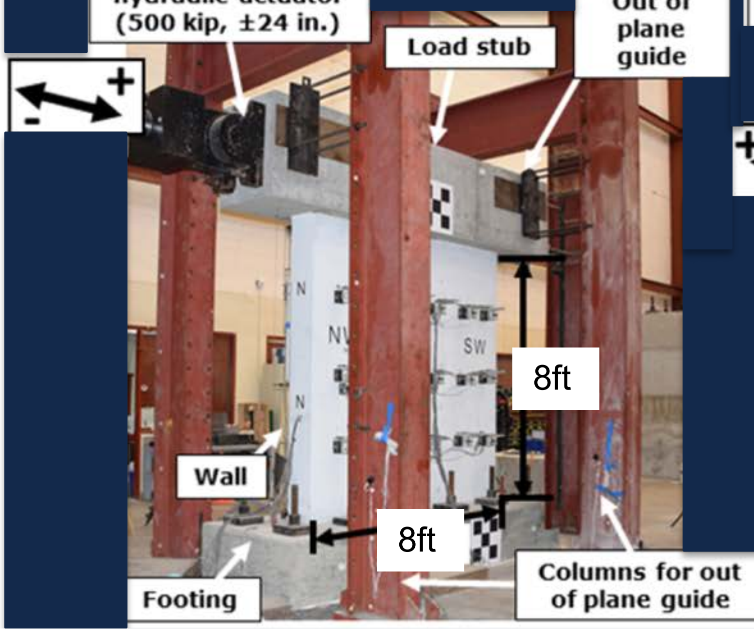
- Boundary elements to engage flexural response and increase displacement capacity of the walls
- Minimum amount of horizontal reinforcement to favorite mixed shear-flexure failure

WALL TEST SETUP

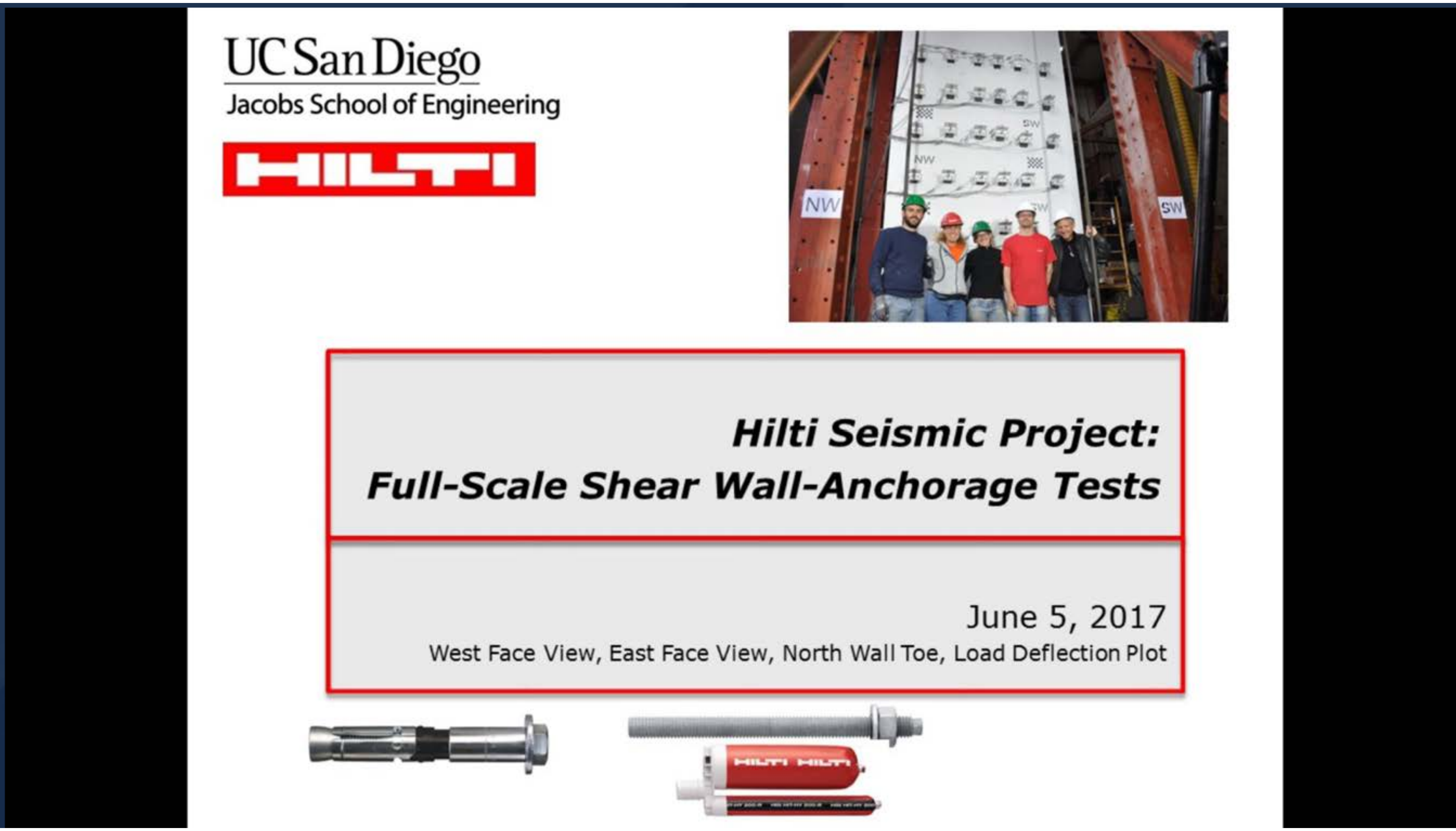


ACI374 displacement protocol

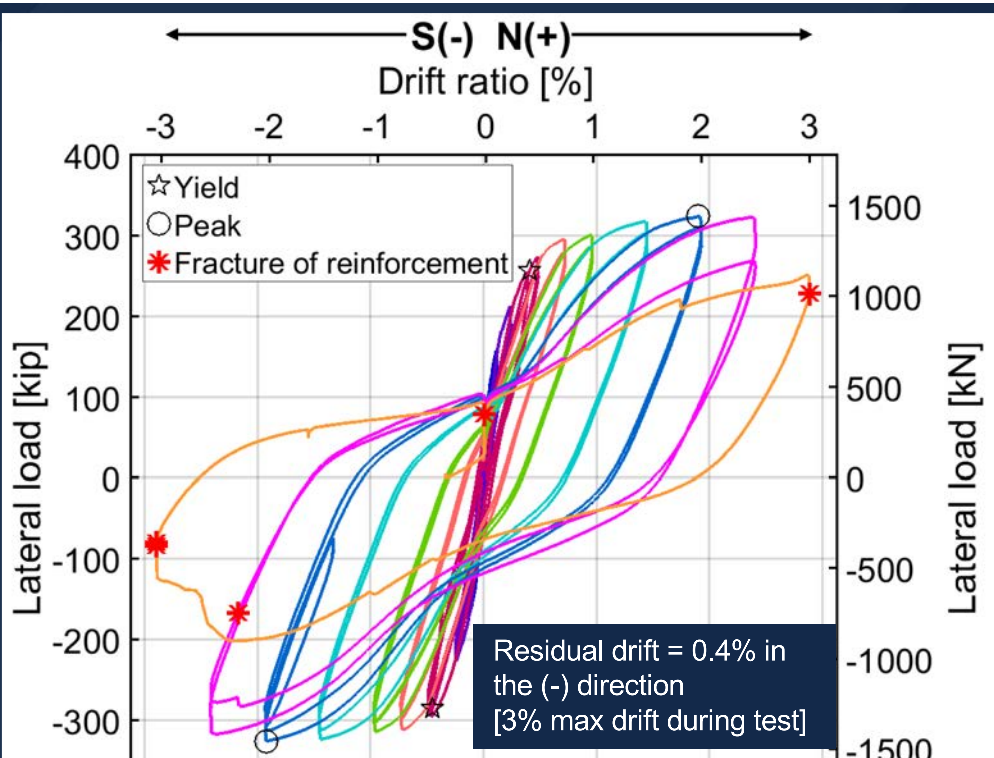


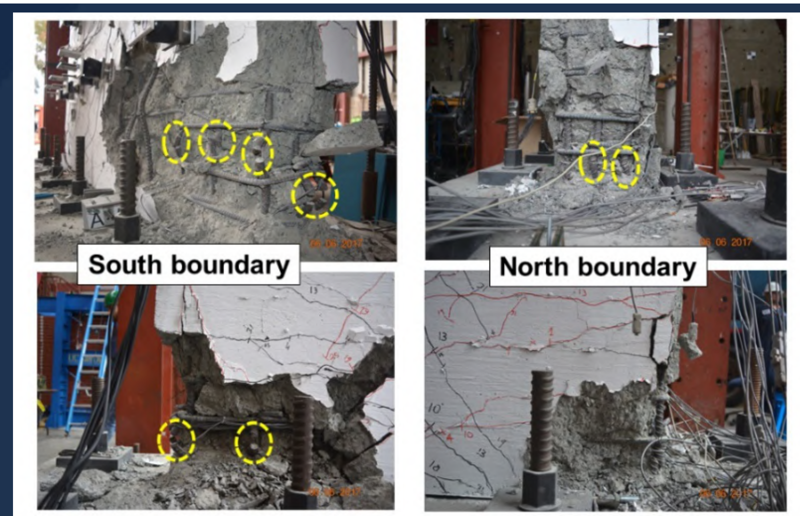


SLENDER WALL CYCLING

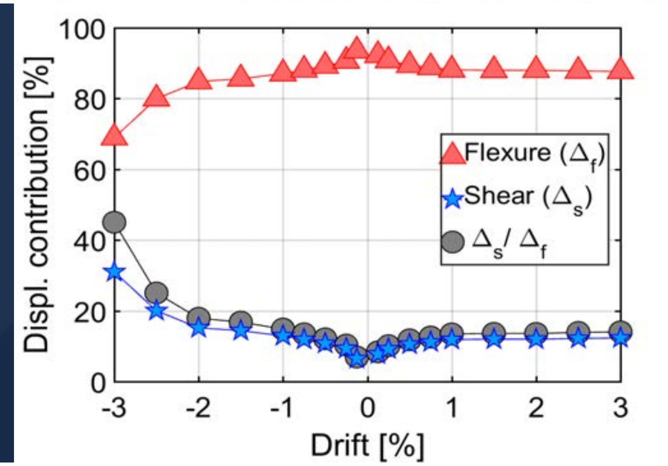


SLENDER WALL GLOBAL RESPONSE



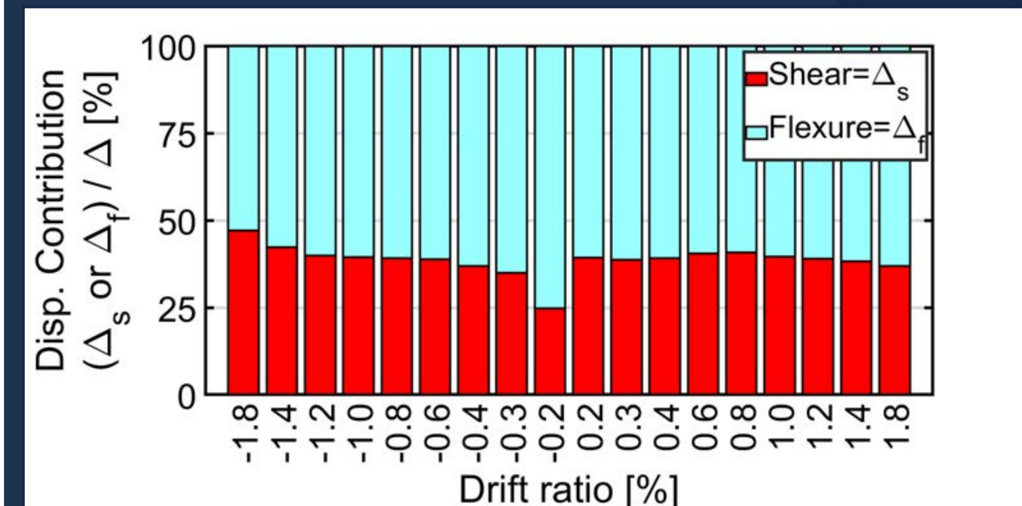


- **Wall failed in flexure**
- Average shear component 15%

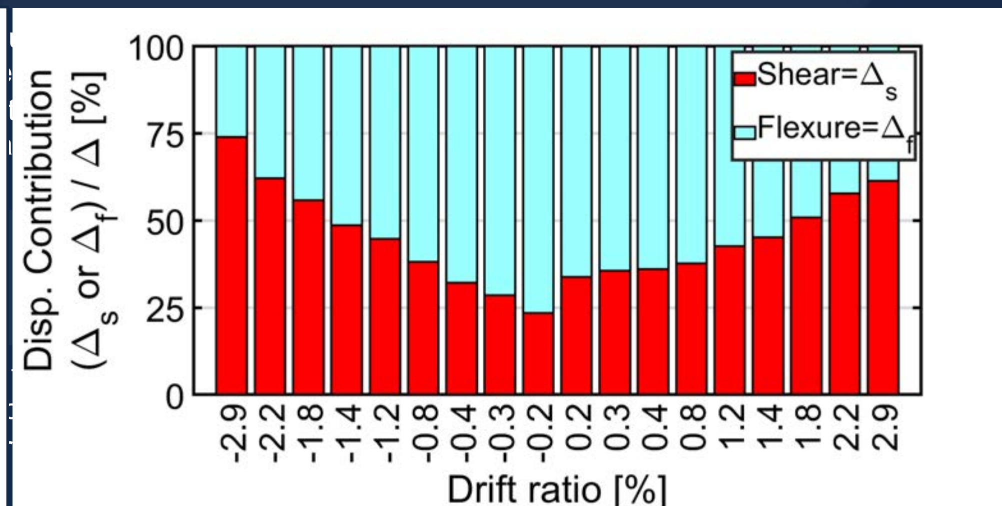


SQUAT WALL GLOBAL RESPONSE

Squat wall tested *with* axial load:



Squat wall tested *without* axial load:

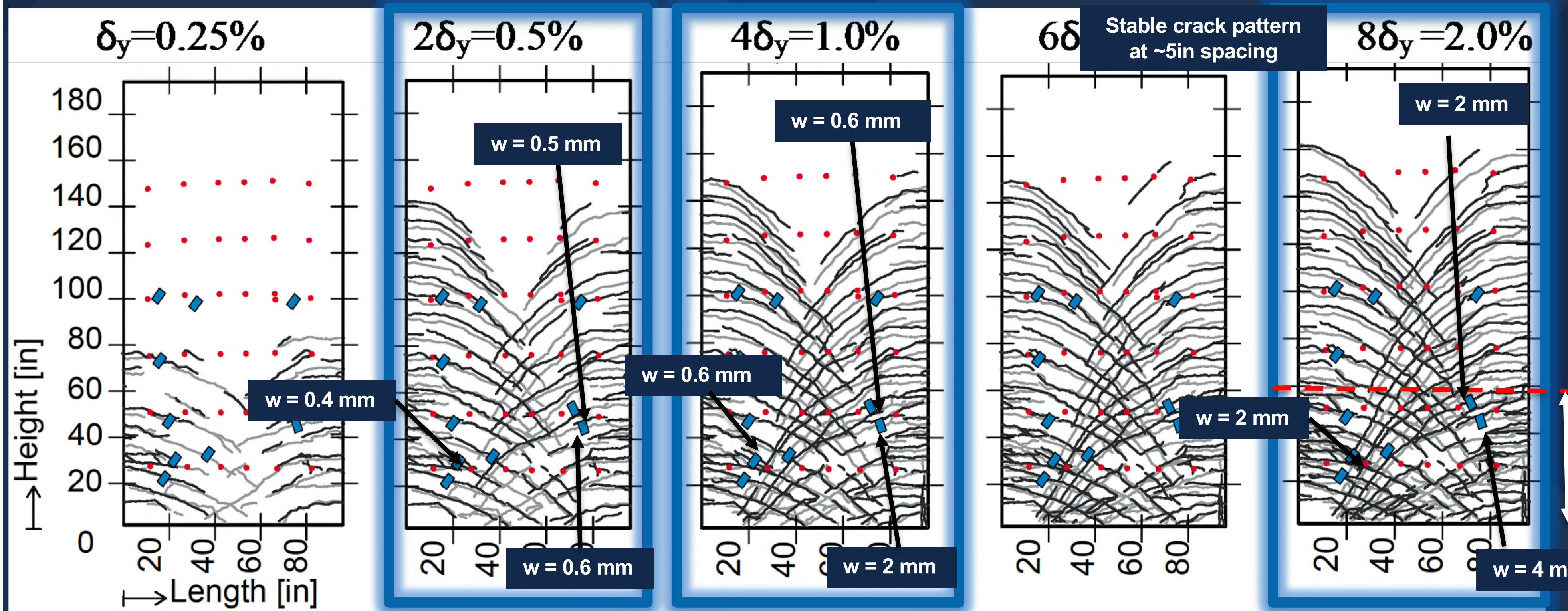


Mean shear displacement contribution ~ 40% for both walls

Presence of axial load on squat walls:

- Increases strength (SQ7.5 ~ 60% stronger than SQ0)
- Reduces drift capacity
- Stabilizes shear to flexure displacement

SLENDER WALL DAMAGE EVOLUTION



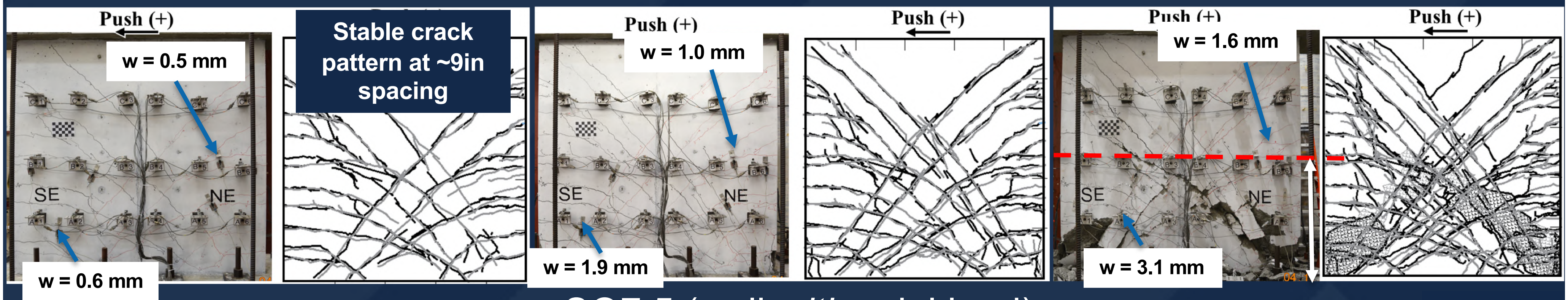
Immediate Occupancy
~ 20% in 50 years

Life Safety
~ 10% in 50 years

Collapse Prevention
~ 2% in 50 years

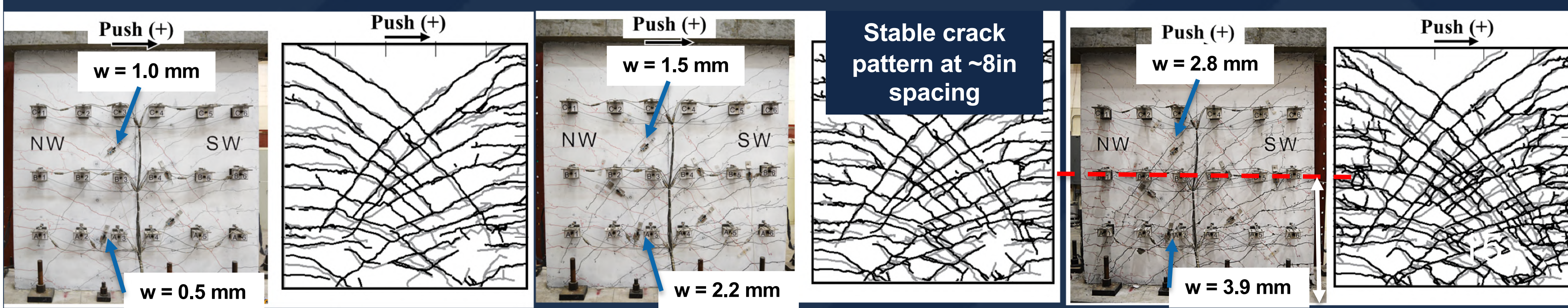
WALL DAMAGE

0.4% drift ~ Immediate Occupancy | 1% drift ~ Life Safety | 2% drift ~ Collapse Prevention



SQ7.5 (wall *with* axial load)

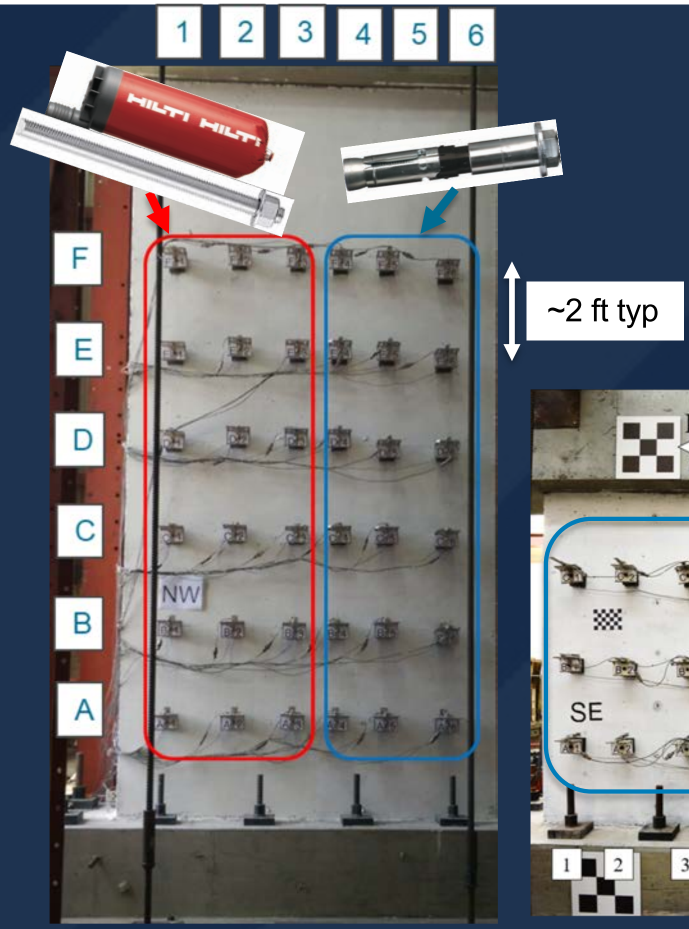
= 0.5 Lw

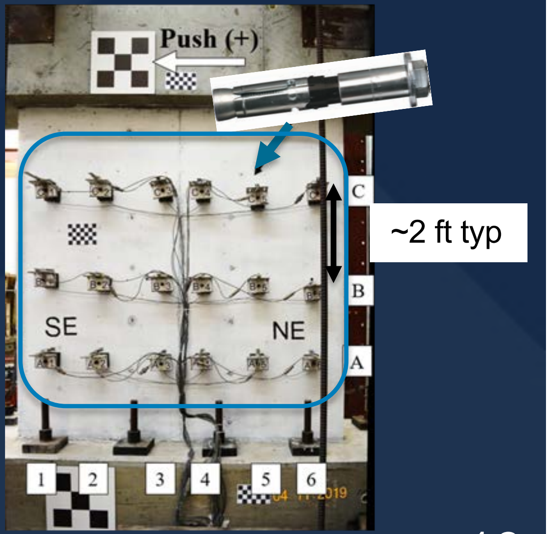


SQ0 (wall *without* axial load)

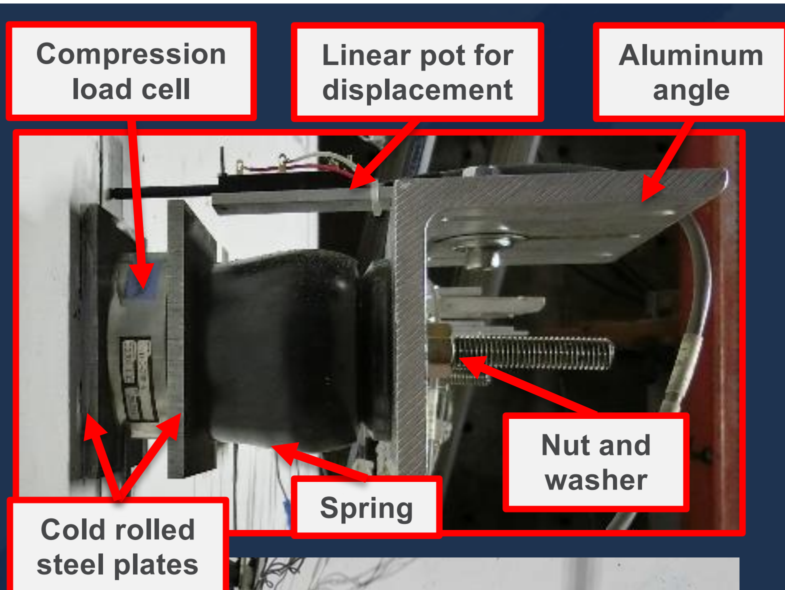
TEST LAYOUT

- **72 total anchors** with Grade 12.9 threaded rod installed **in uncracked wall face** every 2 ft:
  - **Slender wall: 18 bonded + 18 torque-controlled expansion**
  - **Squat walls: 18 torque-controlled expansion anchors**
- Anchors **loaded to design tension** before loading the wall
- ***Boundary Conditions:*** unique crack pattern and concrete damage around each anchor

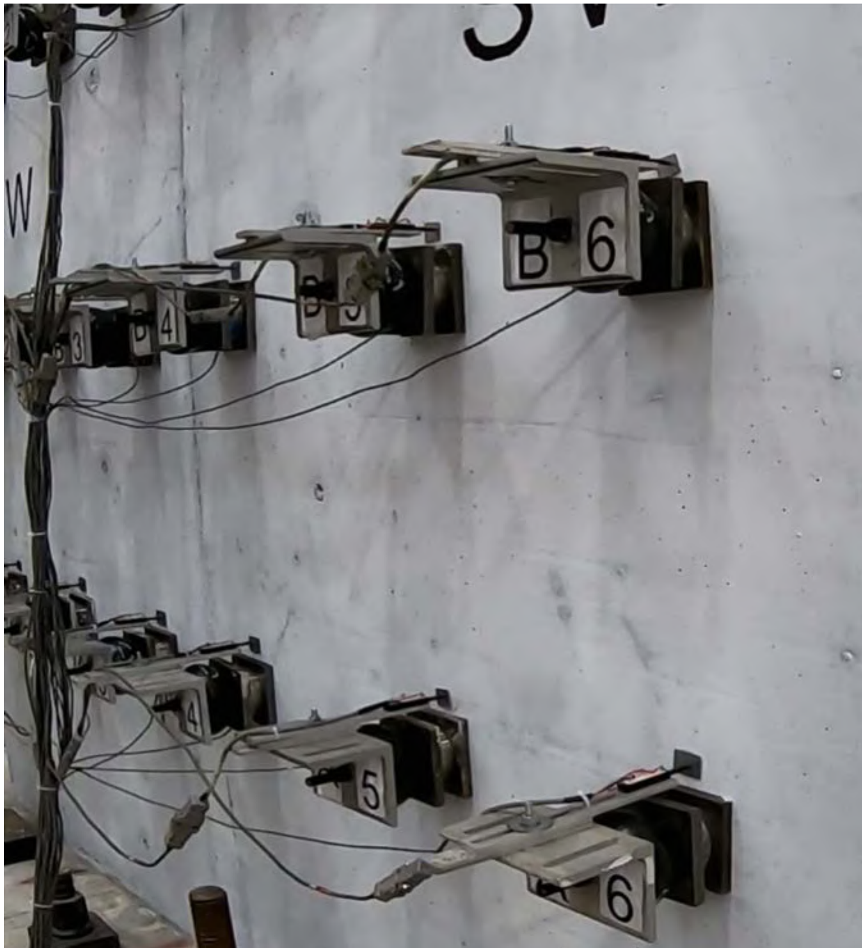


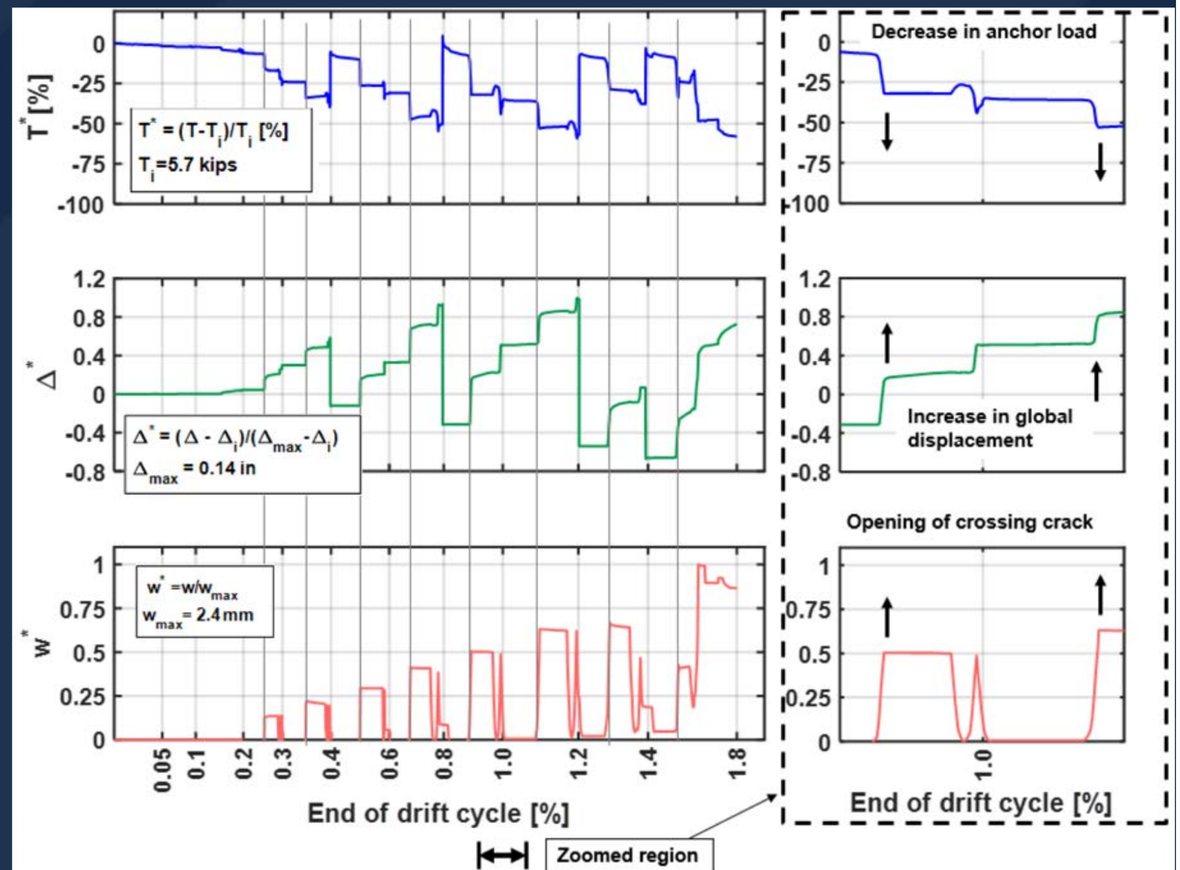


ANCHOR AXIAL LOAD SETUP



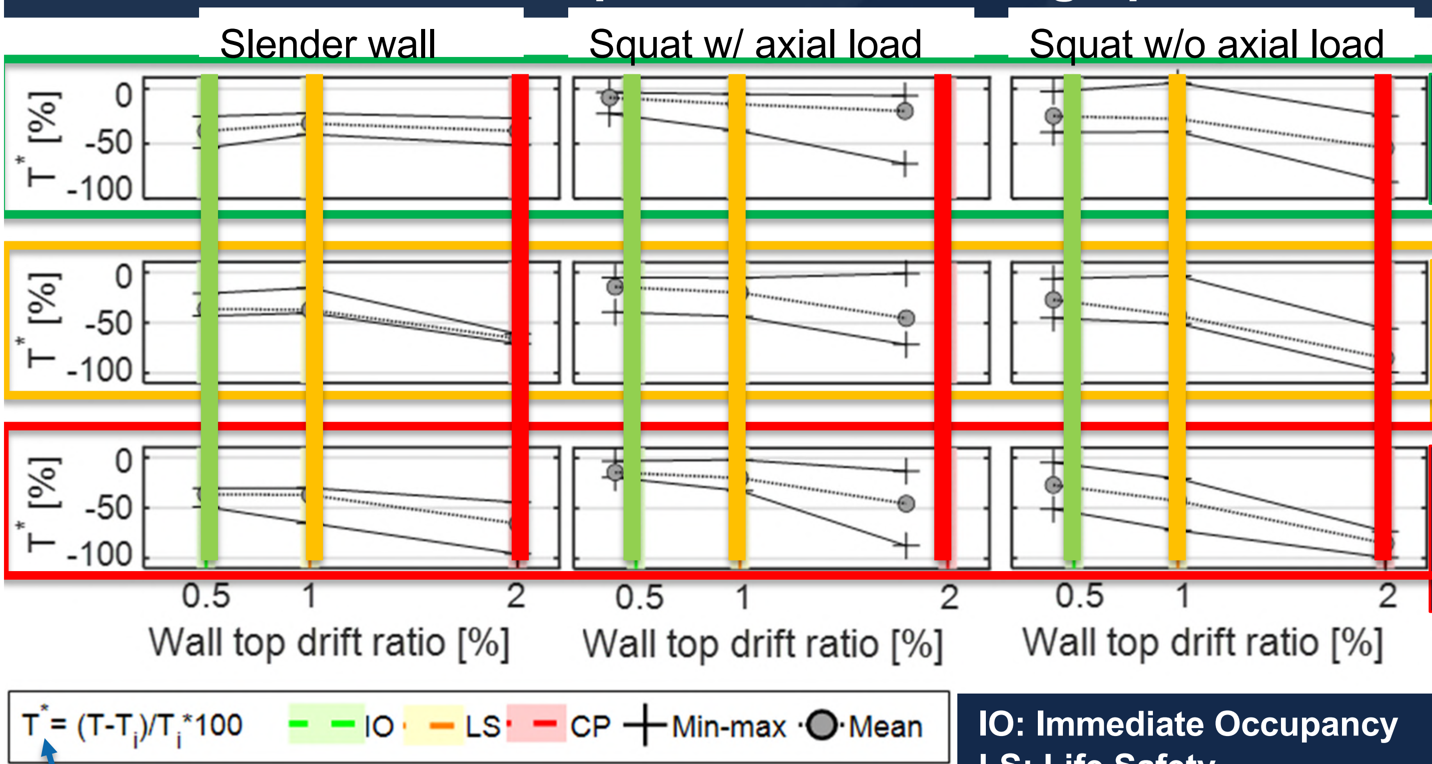
ANCHORS DURING WALL CYCLING



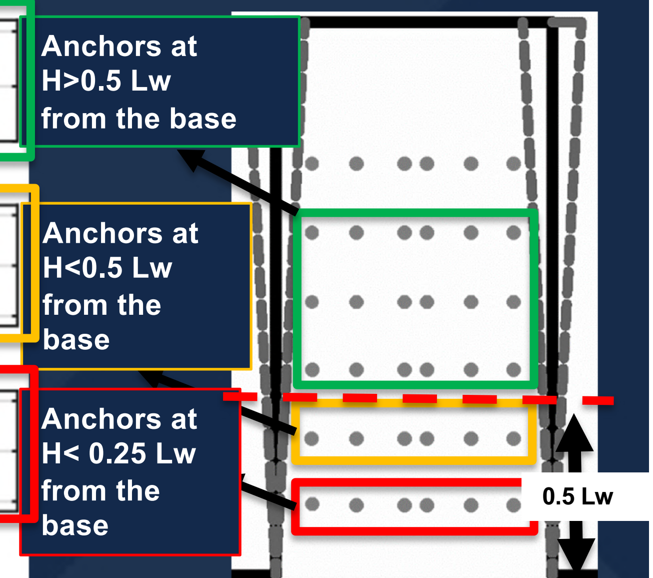


ANCHORS DURING WALL CYCLING

Relate anchor to wall performance through performance limit states

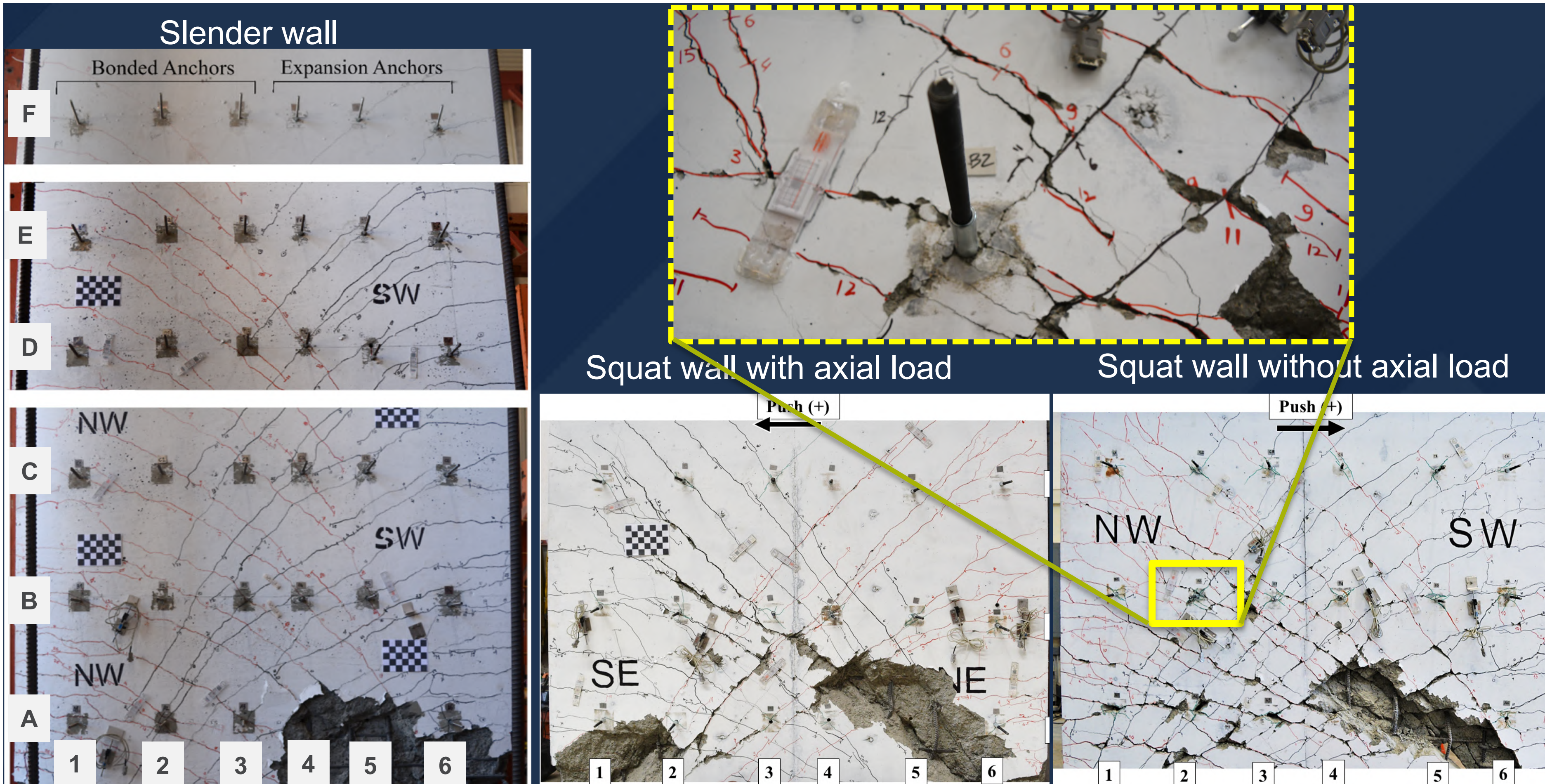


Normalized anchor load



IO: Immediate Occupancy
LS: Life Safety
CP: Collapse Prevention
limit states of wall

ANCHORS AT THE END OF WALL TESTS

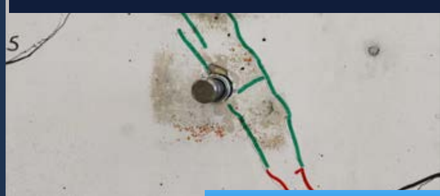


ANCHORS AT THE END OF WALL TESTS

ANCHOR CLASS 1

No cracks through the anchor outside 25 mm radius

- 36% of anchors in slender wall
- 16% of anchors in squat wall w/ axial load
- 0% of anchors in



squat wall w/ axial load

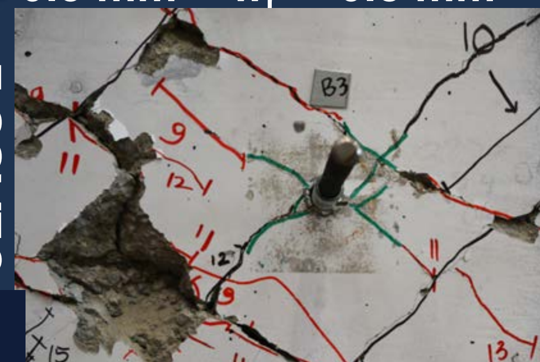
- 11% of anchors in squat wall w/o axial load

- 81% of anchors in the slender wall (93% of bonded anchors)

- Mean of maximum global displacement:
  - Class 1: 0.07 in [1.8 mm]
  - Class 2: 0.2 in [5 mm]
  - Class 3: 0.45 in [11 mm]

ANCHOR CLASS 2

$0.3\ mm < w_r < 0.8\ mm$



- 11% of anchors in slender wall
- 28% of anchors in squat wall w/o axial load

- 40% of anchors in squat wall w/ axial load

ANCHO
CLASS

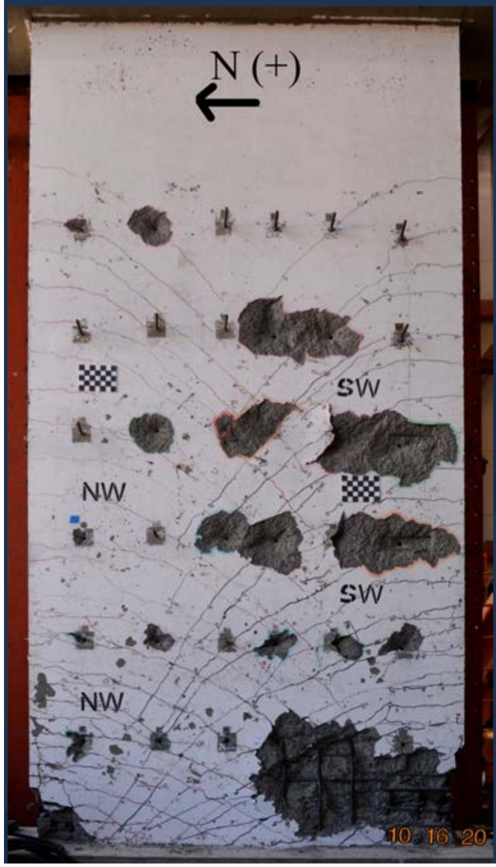
$w_r \geq 0.8\ mm$

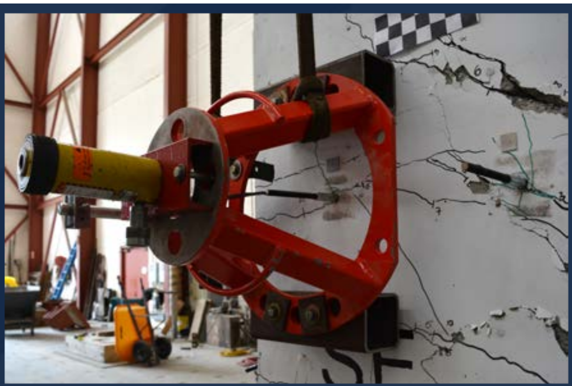
- 8% of anchors in slender wall
- 28% of anchors in squat wall w/ axial load

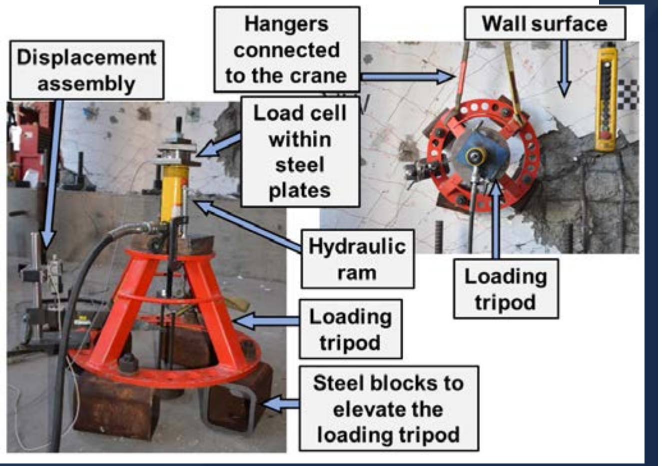
- 61% of anchors in squat wall w/o axial load

TENSION FAILURE TESTS

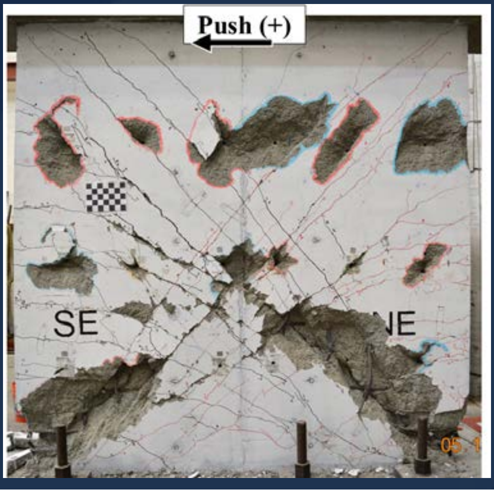
Slender wall



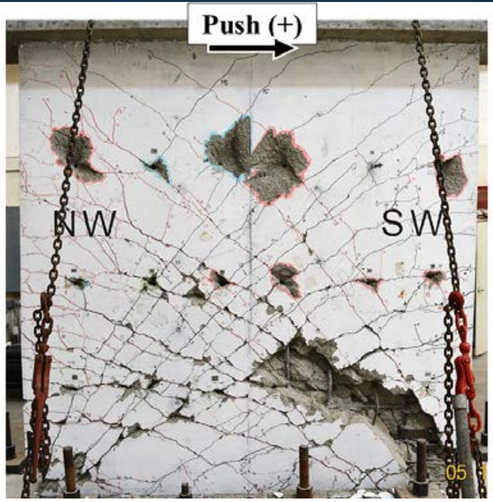




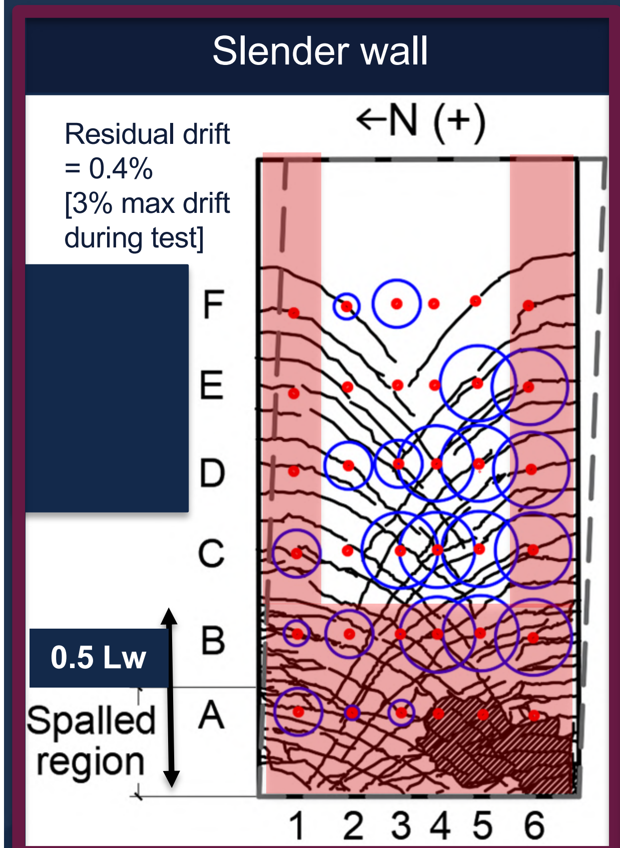
Squat wall with axial load



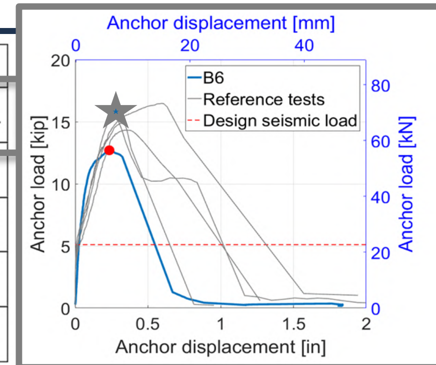
Squat wall without axial load

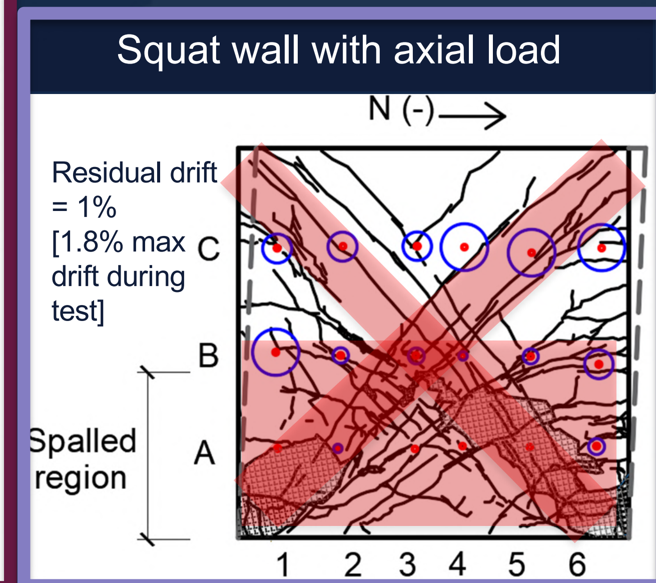


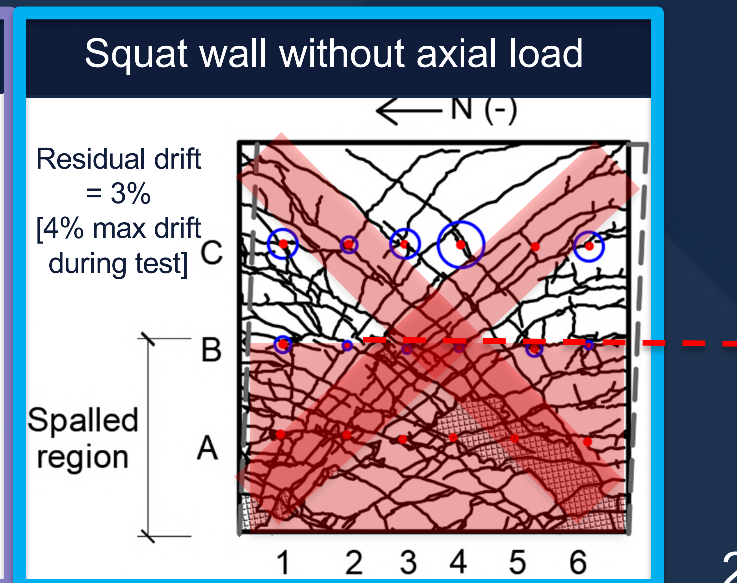
TENSION FAILURE TESTS



Peak load ratio T^*_{res}	
$T^*_{res} = T^{Pk}_{res} / T^{Pk}_{ref, uncr}$	
◯ (large)	$T^*_{res} > 0.75$
◯	$0.5 \leq T^*_{res} < 0.75$
o	$0.25 \leq T^*_{res} < 0.5$
∘ (small)	$T^*_{res} < 0.25$

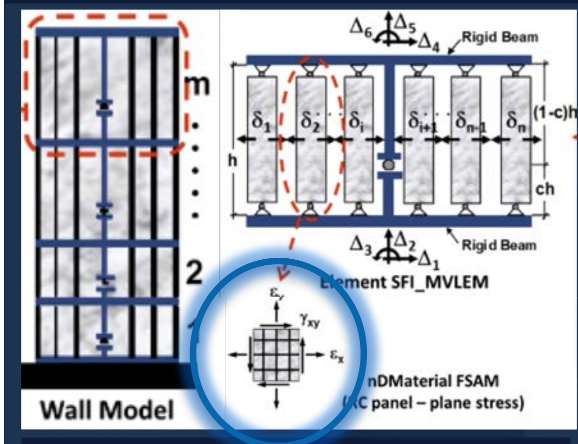






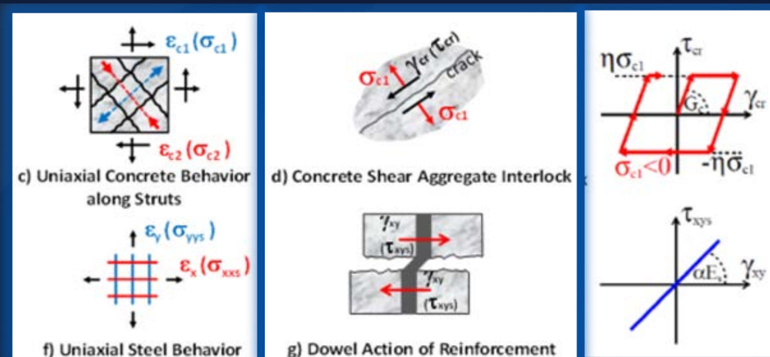
NUMERICAL MODELING: EXTENSION

2Dfiber based macroscopic model
Multiple Vertical Element Line Model with Cyclic Shear-Flexure Interaction Model for RC Walls (SFI-MVLEM)



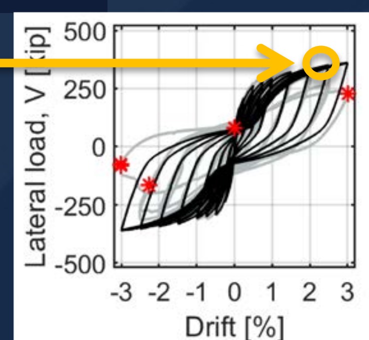
Axial-shear coupling at panel level

Kolozvari et al. "Modeling of Cyclic Shear-Flexure Interaction in Reinforced Concrete Structural Walls. I: Theory." (2014).

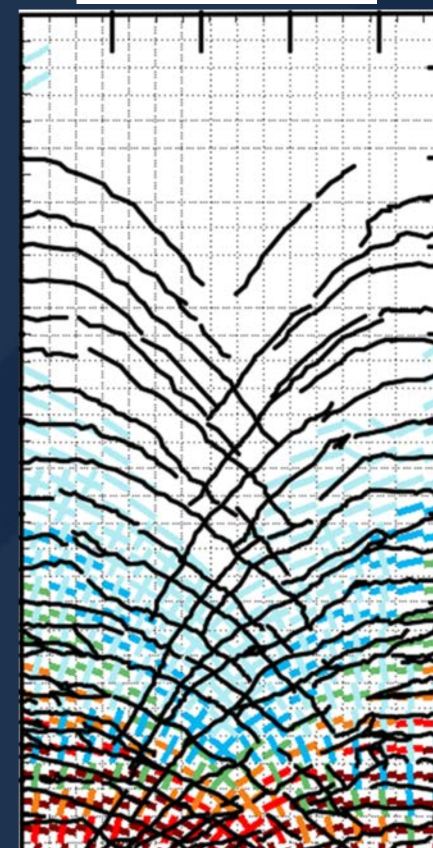


Shear resisting mechanism along concrete cracks

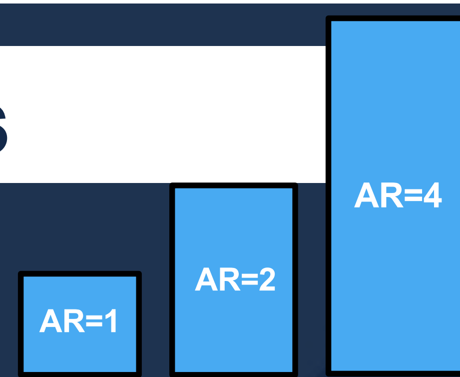
Slender wall @ 2%



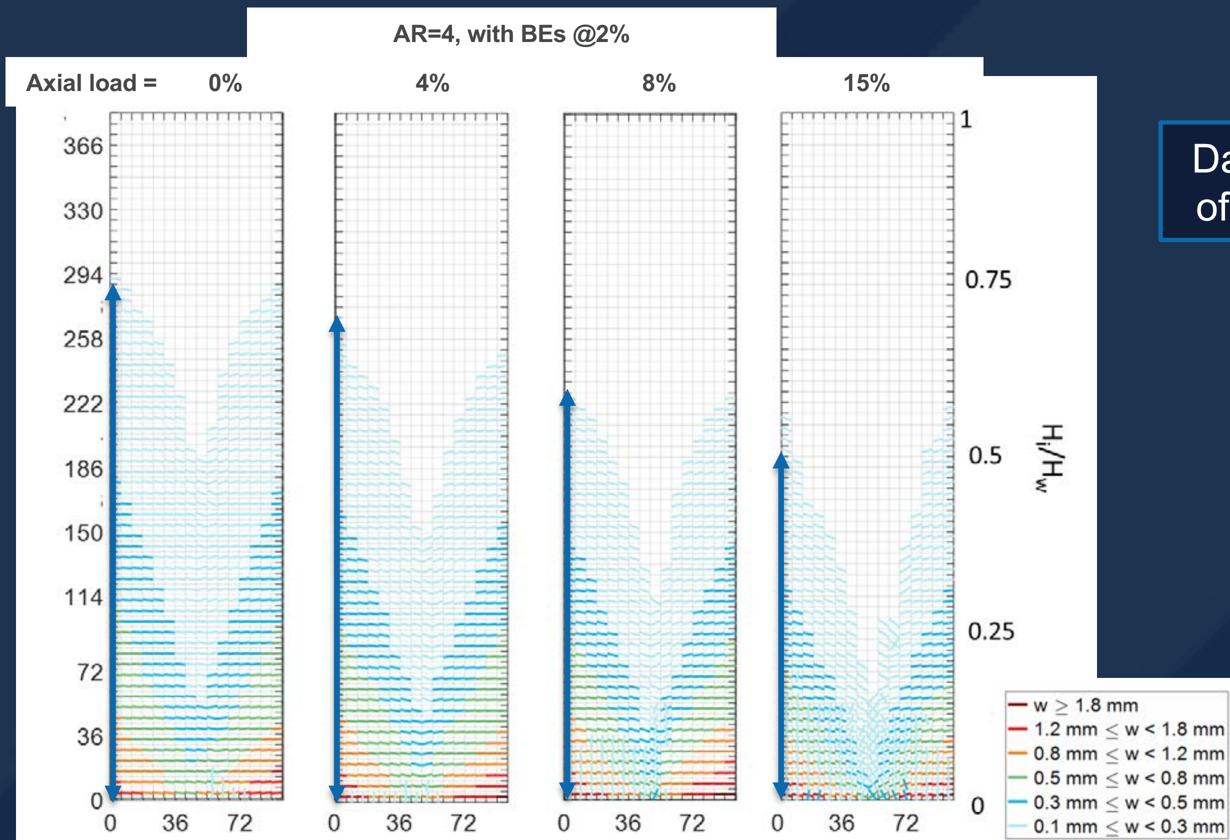
Slender wall load @2%



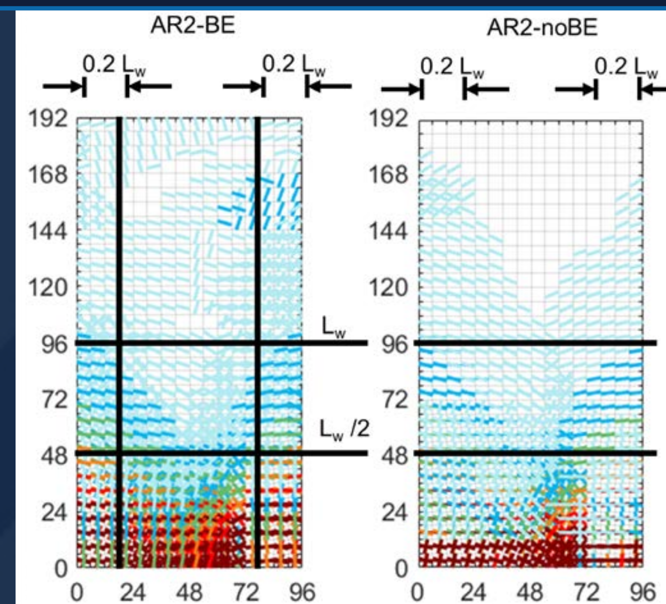
PARAMETRIC STUDY OBSERVATIONS



Restraining effect of axial load on crack elevation



Damage concentration within Lw/2 and effect of boundary elements on cracks propagation



WALL BEHAVIOR: CONCLUSIONS

- **Slender wall failed in flexure** (buckling and rupture of the longitudinal reinforcing bars)
- **Squat walls** showed **mixed shear-flexure** failure
- 40% average shear displacement contribution for squat walls vs 15% for slender wall
- Damage progression and crack propagation overall symmetric

<u>Impact of Axial Load on Wall Response</u>

- **Stabilizes shear-to-flexure displacement** components
- **Facilitates cracks closure** and restrains damage distribution

ANCHOR BEHAVIOR: CONCLUSIONS

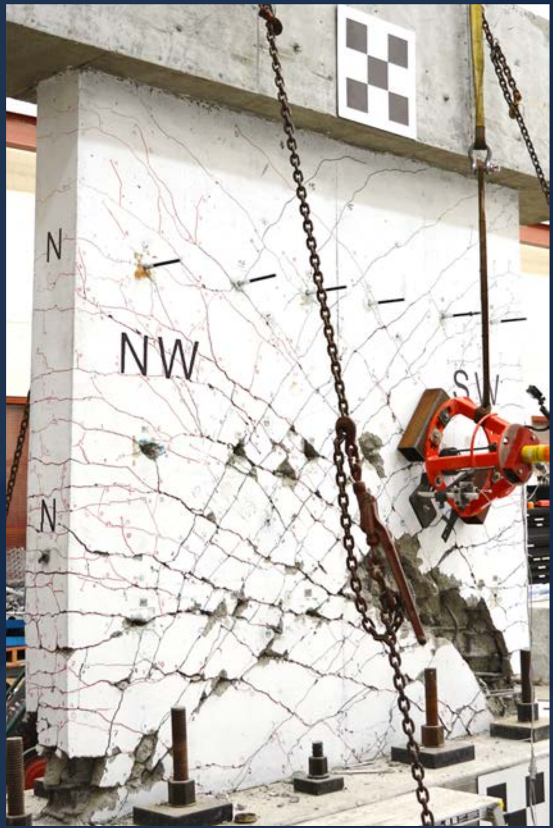
- Effect of cyclic crack opening is observed in anchor load and displacement history
- Anchors within $L_w/2$ in squat wall absent axial load experience 85% initial load reduction versus 45% in squat wall with axial load at CP limit state
- Anchors in the **boundary elements** of the wall, in the **spalled region** or in the **main diagonal** concrete struts are affected by **severe concrete damage**
- **Residual load capacity of anchors in these regions are significantly lower than reference values**

OVERARCHING: PRACTICAL OUTCOMES

1. **Wall response** not affected by anchors presence
2. Crack opening/closing is reflected in anchor load and displacement histories (especially for expansion anchors)

<u>**Anchor design implications in concrete shear walls:**</u>

1. **Severe concrete damage** affects anchor performance in the **boundary elements** of the wall, in the **spalled region** or in the **main diagonal concrete struts**
2. **Residual load capacity of anchors in these regions are significantly lower than reference values**
3. **Axial load on wall may be beneficial to anchor performance (crack closure and limited damage propagation)**
4. **Parametric study shows consistent accumulation of damage within $L_w/2$ from the wall base and along boundary elements**



RELEVANT PUBLICATIONS

1. Faraone, G.; Hutchinson, T.C.; Piccinin, R.; and Silva, J., (2021), “Anchor Performance in Cyclically Loaded Shear Walls,” *ACI Structural Journal* (under review)

2. Faraone, G.; Hutchinson, T.C.; Piccinin, R.; and Silva, J., (2021), “Performance of Full-Scale Reinforced Concrete Shear Walls of Different Aspect Ratios,” *ACI Structural Journal* (under review)

3. Faraone, G., Hutchinson, T.C., Piccinin, R., and Silva, J. (2019). “Full-Scale Shear Wall Response under Lateral Cyclic Loading.” *ACI Structural Journal*

4. Faraone, G., Hutchinson, T.C., Piccinin, R., and Silva, J. (2019). “Performance of Post-Installed Anchors in Progressively Damaged Concrete Shear Wall.” *ACI Structural Journal*

5. Faraone, G., Hutchinson, T.C., Piccinin, R., and Silva, J., 2020, “Damage Patterns in Squat and Flexural RC Shear Walls,” Proceedings of the 2020 ASCE Structures Congress, St. Louis, Missouri

6. Faraone, G. and Hutchinson, T.C. (2021). “Behavior of post-installed anchors in reinforced concrete shear walls subjected to cyclic lateral loading. Part I: slender wall test program.” SSRP 2021/01, UC San Diego

7. Faraone, G. and Hutchinson, T.C. (2018). “Behavior of post-installed anchors in reinforced concrete shear walls subjected to cyclic lateral loading. Part II: slender wall test program.” SSRP 2018/05, UC San Diego

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Thank you ☺



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