SEISMIC ACADEMY

Hilti-Sponsored Research in Structural Connection Design – Past and Present

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WHY DOES HILTI SUPPORT RESEARCH IN CONNECTION DESIGN?

1. Because it’s the right thing to do. Steel to concrete connection design is a significantly underserved topic in structural engineering.

2. Because an improved understanding of connection design enables Hilti to innovate in the anchor arena with greater success.

WHY DOES HILTI SUPPORT RESEARCH IN CONNECTION DESIGN?

Connections are the “glue” that holds buildings together. Their design is critical for success of any seismic force-resisting system.

Structure magazine: Nieblas, G., “Wilshire Grand” 2015

BRBF-core wall system for Wilshire Grand hotel, Los Angeles (Brandow and Johnston)

WHY DOES HILTI SUPPORT RESEARCH IN CONNECTION DESIGN?

At a different scale, connections of nonstructural equipment determine whether a critical facility will remain operational following an earthquake.

Hilti-funded research into anchorage of nonstructural components – UC Berkeley

TOPIC 1: BEHAVIOR OF CONNECTIONS TO CONCRETE UNDER EARTHQUAKE CONDITIONS

Hilti has been engaged in research in this area at UC San Diego and San Diego State University for many years, working first with Frieder Seible, then Tara Hutchinson and Robert Dowell. Over the past decade, Hilti has supported numerous PhD candidates.

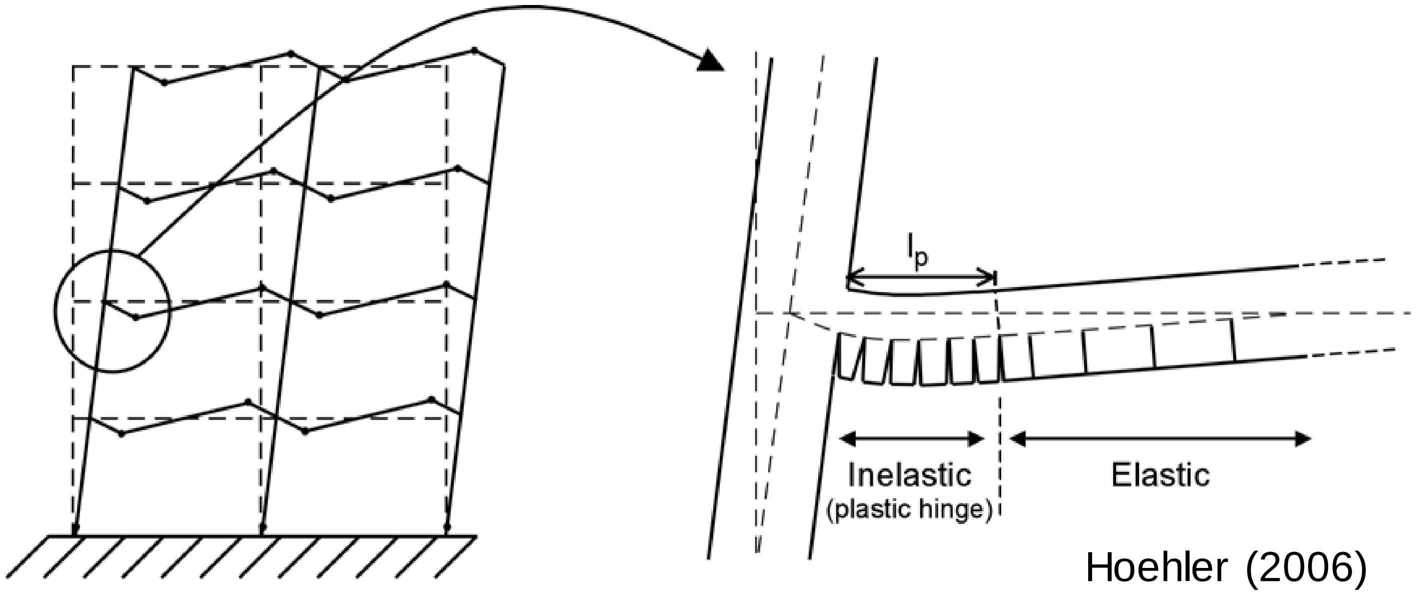
No. of doctoral degrees financed: 6

No. of peer reviewed journal papers: 30+

TOPIC 1: BEHAVIOR OF CONNECTIONS TO CONCRETE UNDER EARTHQUAKE CONDITIONS

Research directed at open questions.

➡ Observation: Initial investigations of crack width and cycling for C2 were focused on RC frame behavior.



Hoehler (2006)

TOPIC 1: BEHAVIOR OF CONNECTIONS TO CONCRETE UNDER EARTHQUAKE CONDITIONS

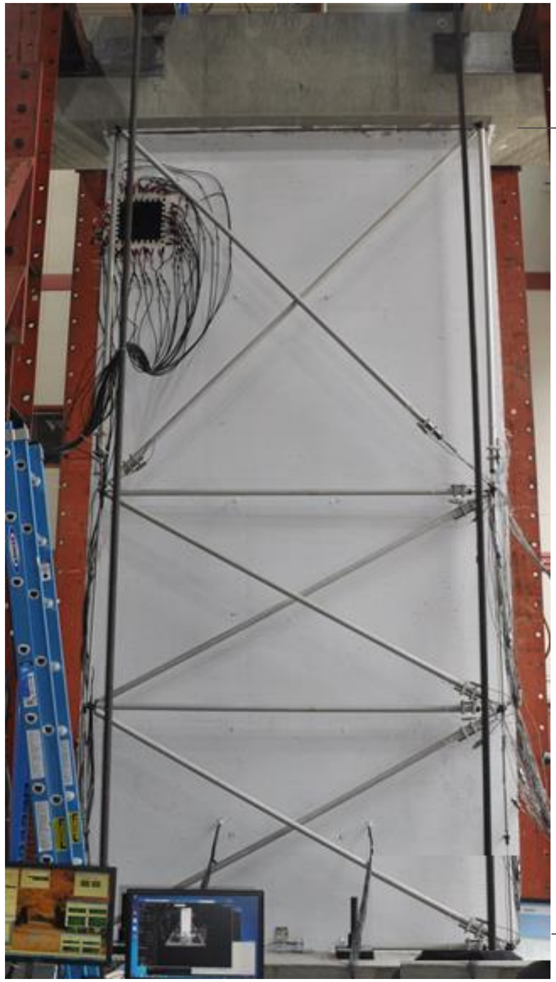
Question: What is the crack development in planar elements (specifically, shear walls)?

TOPIC 1: BEHAVIOR OF CONNECTIONS TO CONCRETE UNDER EARTHQUAKE CONDITIONS

Investigation: Full-scale shear wall tests conducted over a 5-year period at UCSD

8 ft (2.4m)

Low-aspect ratio wall

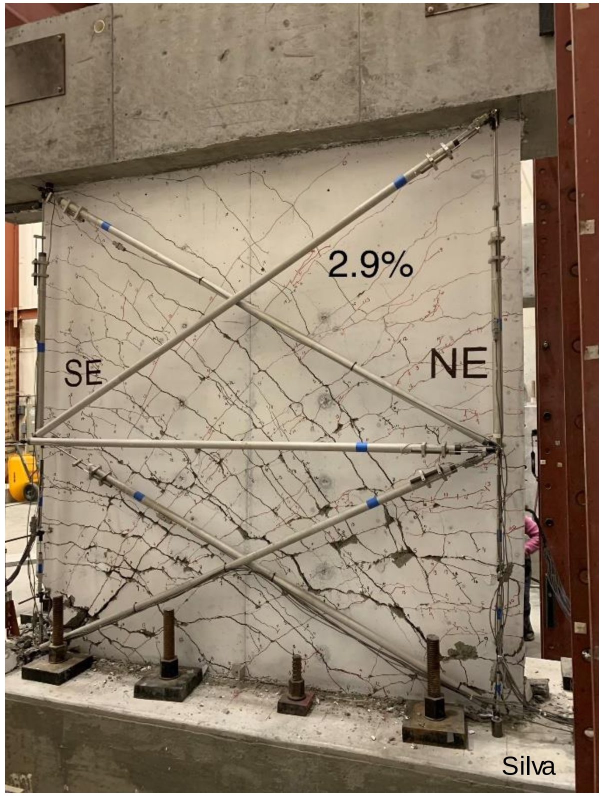


16 ft (4.9m)

Flexural wall

TOPIC 1: BEHAVIOR OF CONNECTIONS TO CONCRETE UNDER EARTHQUAKE CONDITIONS

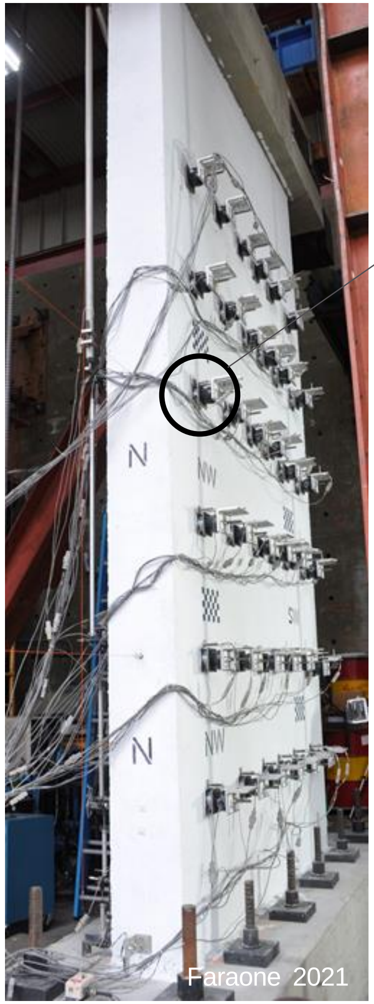
Cyclic testing to increasing drift levels

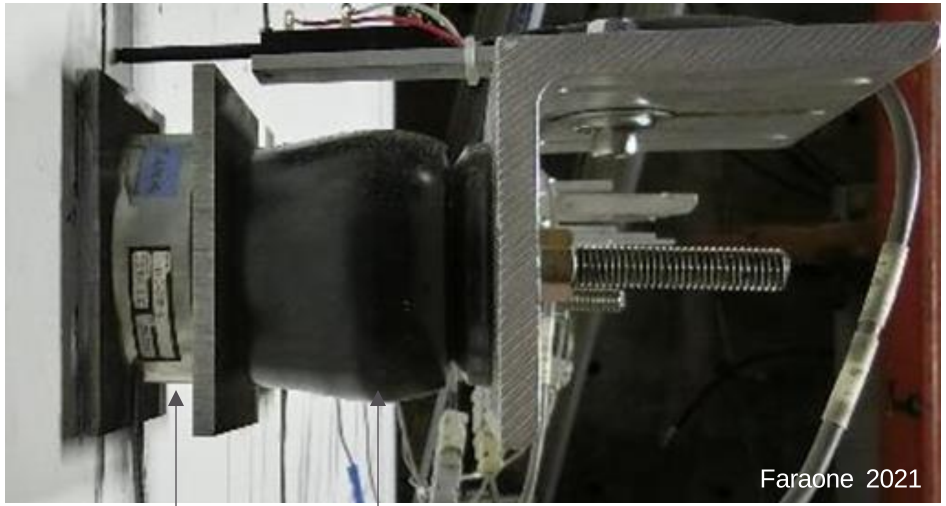


Low-aspect ratio wall

Flexural wall

TOPIC 1: BEHAVIOR OF CONNECTIONS TO CONCRETE UNDER EARTHQUAKE CONDITIONS



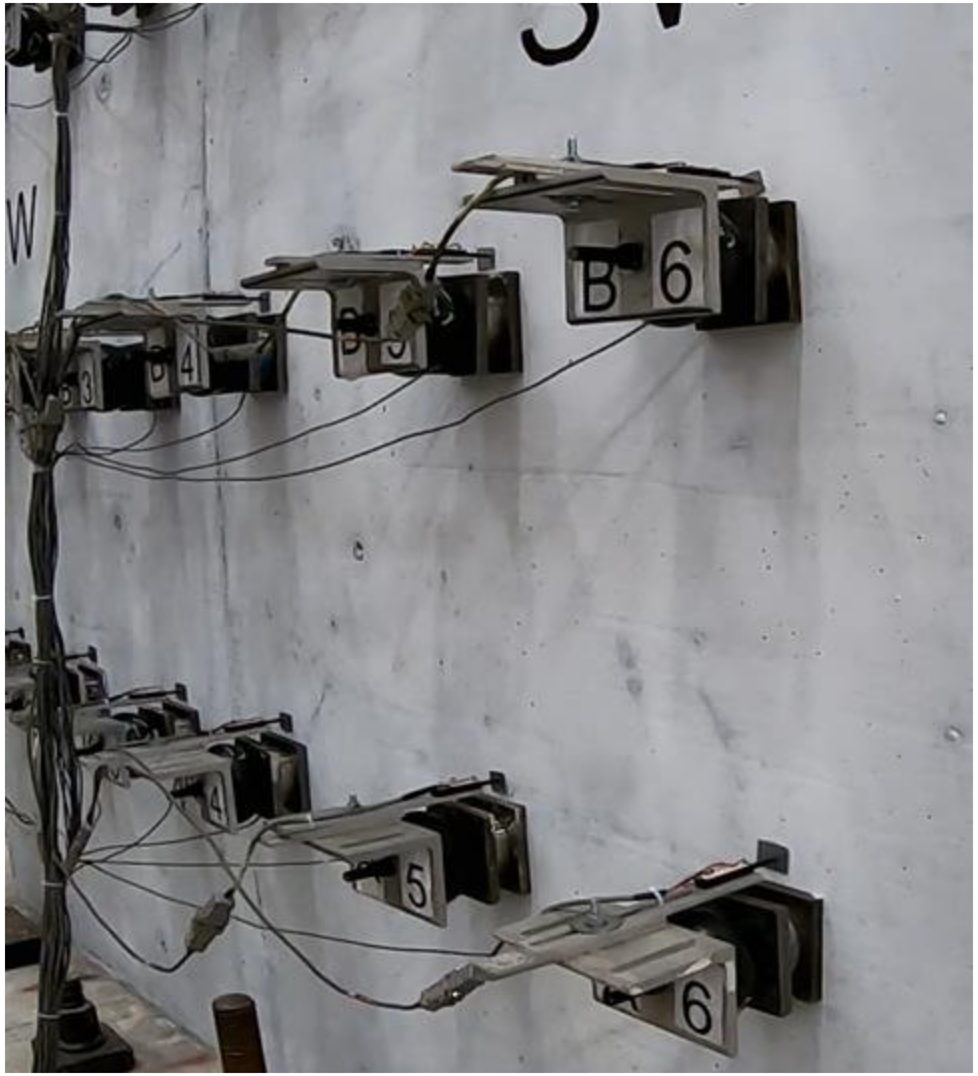


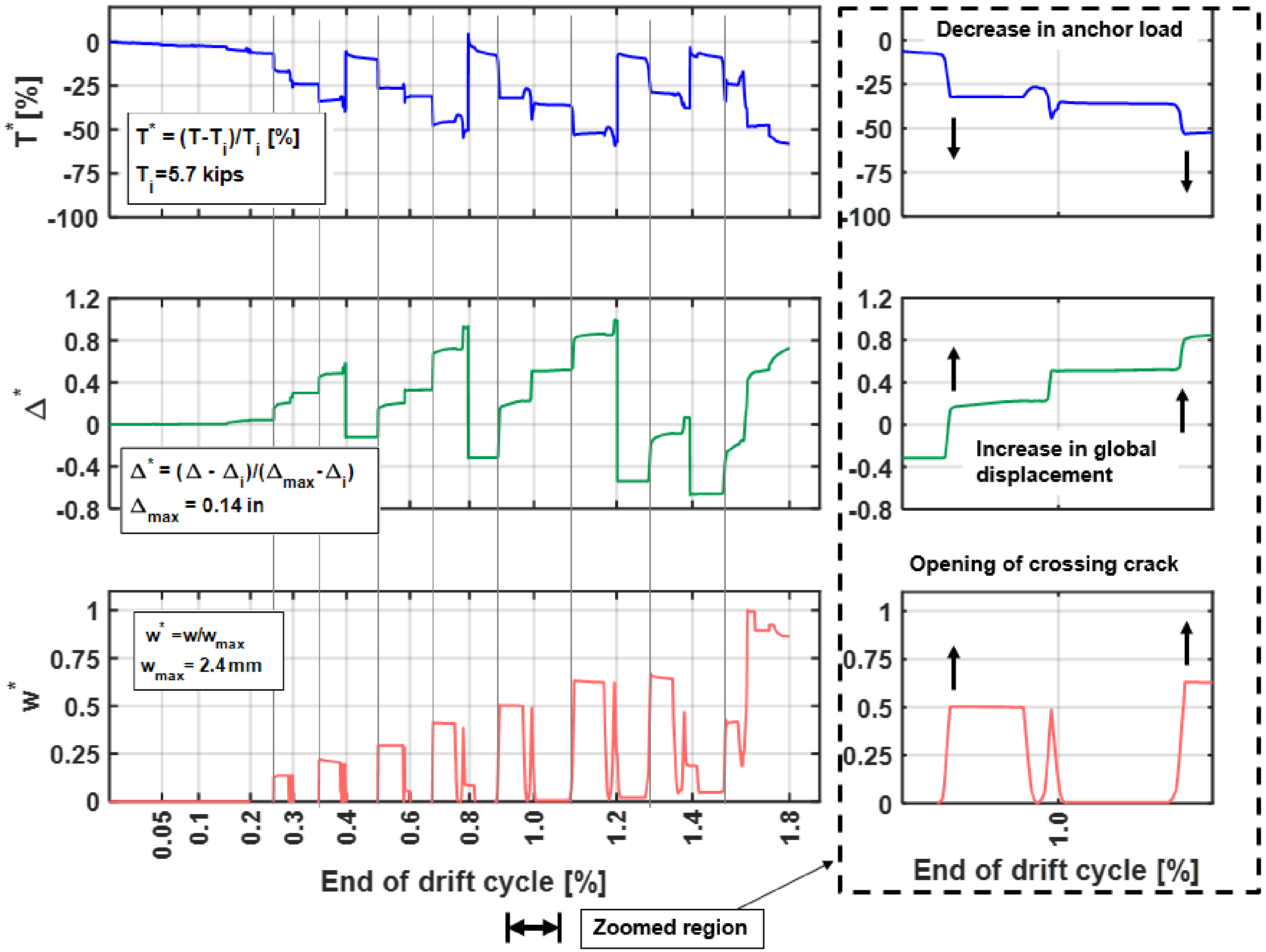
Load cell

Spring

Expansion anchor following test

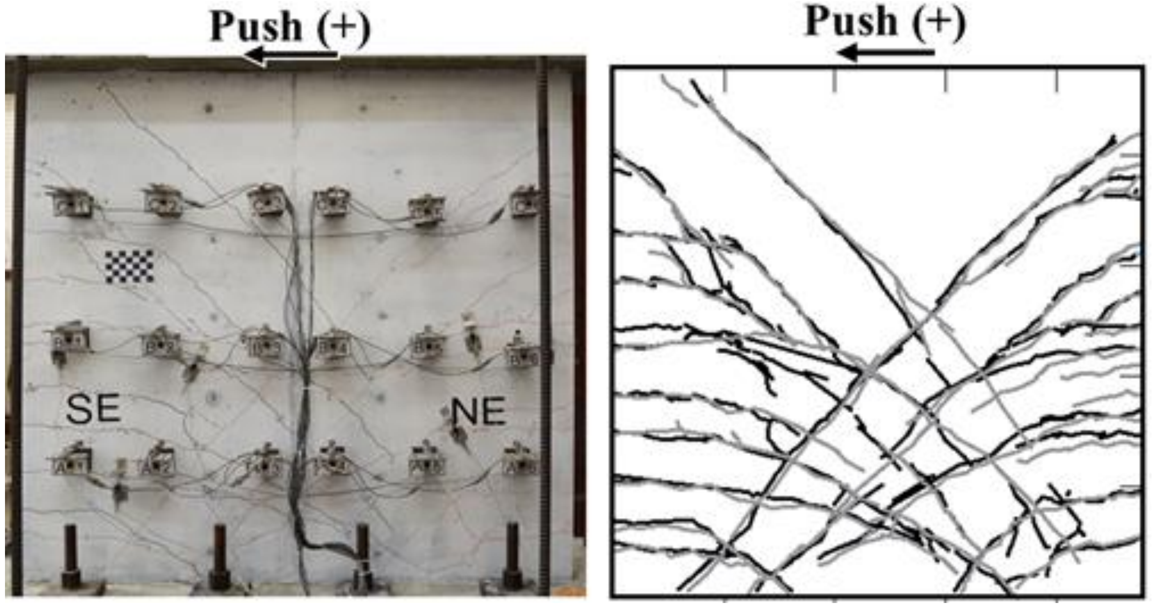
TOPIC 1: BEHAVIOR OF CONNECTIONS TO CONCRETE UNDER EARTHQUAKE CONDITIONS



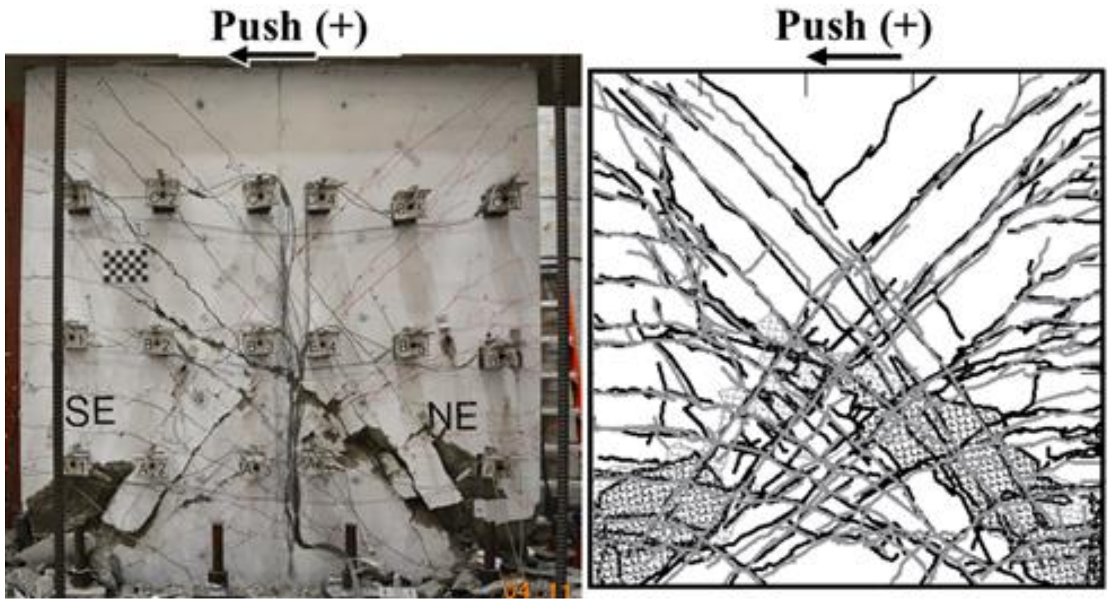


TOPIC 1: BEHAVIOR OF CONNECTIONS TO CONCRETE UNDER EARTHQUAKE CONDITIONS

0.4% drift



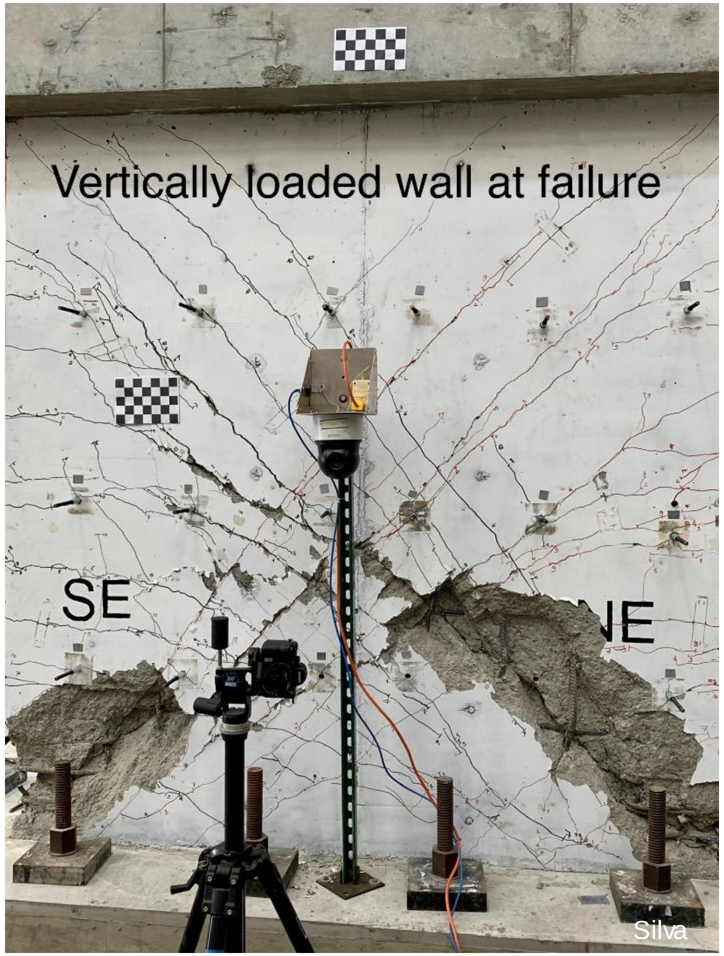
2% drift



Hutchinson 2021

Low aspect wall with axial load

TOPIC 1: BEHAVIOR OF CONNECTIONS TO CONCRETE UNDER EARTHQUAKE CONDITIONS



Low-aspect ratio wall strut failure

Flexural wall toe failure

TOPIC 1: BEHAVIOR OF CONNECTIONS TO CONCRETE UNDER EARTHQUAKE CONDITIONS

What have we learned from this work?

1. Cracking in low aspect walls can be predicted with relatively simple numerical models*.

2. Crack widths reflected in C2 anchor testing and assessment are adequate for both frame and wall structures.

3. However, anchors are generally prohibited from "plastic hinge zones" due to the potential for extreme damage. In frame structures, the definition of a plastic hinge is reasonably straightforward. Not so in shear walls. Stay tuned.

*Faraone, G., et al. (2022) "Numerical response prediction of full-scale concrete walls subjected to simulated in-plane seismic loading," *Engineering Structures* June 2, 14 pp.

TOPIC 2: RESOLVING INCONSISTENCIES IN ANCHORAGE USING REINFORCING AND ANCHORS

In the U.S., for structures constructed in steel, connection design is addressed by AISC (American Inst. of Steel Construction).

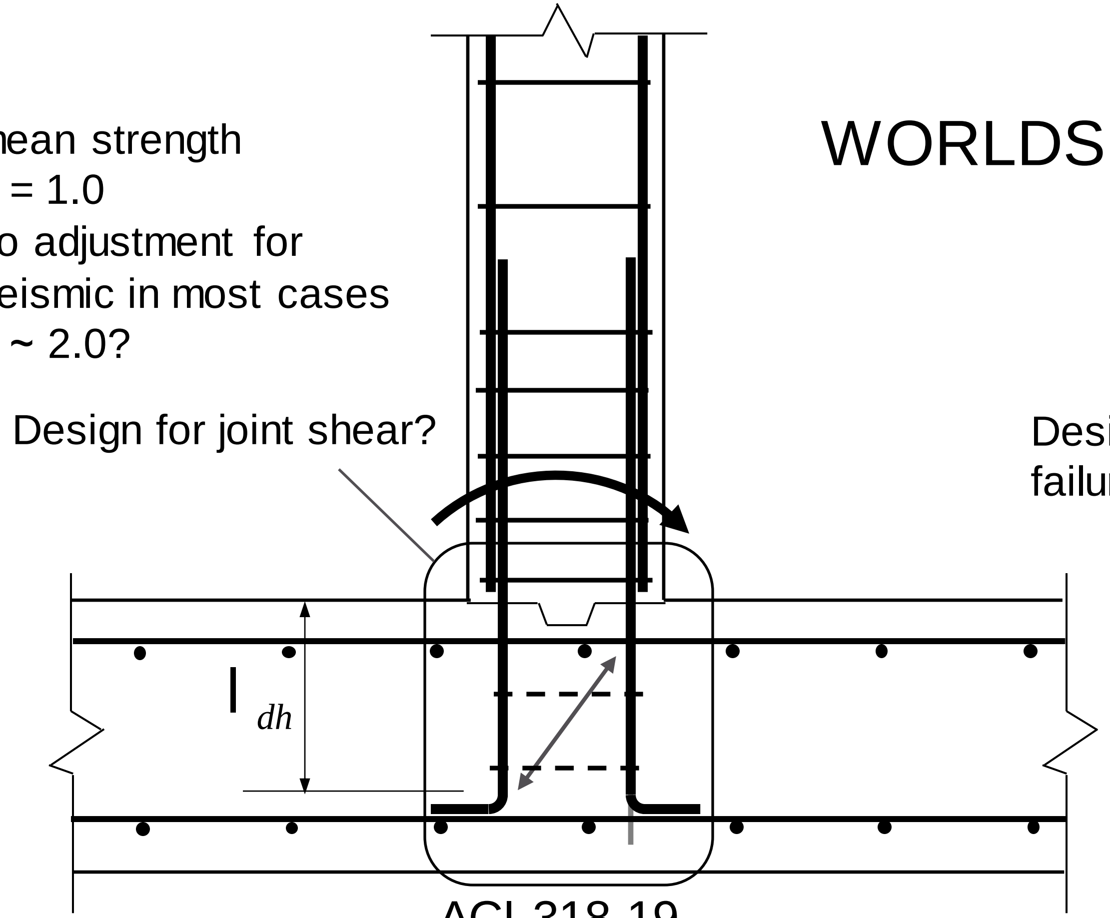
For structures constructed in reinforced concrete, connection design is addressed by ACI (American Concrete Inst.)

For structures constructed in concrete and steel, connections between concrete and steel are addressed independently (and often incoherently) by ACI and AISC.

TOPIC 2: RESOLVING INCONSISTENCIES IN ANCHORAGE USING REINFORCING AND ANCHORS

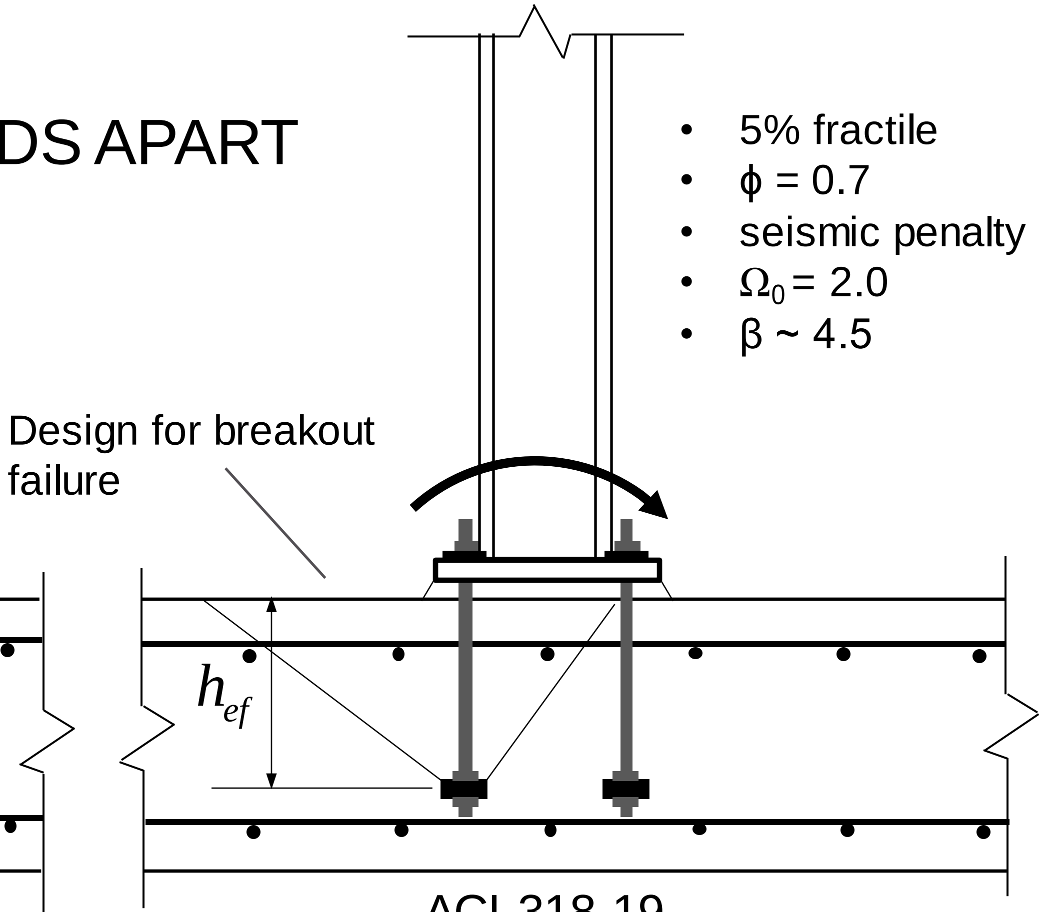
WORLDS APART

- mean strength
- $\phi = 1.0$
- no adjustment for seismic in most cases
- $\beta \sim 2.0$?



ACI 318-19
§25.4.4

- 5% fractile
- $\phi = 0.7$
- seismic penalty of 0.75
- $\Omega_0 = 2.0$
- $\beta \sim 4.5$



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§17.6.2

TOPIC 2: RESOLVING INCONSISTENCIES IN ANCHORAGE USING REINFORCING AND ANCHORS

How this plays out in practice:

Confusion regarding use of reinforcing bars as “anchorage”.

Lack of understanding of failure modes.

No consistency in reliabilities associated with development and anchorage.

Poor definition of steel behavior for things other than reinforcing bars.

TOPIC 2: RESOLVING INCONSISTENCIES IN ANCHORAGE USING REINFORCING AND ANCHORS

Common practice since the 1970s in nuclear construction (worldwide) has been to use welded straight bars (or DWAs) for anchorage of embed plates in walls, etc.

These connections were (are) designed for the nominal yield strength of the reinforcing bars without regard for concrete failure modes.

$$N_n = n \cdot A_b \cdot f_y$$

tsamfg.com

StelCrete Industries @StelCrete

TOPIC 2: RESOLVING INCONSISTENCIES IN ANCHORAGE USING REINFORCING AND ANCHORS

Concrete breakout of a group of straight reinforcing bars embedded to development length

Chicchi, R., Varma, A., Seo, J., Bradt, T., and McCarty, E. (2020), Experimental Testing of Tension-Loaded Deformed Anchors in Concrete, ACI Structural Journal, V. 117, No. 5, pp. 133-146.

TOPIC 2: RESOLVING INCONSISTENCIES IN ANCHORAGE USING REINFORCING AND ANCHORS

This has led to a general investigation of the use of groups of reinforcing bars, particularly hooked and headed bars, for anchorage, e.g., of columns to foundations.

Preliminary findings indicate that common assumptions regarding joint behavior (whether steel to concrete or concrete to concrete) may not be correct.

TOPIC 2: RESOLVING INCONSISTENCIES IN ANCHORAGE USING REINFORCING AND ANCHORS

#8 headed bars, Gr. 80   8 ksi (55Mpa) concrete, group of 9 bars, design for bar yield

$$l_{dt} = \left(\frac{f_y \cdot \psi_e \cdot \psi_p \cdot \psi_o \cdot \psi_c}{75\sqrt{f_c'}} \right) d_b^{1.5}$$

$$= \left(\frac{80000 \cdot 1 \cdot 1.6 \cdot 1 \cdot 1}{75\sqrt{8000}} \right) 1.0^{1.5} = 19.0\ in. \quad (483mm)$$

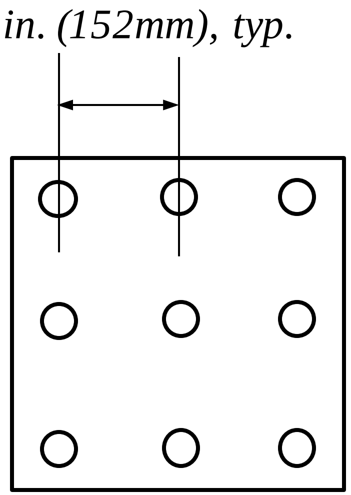
$$n \cdot A_b \cdot f_y = 9 \cdot 0.79 \cdot 80\ ksi = 569\ k \quad (2532\ kN)$$

$$N_{cb,m} = 40 \cdot \sqrt{8000} \cdot 19^{1.5} = 296.3\ k \quad (1319\ kN)$$

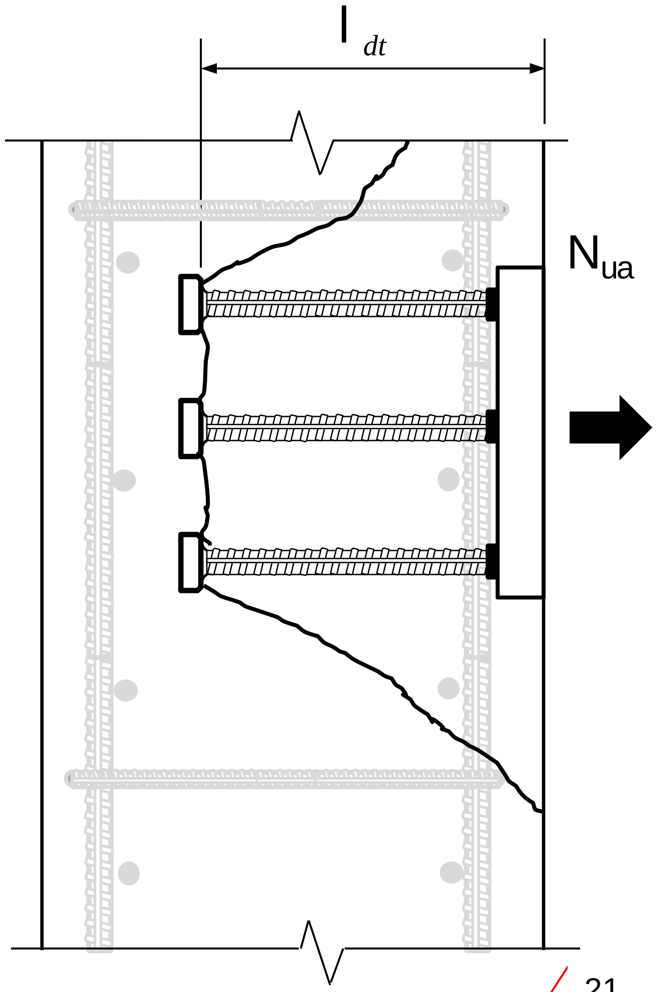
$$A_{No} = 9(19)^2 = 3249\ in^2$$

$$A_N = (3 \cdot 19 + 12)^2 = 4761\ in^2$$

$$N_{cbg,m} = 296.3 \cdot \frac{4761}{3249} ;\ 434\ k \quad (1931\ kN)$$



single anchor, mean strength



TOPIC 2: RESOLVING INCONSISTENCIES IN ANCHORAGE USING REINFORCING AND ANCHORS

Same case, but with sufficient confinement reinforcement to avoid the 1.6 penalty on development length…

$$l_{dt} = \left(\frac{f_y \cdot \Psi_e \cdot \Psi_p \cdot \Psi_o \cdot \Psi_c}{75\sqrt{f'_c}} \right) d_b^{1.5}$$

$$= \left(\frac{80000 \cdot 1 \cdot 1 \cdot 1 \cdot 1}{75\sqrt{8000}} \right) 1.0^{1.5} = 11.9\ in. \quad (302mm)$$

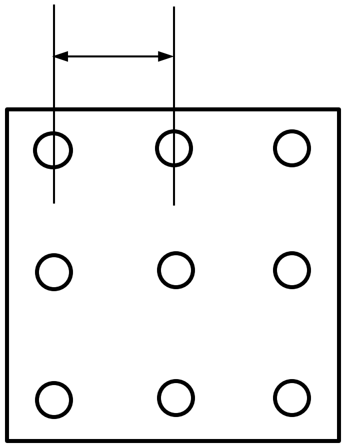
$$n \cdot A_b \cdot f_y = 9 \cdot 0.79 \cdot 80\ ksi = 569\ k\ (2532\ kN)$$

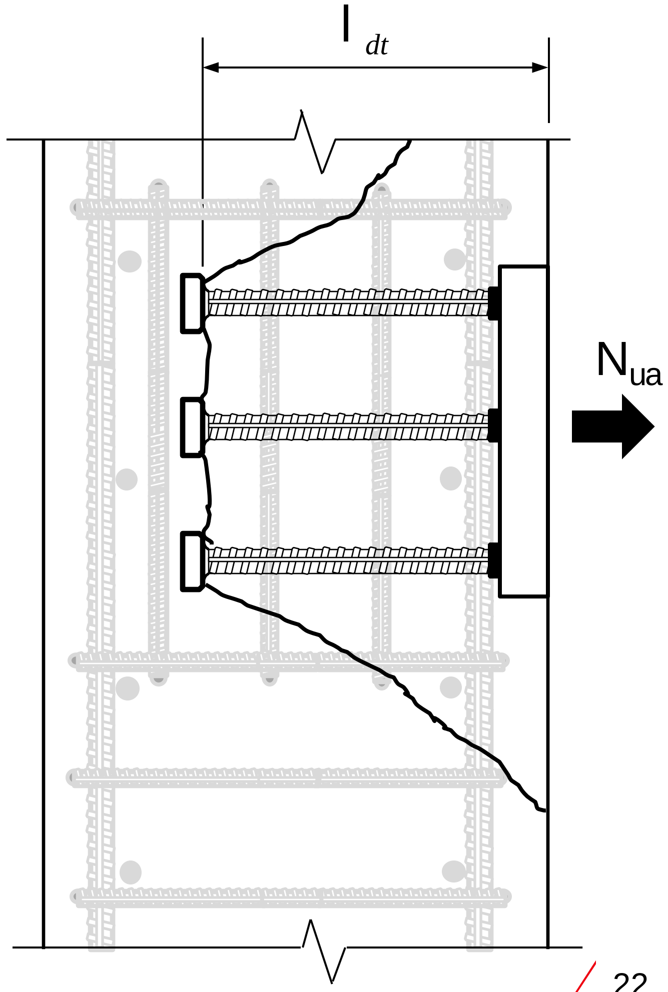
$$N_{cb,m} = 40 \cdot \sqrt{8000} \cdot 11.9^{1.5} = 146.9\ k\ (6537\ kN)$$

$$A_{No} = 9(11.9)^2 = 1275\ in^2$$

$$A_N = (3 \cdot 11.9 + 12)^2 = 2283\ in^2$$

$$N_{cbg,m} = 146.9 \cdot \frac{2283}{1275};\ \ 263\ k\ (1170\ kN)$$





TOPIC 2: RESOLVING INCONSISTENCIES IN ANCHORAGE USING REINFORCING AND ANCHORS

Hilti has sponsored research at UC Berkeley over the past 5 years to study this issue with Prof. Jack Moehle.

Column to foundation under applied moment and shear – full scale

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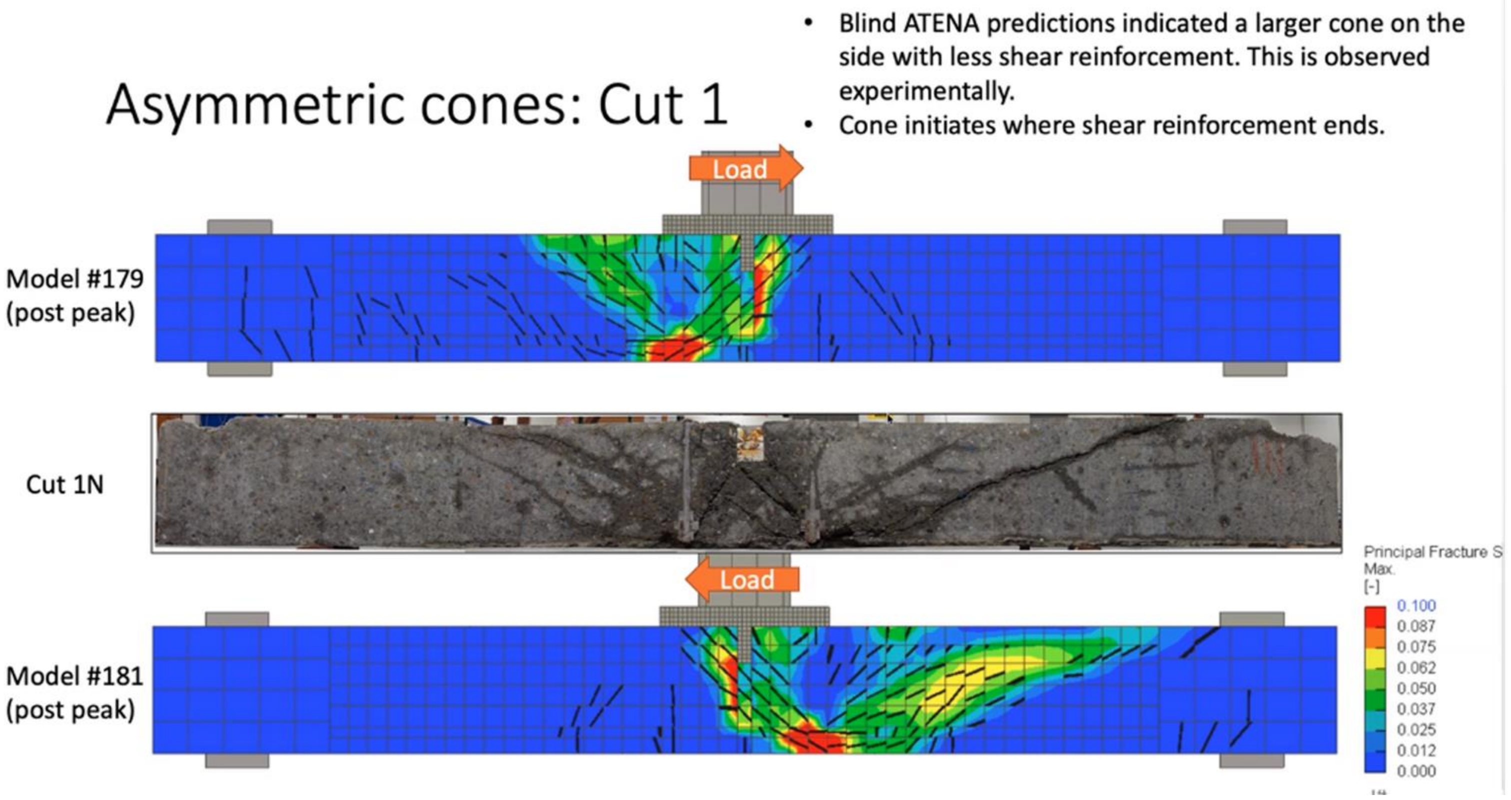
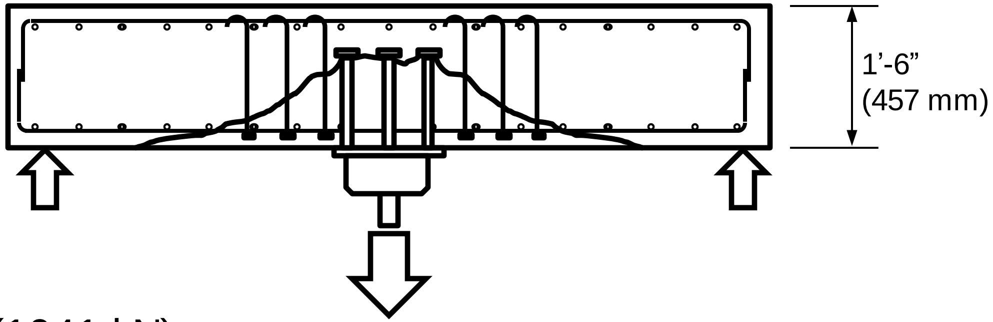
The results provide clear evidence that concrete breakout is the dominant failure mode for these connections.

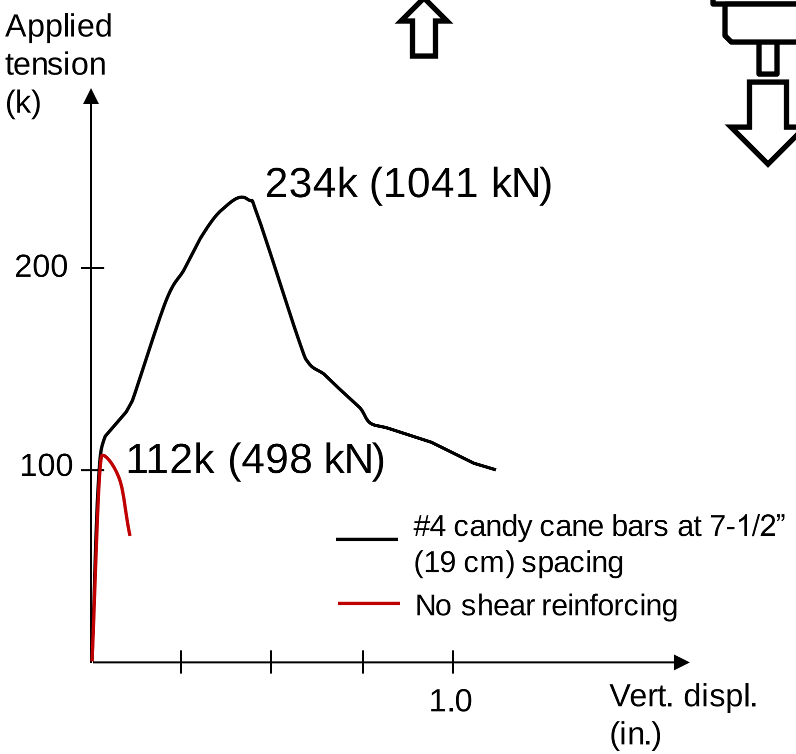


Worsfold, B. and Moehle, J., 2019, “Laboratory Tests of Column-Foundation Moment Transfer Connections with Headed Anchors,” Structural Engineering, Mechanics, and Materials (SEMM) Report, University of California, Berkeley, UCB/SEMM-2019/01, 171 pp.

TOPIC 2: RESOLVING INCONSISTENCIES IN ANCHORAGE USING REINFORCING AND ANCHORS

…and that we can improve the breakout strength significantly.





TOPIC 2: RESOLVING INCONSISTENCIES IN ANCHORAGE USING REINFORCING AND ANCHORS

#8 headed bars, Gr. 80 8 ksi (55Mpa) concrete, group of 4 bars spaced 3 in. as girder top reinforcing, closed hoops #5 Gr. 60

$l_{dt} = 11.9\ in. \quad (302 mm)$

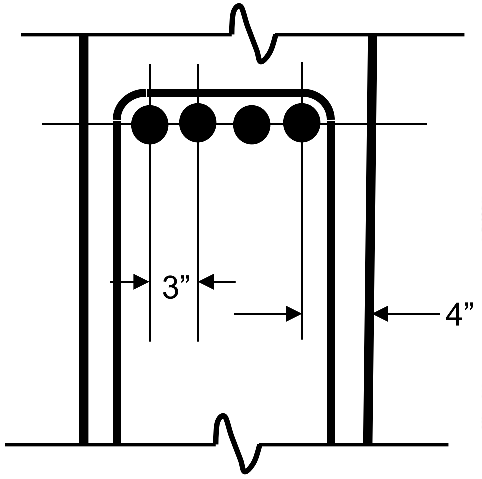
$n \cdot A_b \cdot f_y = 253\ k \quad (1126\ kN)$

$N_{cbg,m} = 147 \cdot \frac{607}{1275};\ 70\ k \quad (312\ kN)$

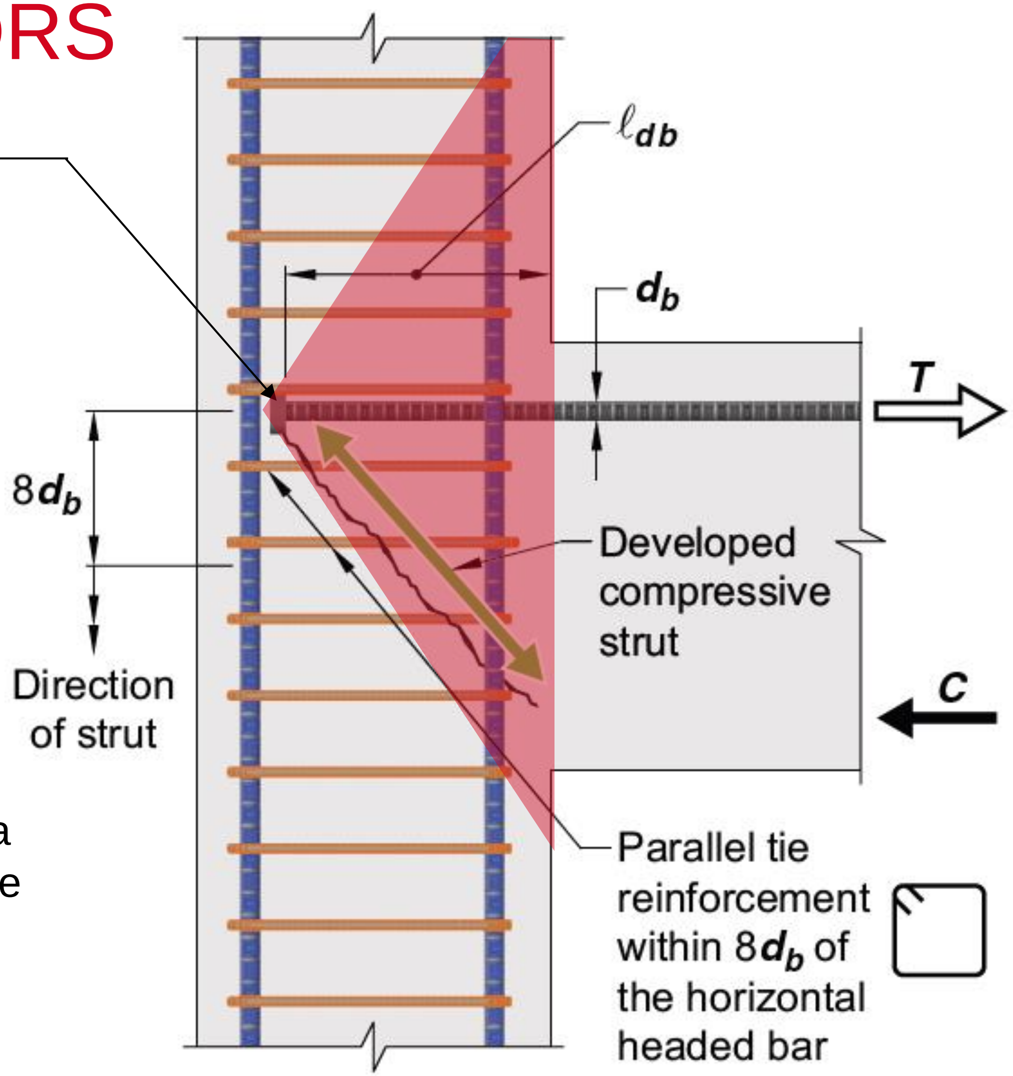
$N_s = 2 \cdot 6 \cdot 0.31 \cdot 60 = 223\ k \quad (993\ kN)$

$293\ k \quad (1304\ kN)$

6 hoops with 2 legs each



Add contribution of closed hoops within a distance $0.75h_{ef}$ of the anchorage.



ACI 318-19 R25.4.4.4

TOPIC 2: RESOLVING INCONSISTENCIES IN ANCHORAGE USING REINFORCING AND ANCHORS

Initiatives:

ACI 318-25: ad hoc subcommittee (1R) formed for "resolution of anchorage and development provisions"

2026 NEHRP Recommended Provisions Update Committee Issue Team on steel-concrete connection design for seismic forces.

SUMMARY

Hilti's commitment to supporting research into seismic connection design has resulted in important initiatives in the world of building code development.

It has also brought us into close alignment with leading research institutions around the globe, as well as fostering ongoing dialog with some of the best minds in structural engineering.

That's worthwhile work.

IN MEMORY OF STEVE MAHIN. A BRILLIANT STRUCTURAL ENGINEER AND A FRIEND.

Professor Steven A. Mahin
1946-2018

GRAZIE