Residual Capacity of Damaged and Epoxy-Repaired Reinforced Concrete Plastic Hinges

Kai Marder, Chris Motter and Kenneth J Elwood

Objective and scope

Key questions:

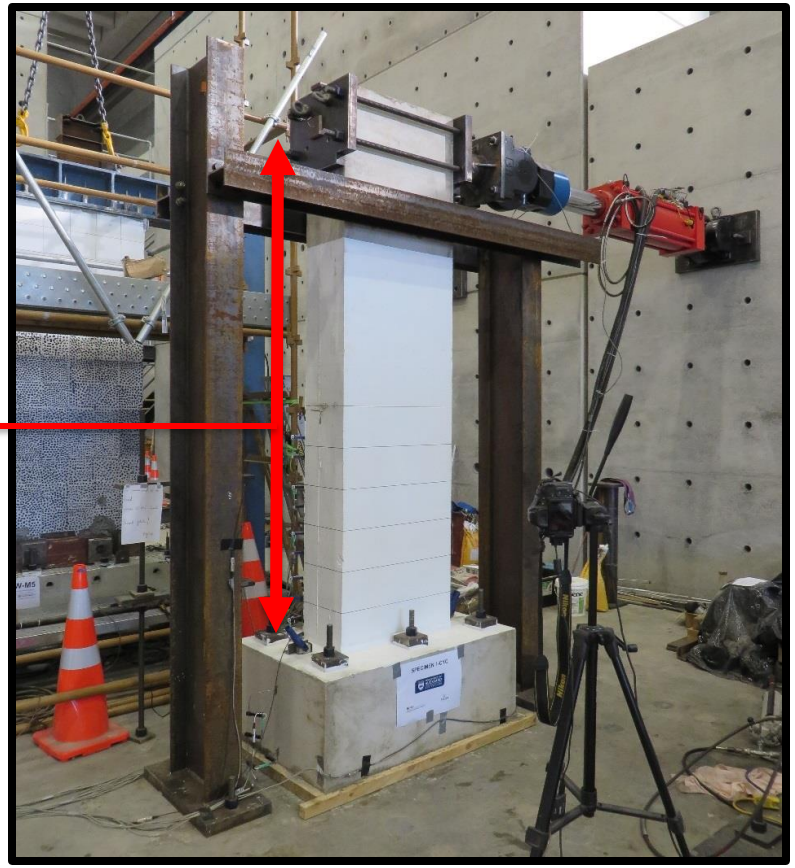
- What are the implications of the observable damage?
- What is the capacity in the damaged state?
- What is the capacity after epoxy repair?

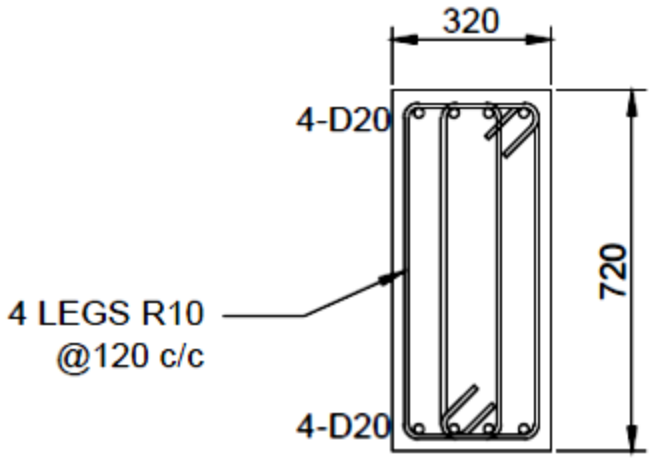
Focus is on 'moderate' plastic hinging damage:

- No crushing of core concrete
- No buckled or fractured reinforcement
- No wide shear cracks indicating yielded transverse reinforcement

Focus is on beams, but the research has implications for columns and walls

Test program (17 identical beam specimens)

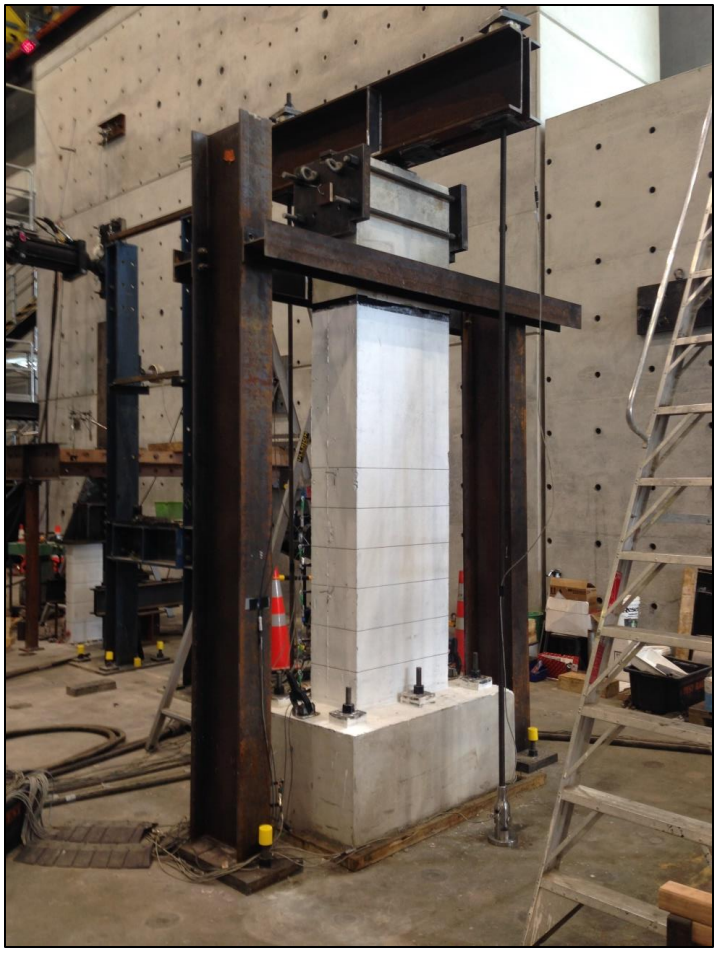


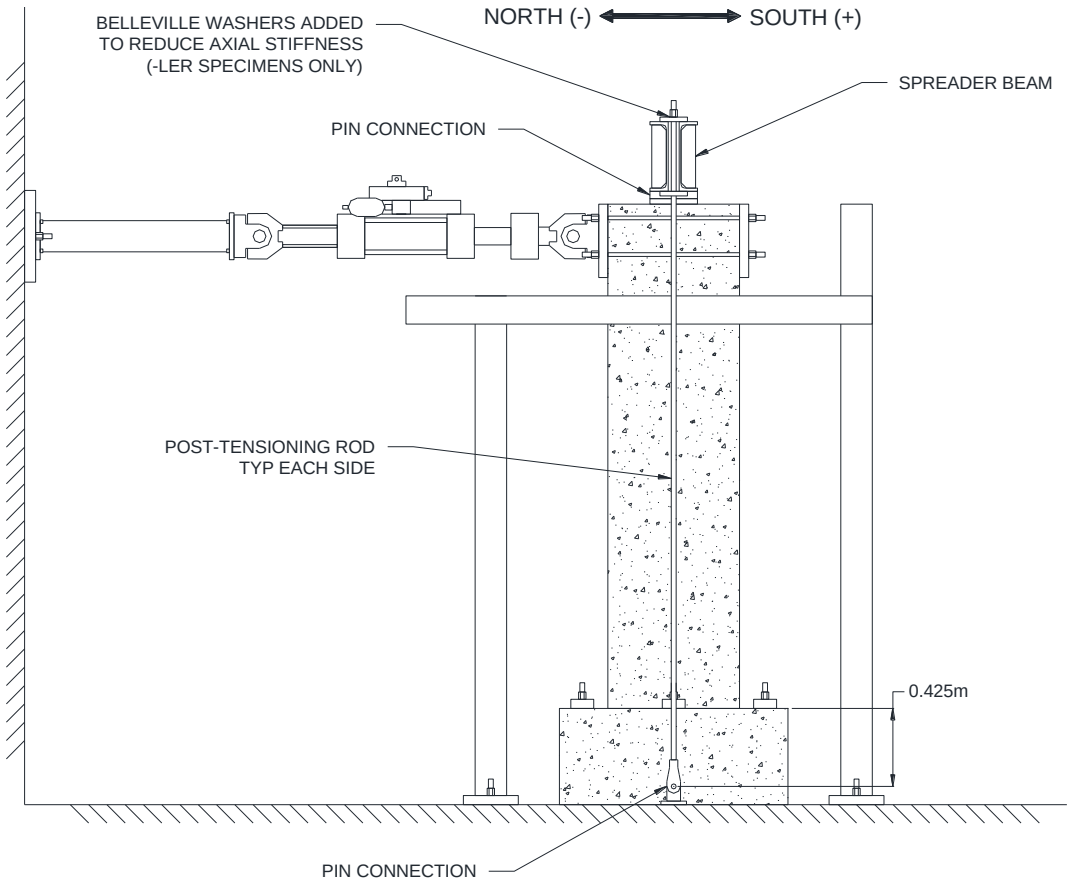


Complies with ACI 318 SMRF and NZS 3101:2006 'ductile' beam

Marder, K., Motter, C. J., Elwood, K. J., & Clifton, G. C. (2018). Testing of Seventeen Identical Ductile Reinforced Concrete Beams with Various Loading Protocols and Boundary Conditions. *Earthquake Spectra*.

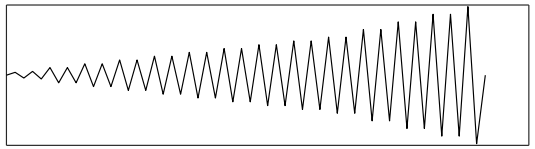
Axial restraint system



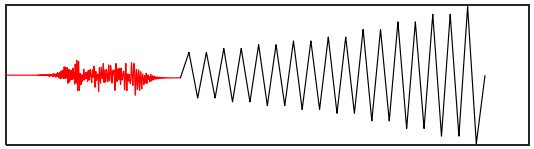


Loading protocols

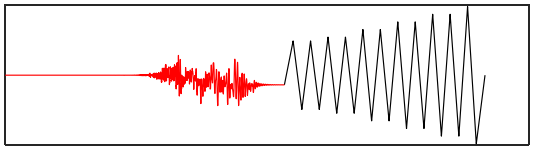
Type CYC



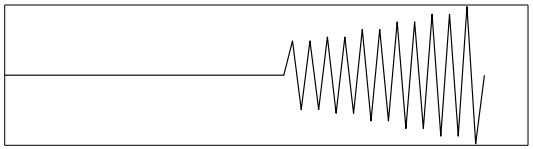
Type LD-1



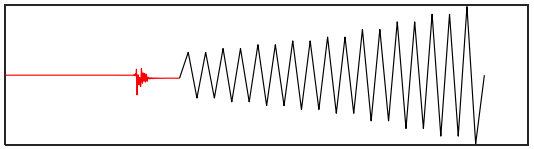
Type LD-2



Type CYC-NOEQ

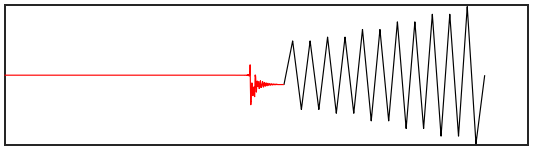


Type P-1



1.4% peak drift during earthquake

Type P-2



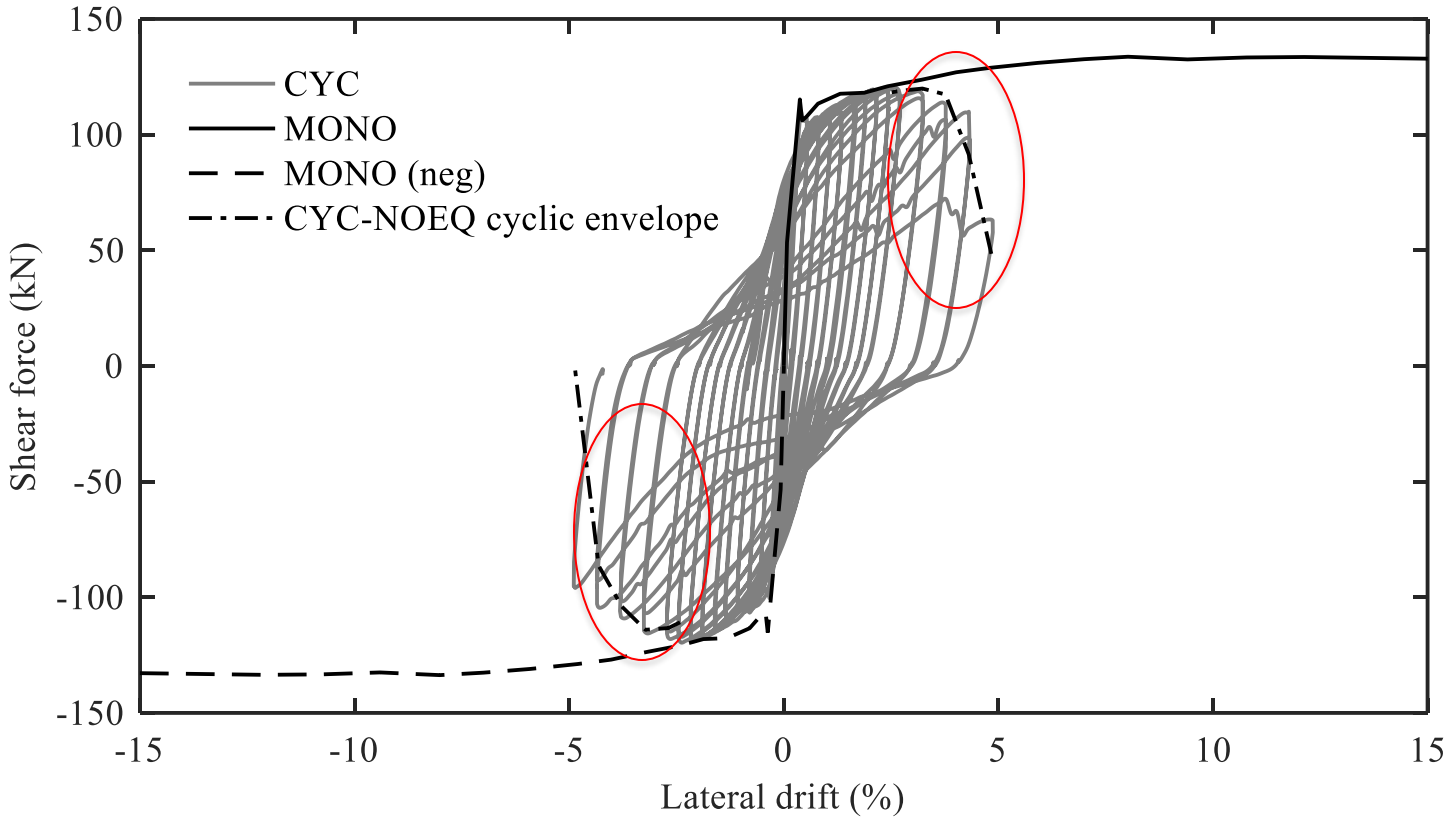
2.2% peak drift during earthquake

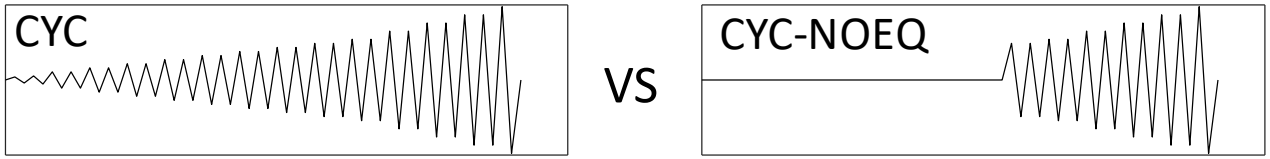
Red = Earthquake-type displacement history

LD = Earthquake displacement history derived using a **long duration** ground motion

P = Earthquake displacement history derived using a **pulse-type** ground motion

Effect of moderate-level loading cycles

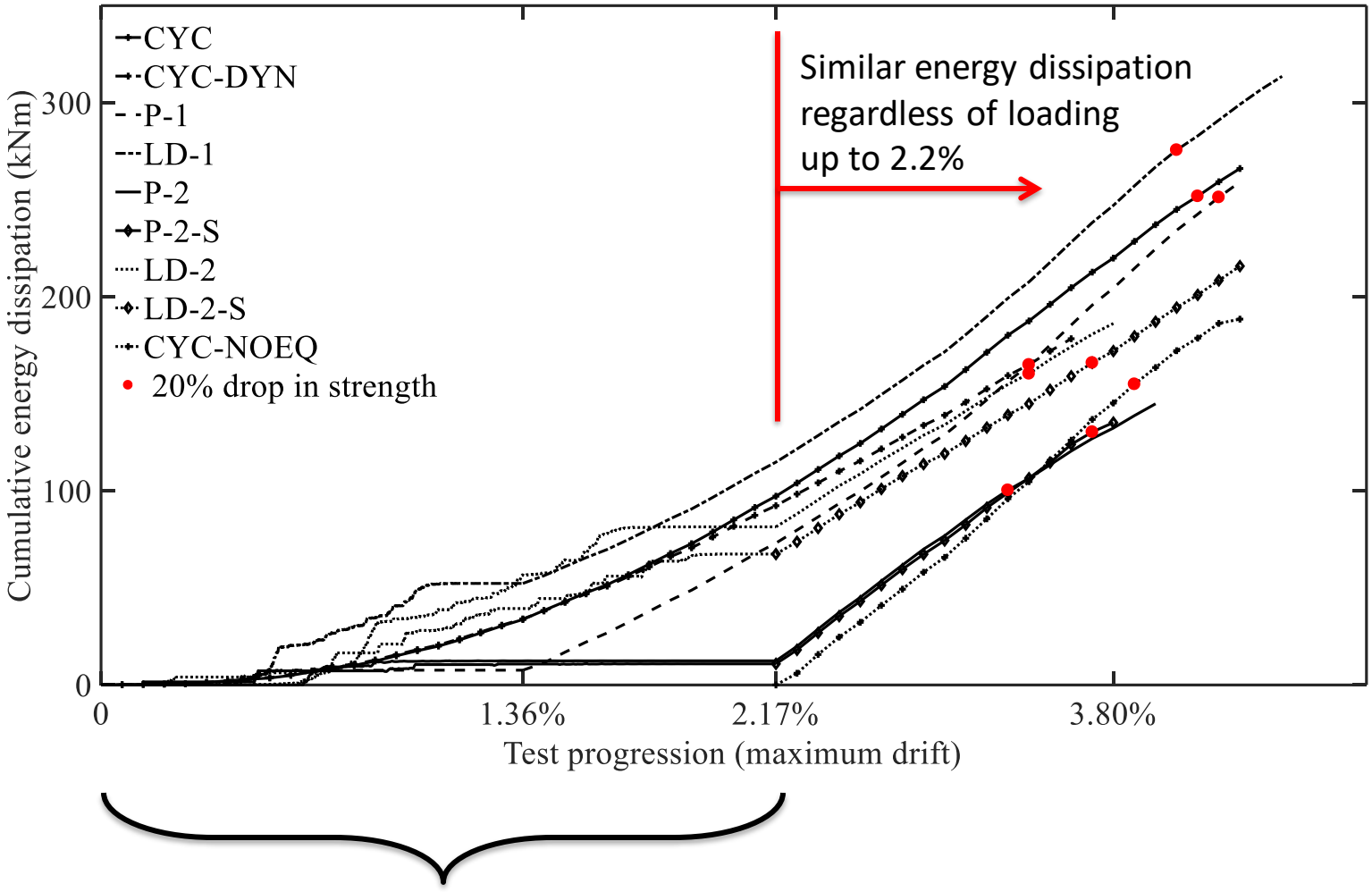




No change in deformation capacity!

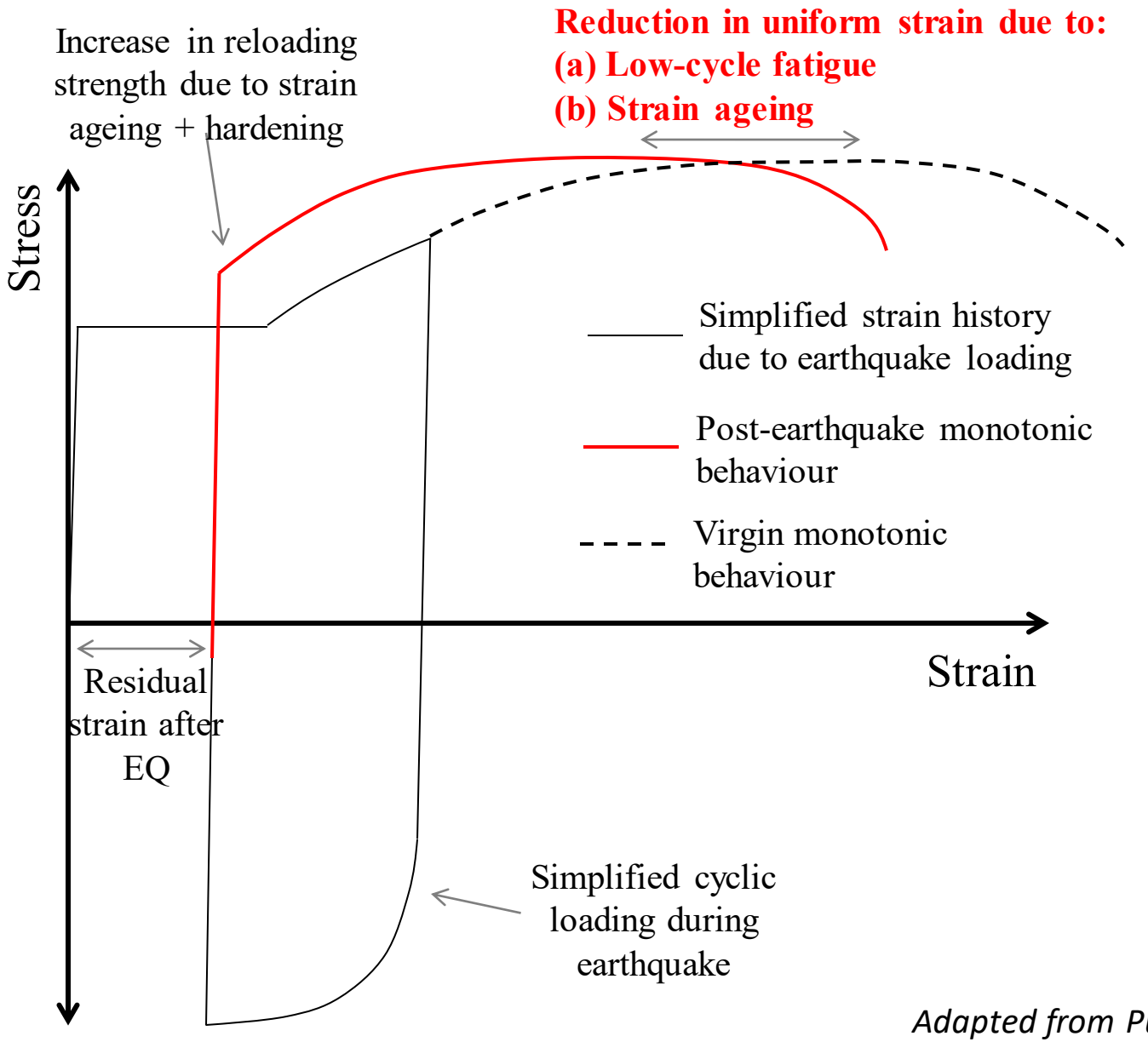
Marder, K. J., Motter, C. J., Elwood, K. J., & Clifton, G. C. (2018). Effects of variation in loading protocol on the strength and deformation capacity of ductile reinforced concrete beams. *Earthquake Eng and Structural Dynamics*

Effect of moderate-level loading cycles



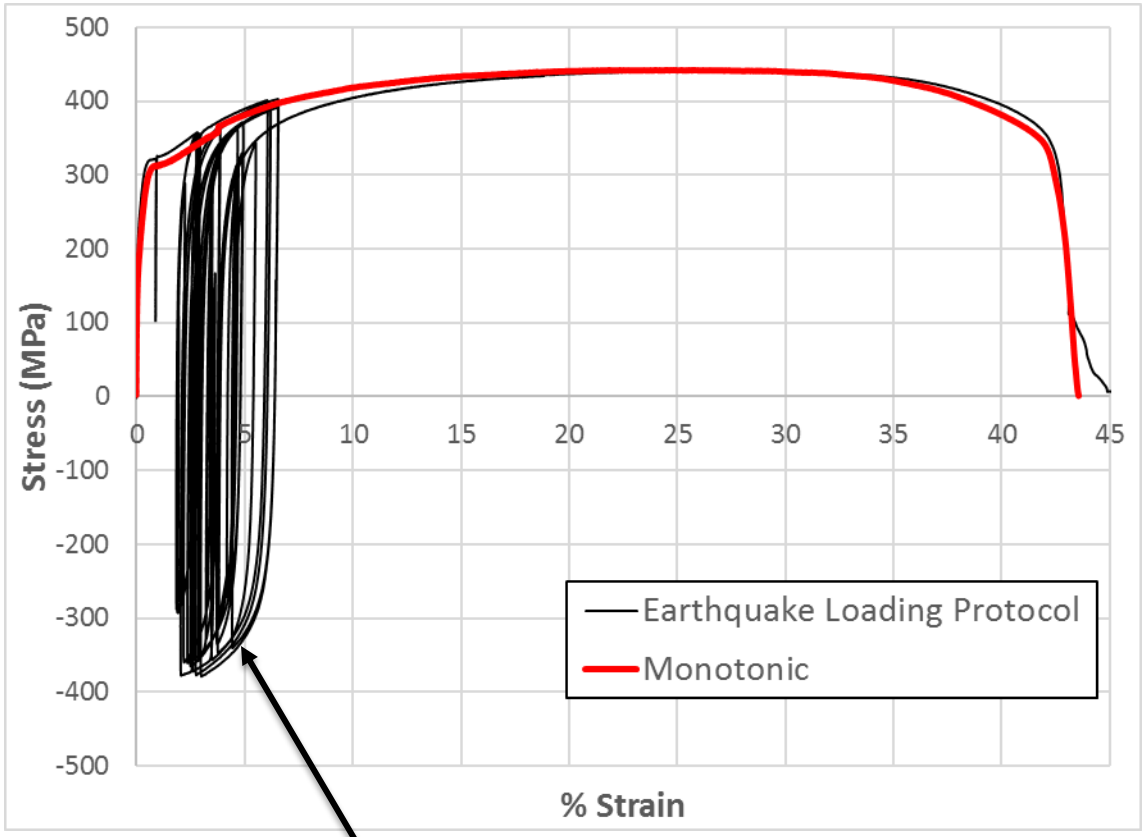
Variation in energy dissipation due to the different loading protocols carried through until failure.

Reduction in steel strain capacity



Adapted from Pussegoda (1978)

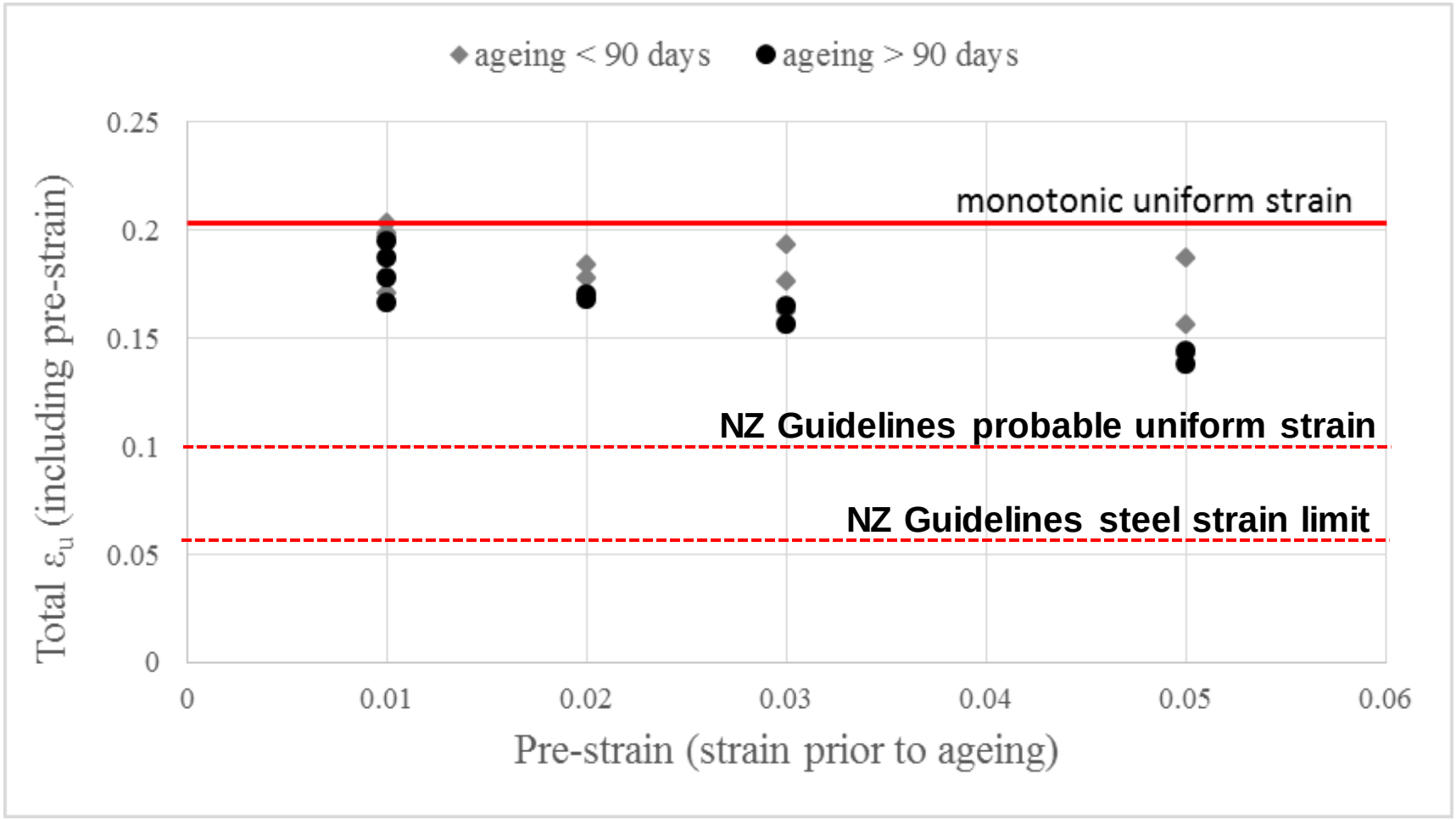
Reduction in steel strain capacity
-Low-cycle fatigue



Strain demands from bar from long-duration beam test scaled to 6% max strain

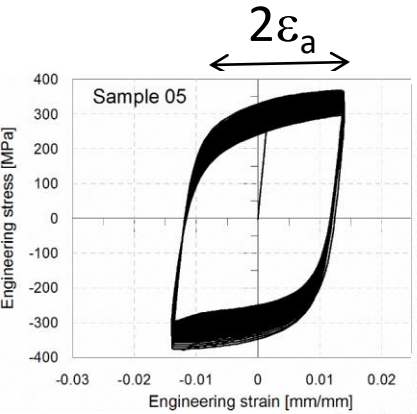
Marder (2018)

Reduction in steel strain capacity
- Strain ageing

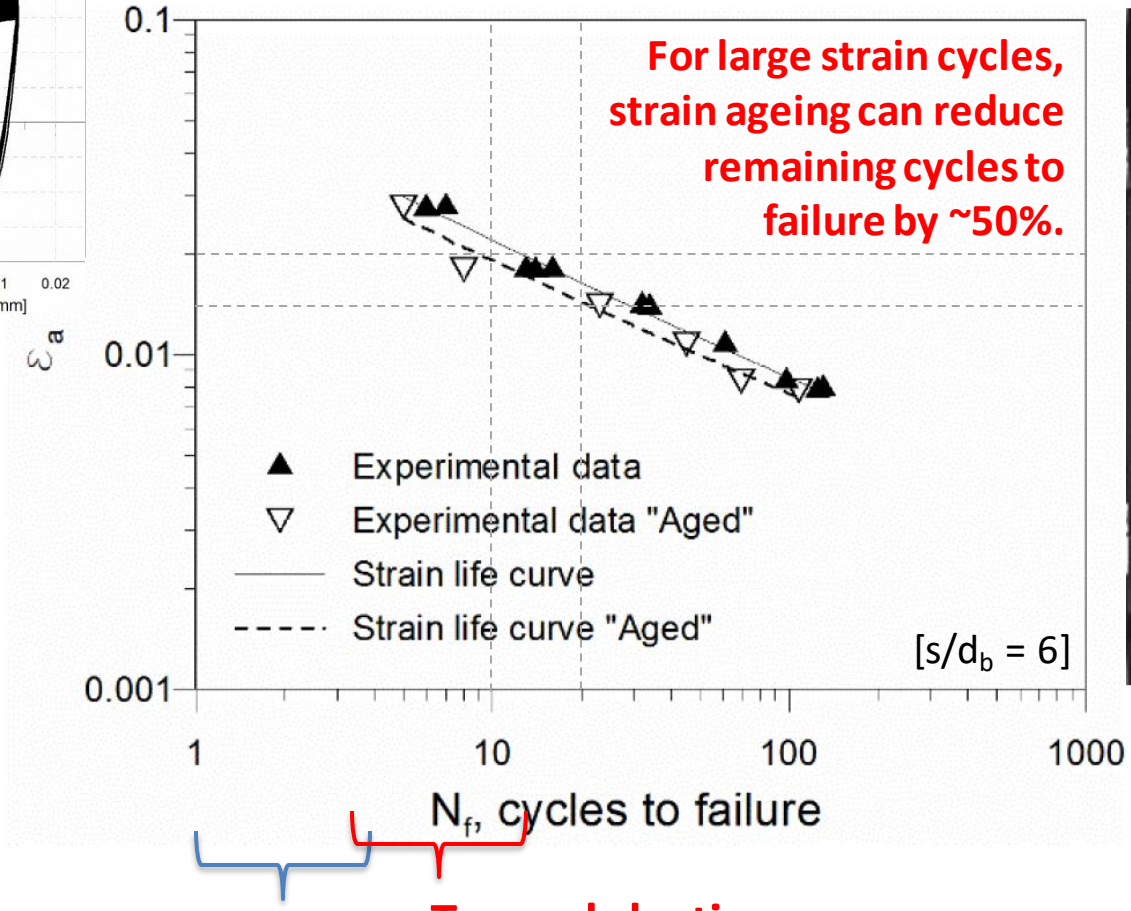


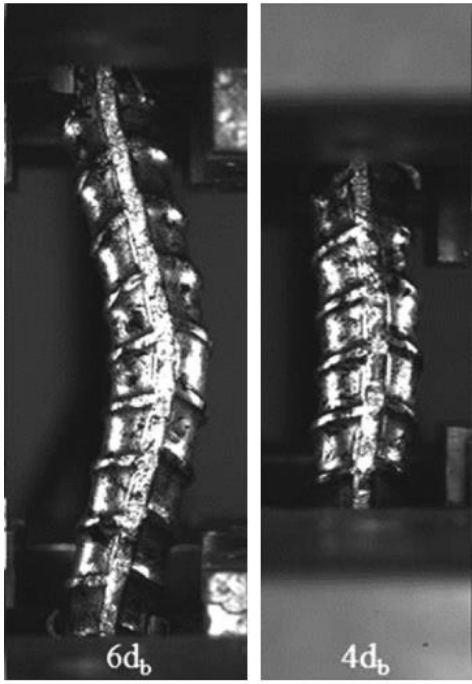
Data: Restrepo-Posada et al (1994) and Loporcaro et al (2016)

Reduction in steel strain capacity
- Strain ageing *+ LCF*



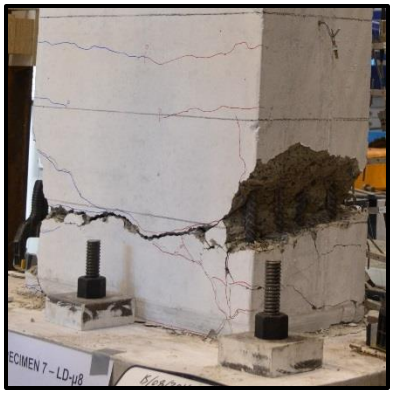
Loporcaro (2017)



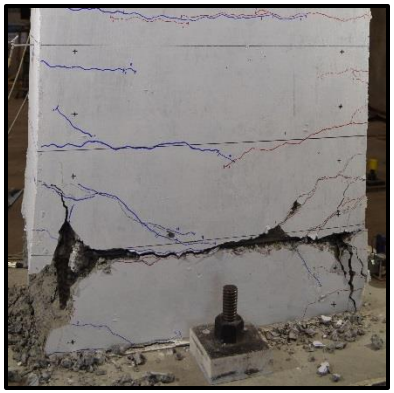


Ghannoum and Slavin (2016)

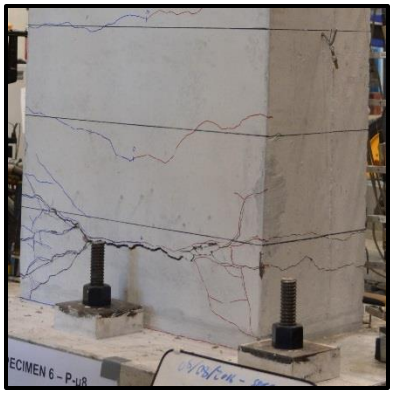
So does moderate damage ‘reduce’ the residual capacity?



LD-2

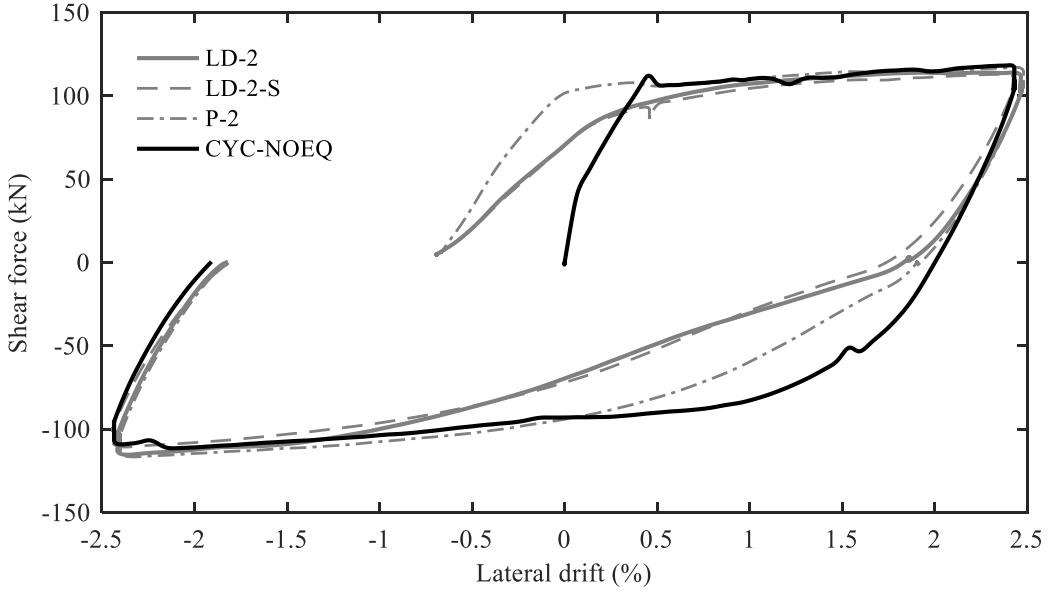


LD-2-S



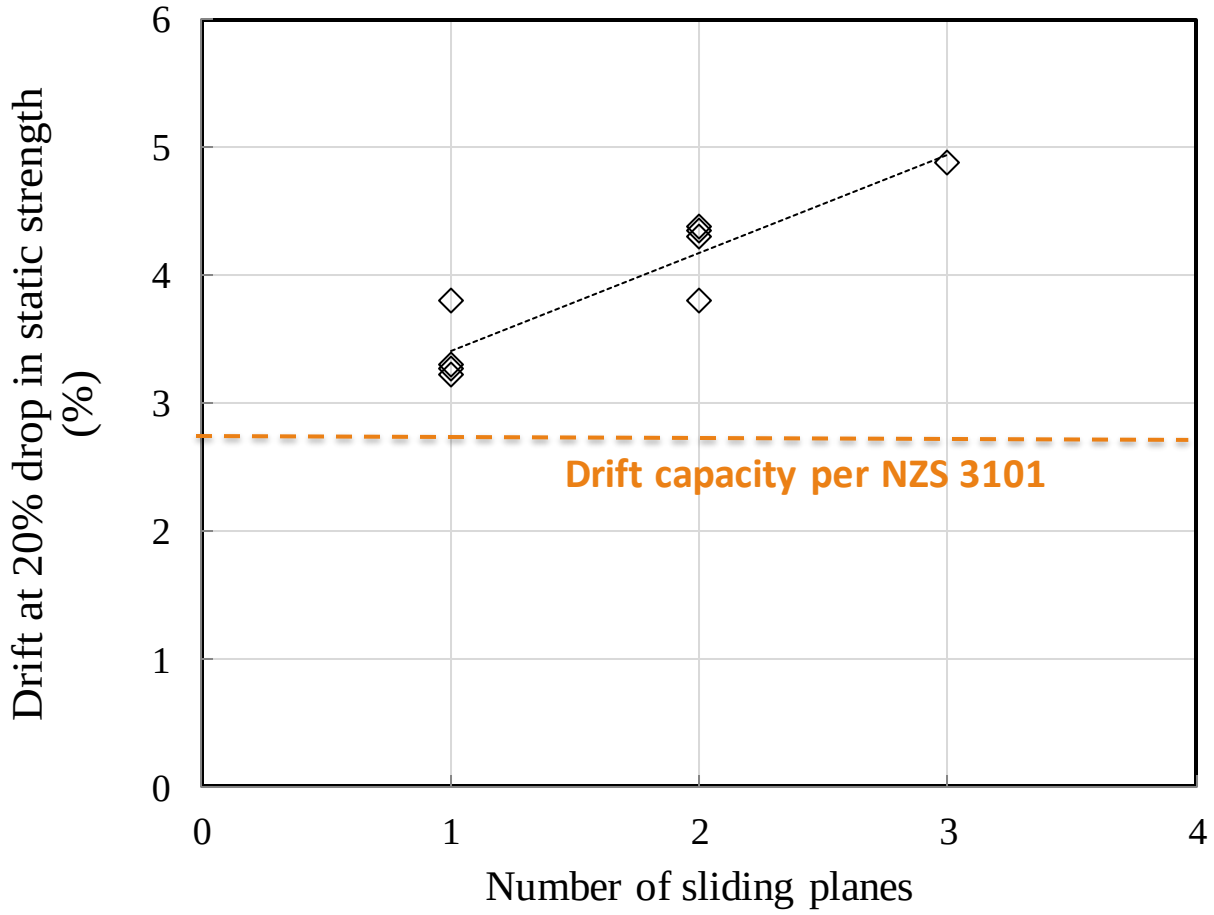
P-2

CYC-NOEQ



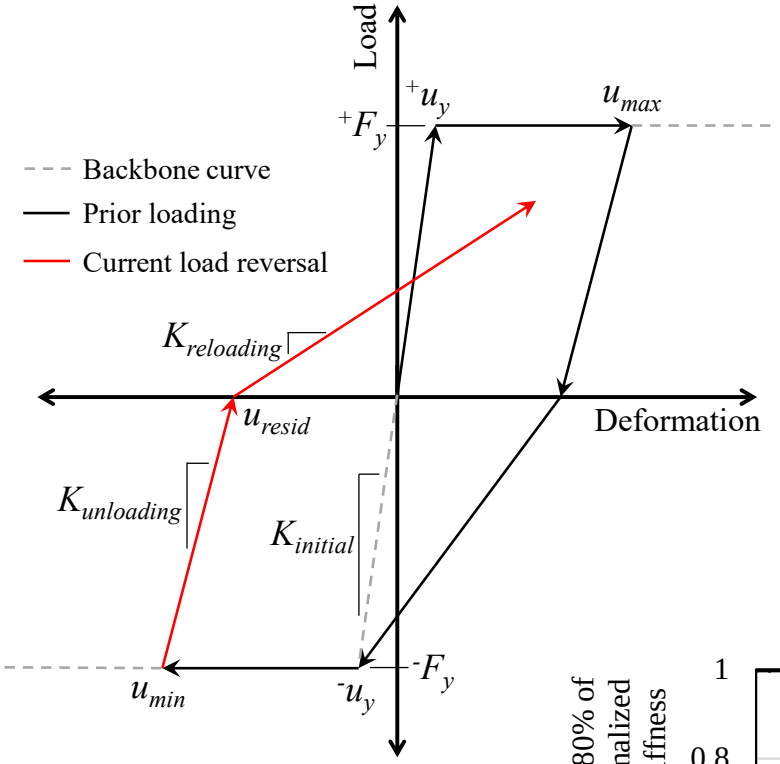
- Stiffness is reduced
- Strength is not reduced
- Deformation capacity is not ‘reduced’ – but post-earthquake assessments may provide insight for improved assessment of deformation capacity

Damage → Drift capacity?

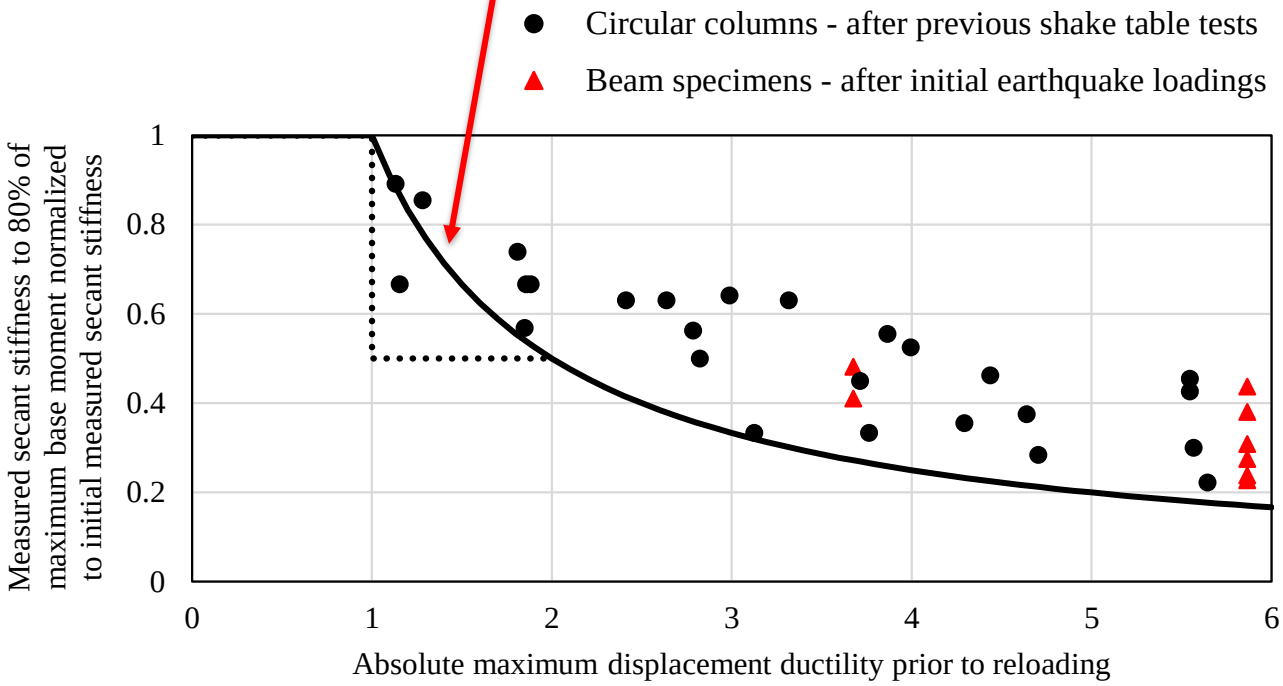


→ *Drift capacity correlated with number of sliding planes.*

How much stiffness is lost?



$$\frac{K_r}{K_y} = \frac{1}{\mu}$$

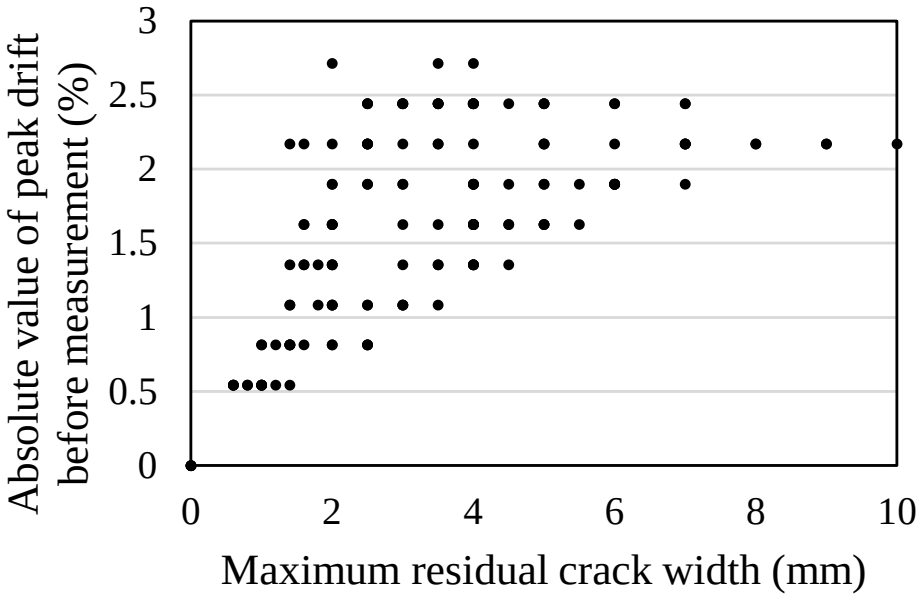


How to estimate the peak deformation demands during the damaging earthquake?

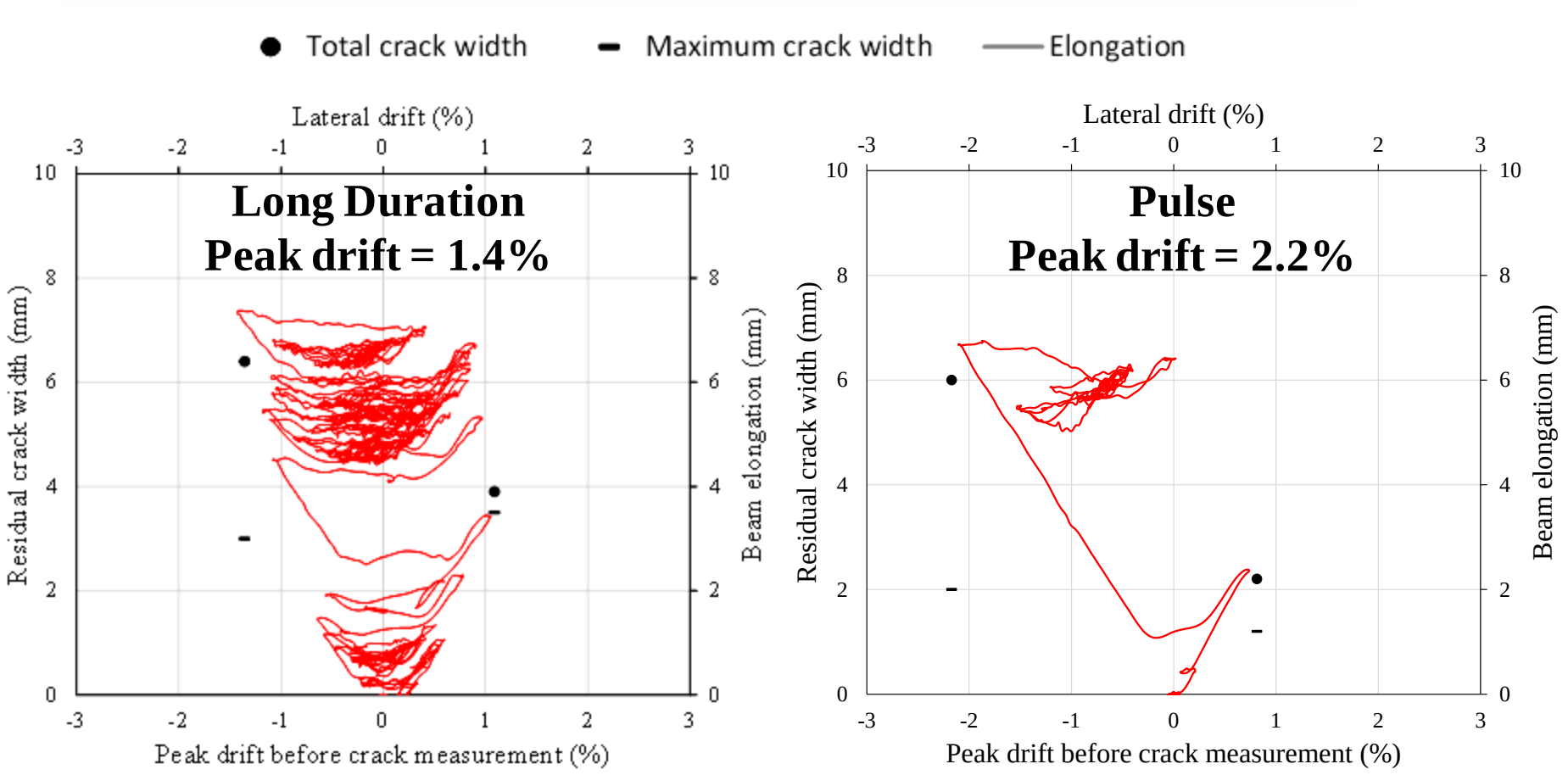
- Very important to understand the demands imposed on a damaged building before trying to assess it.

- No sense conducting a detailed seismic assessment on a damaged building if you can't evaluate how it responded in the first earthquake!

Existing post-earthquake assessment guidelines use the maximum residual crack width as a key damage indicator

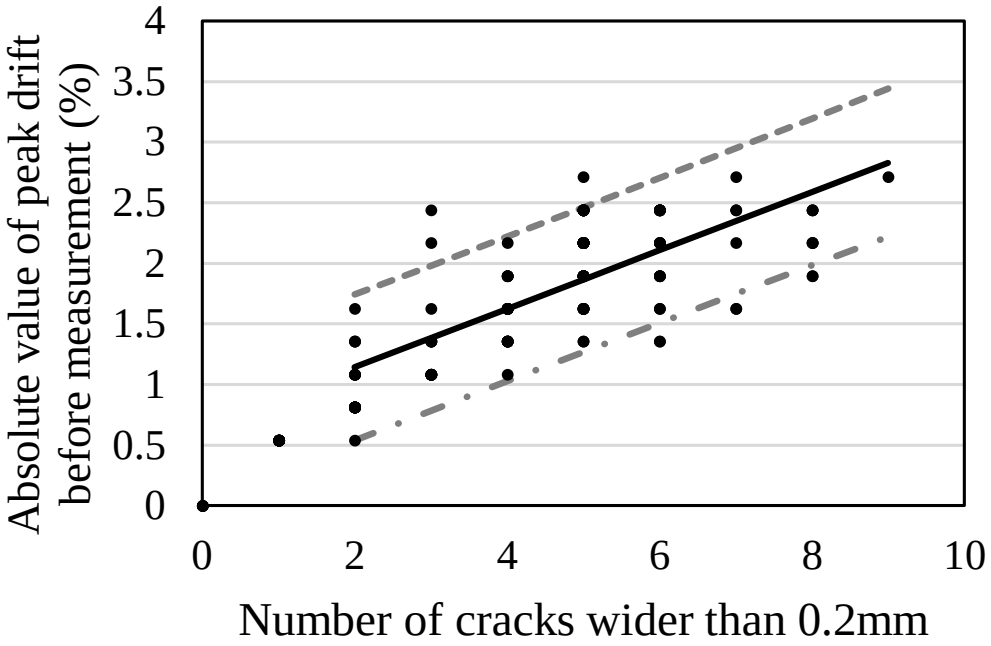


Residual crack widths versus elongation



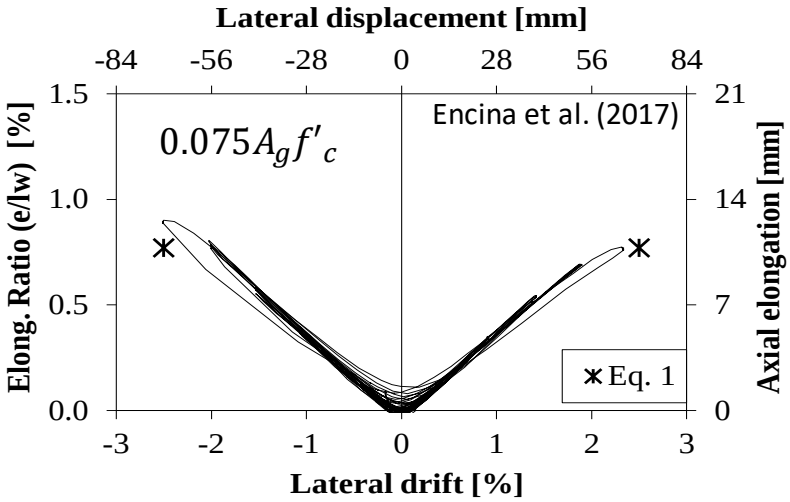
Similar residual crack widths!

Distribution of cracking metrics?

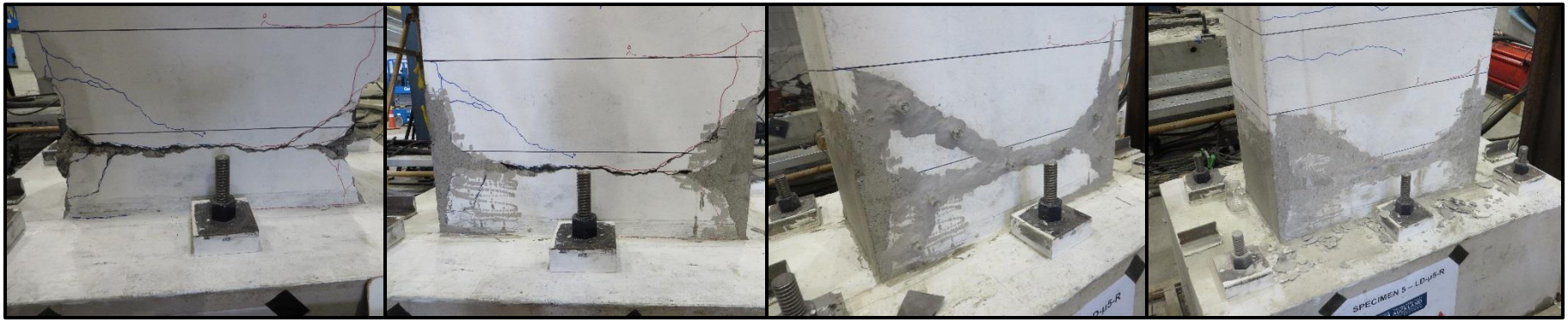


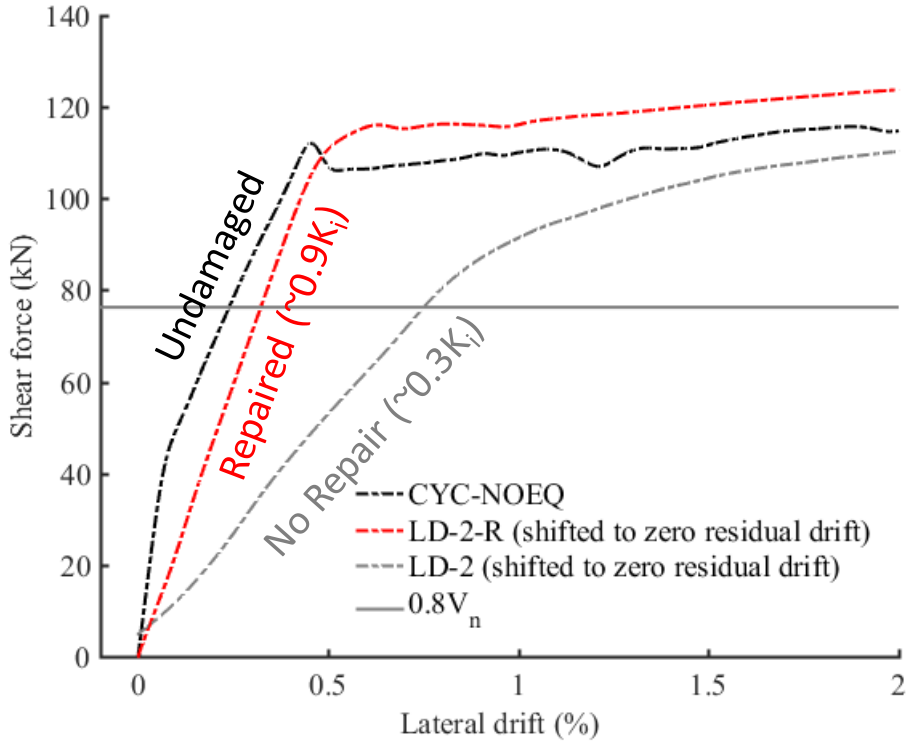
Single crack in beams (with min. reo) is an indicator of low rotation demands

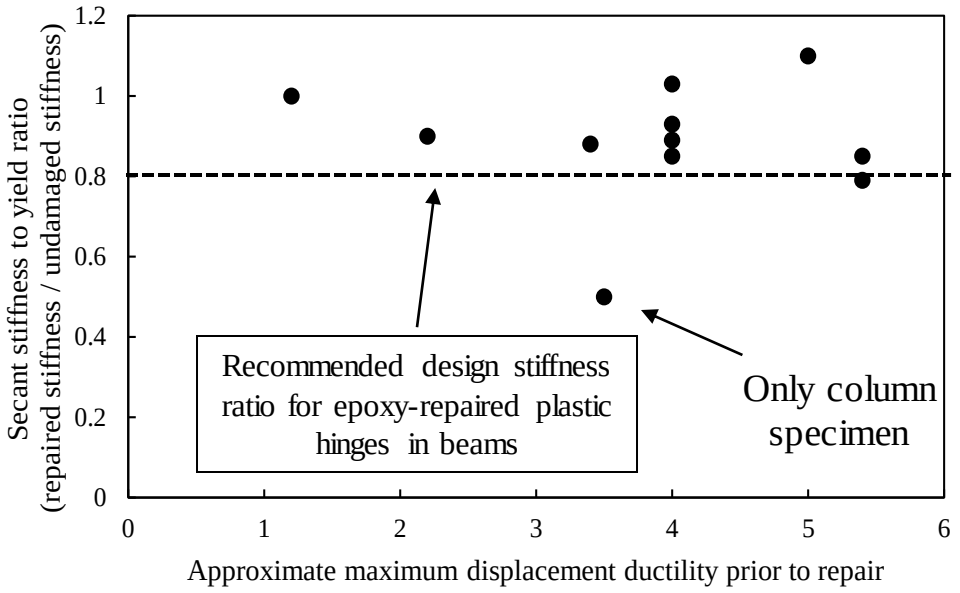
Columns & Walls?



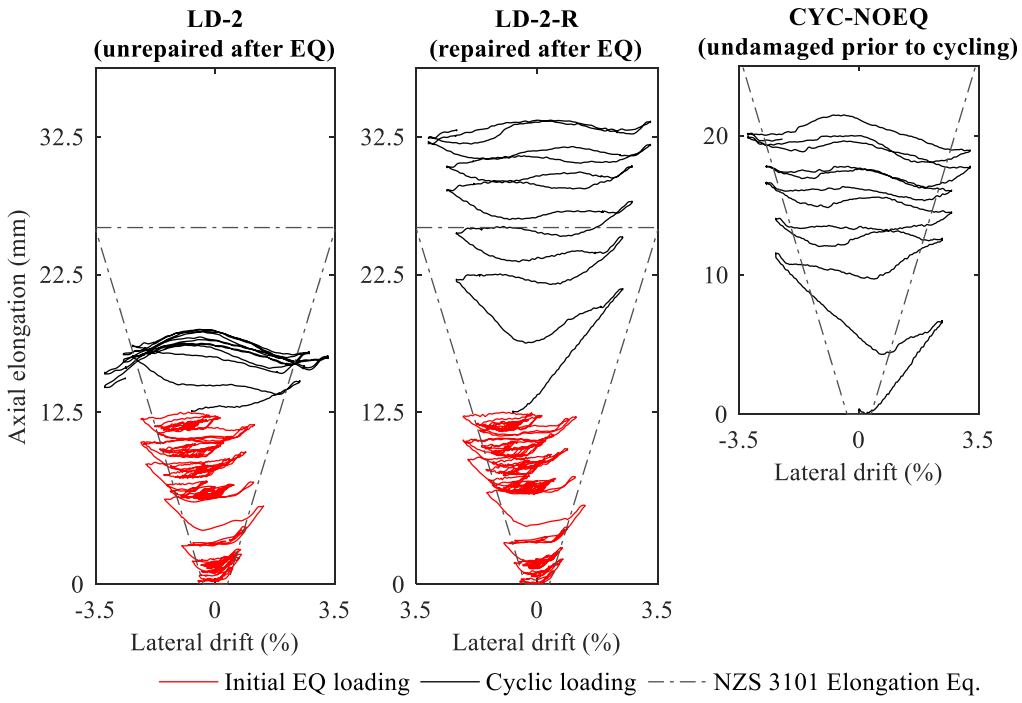
Epoxy repair





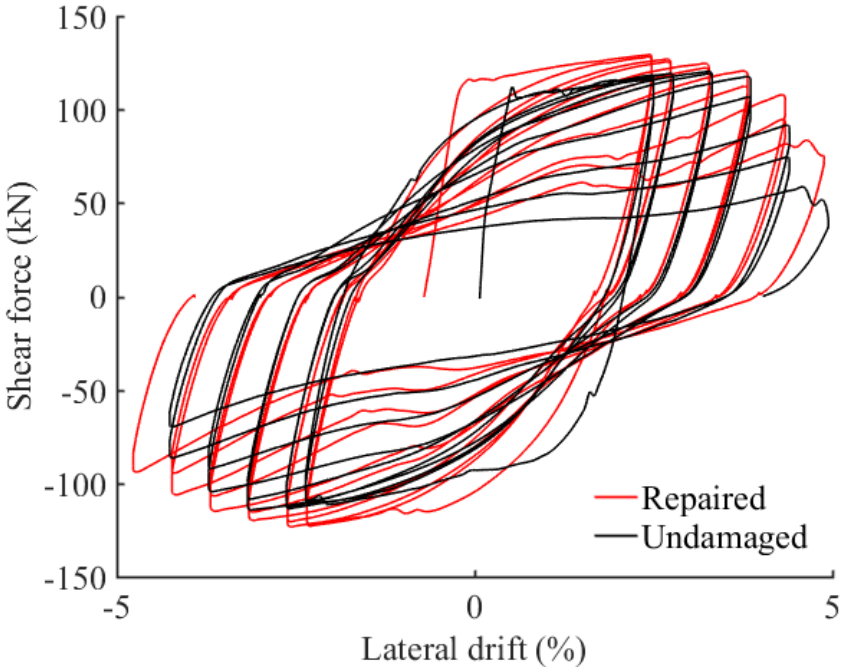


Epoxy repair

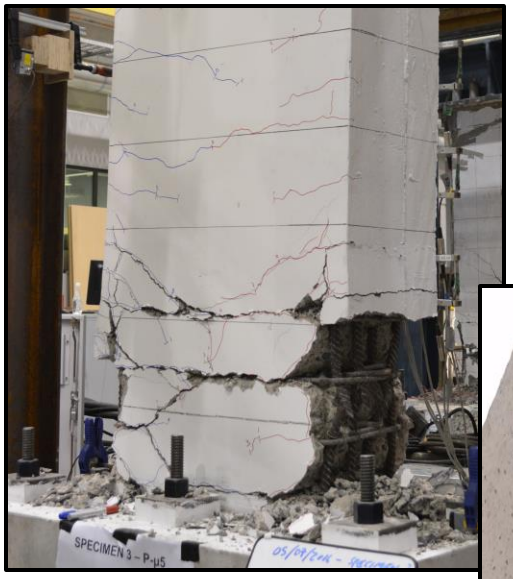


Residual elongation at the time of repair causes an **increase in cumulative elongation** (and therefore longitudinal reo strain!)

- Post-repair **strength increases** as a result of higher reo strain.
- **Deformation capacity is similar** between repaired and undamaged cases

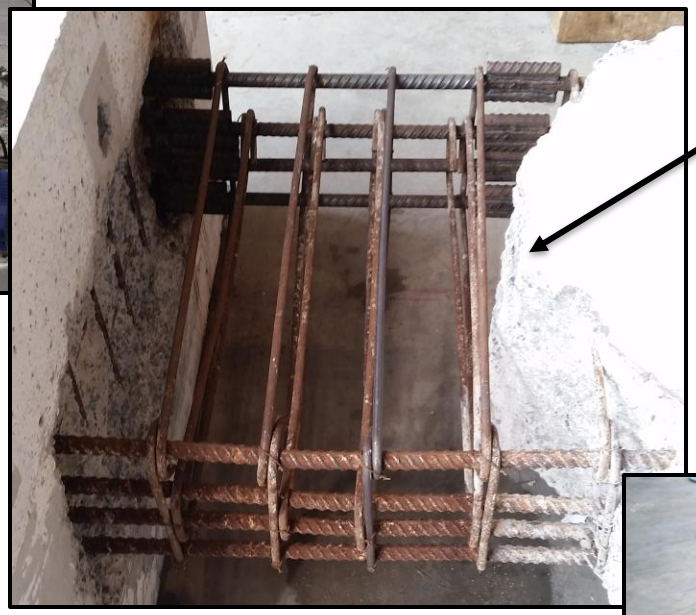


Repair after failure – strain aged bars



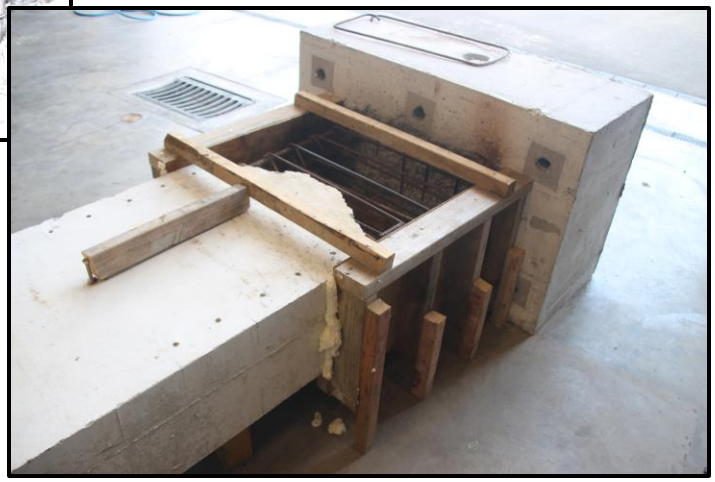
Damage after original test: Bars only buckled on one side. Approx. 25mm residual elongation.

New bars welded in on side with buckled bars



Old concrete hydro-demoed

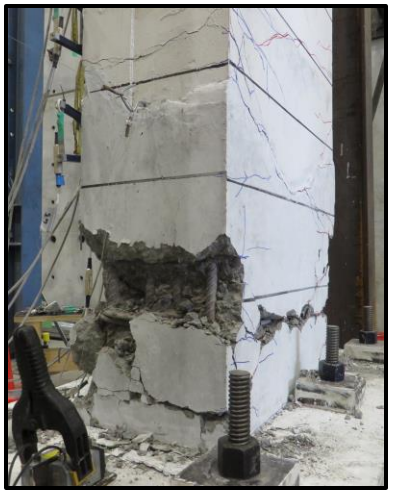
New concrete poured



Unbuckled bars left in place

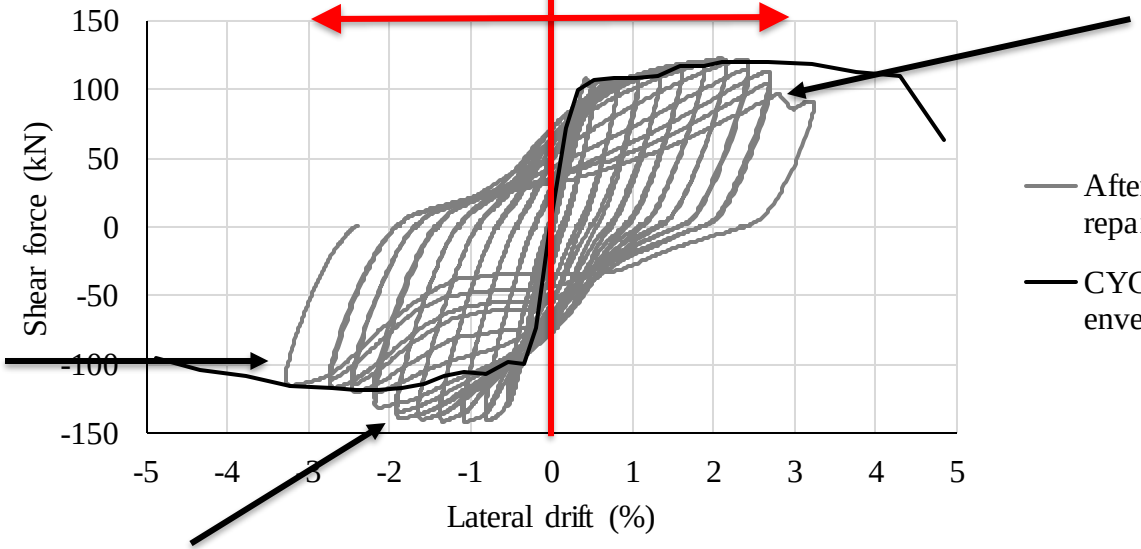
Repair after failure – strain aged bars

Testing six months after original test. Strain aged bars again didn't buckle



Prior strained bars in tension

Repaired bars in tension



Early failure in new bars due to strain concentration between welds

No fracture of strain aged bars

Strength increase due to strain ageing

Summary

- Prior loading cycles below 2% drift have minimal impact on drift or energy dissipation capacity.
- Residual crack widths alone do not provide reliable estimate of peak drift demands.
- Prior earthquake loading results in reduction in stiffness proportional with ductility demand.
  - Epoxy repair can recover 80% of original stiffness

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Thank you

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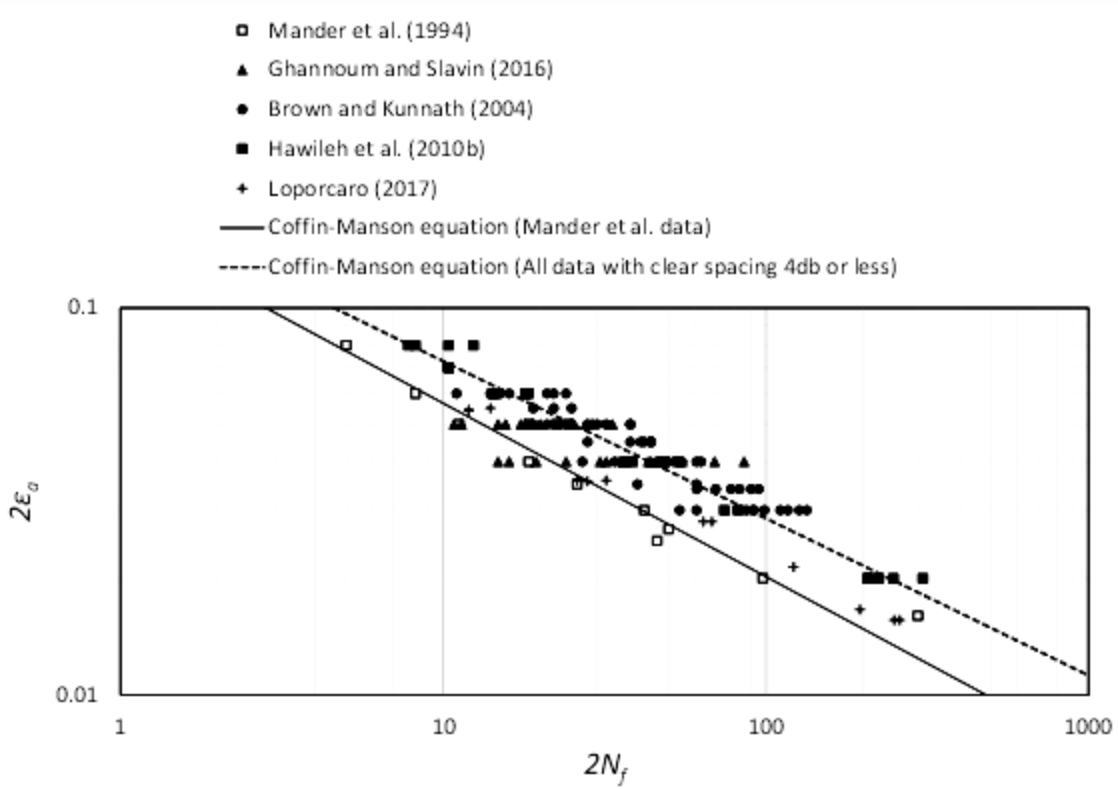
What about low-cycle fatigue?

Coffin-Manson equation: $\varepsilon_a = \varepsilon'_f (2N_f)^c$



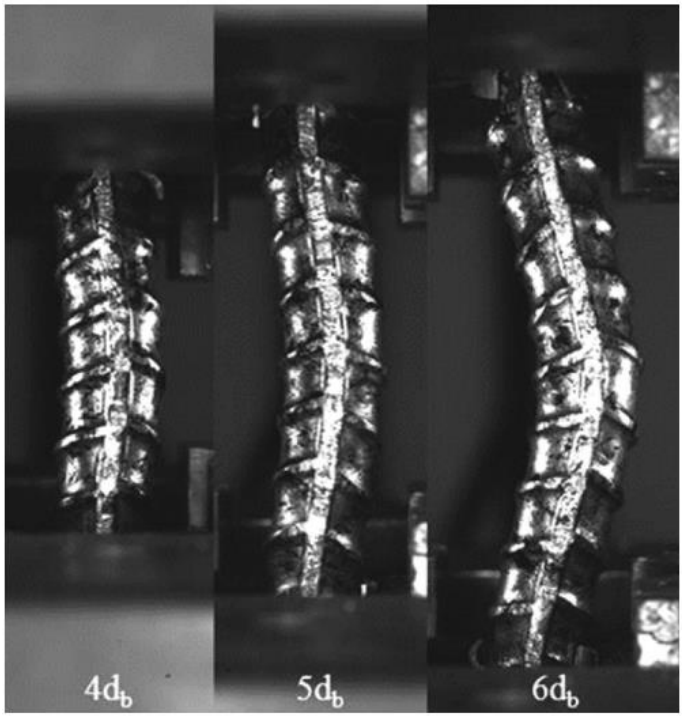


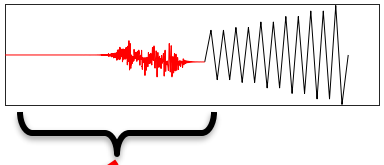
Figure taken from Ghannoum and Slavin (2016)

For unbuckled bars: $\varepsilon_a = 0.093(2N_f)^{-0.41}$

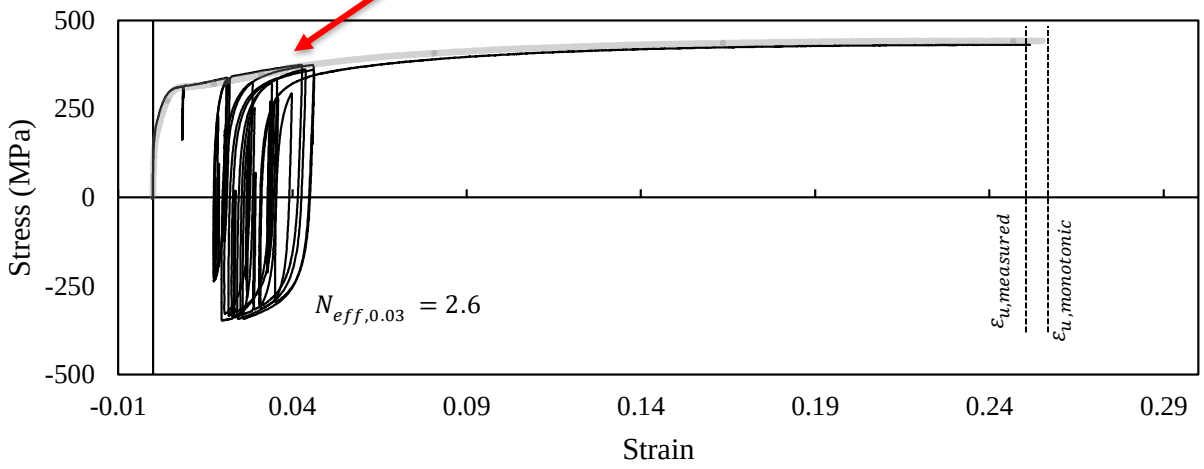
Equivalent to 40 cycles at a strain reversal of 0.03

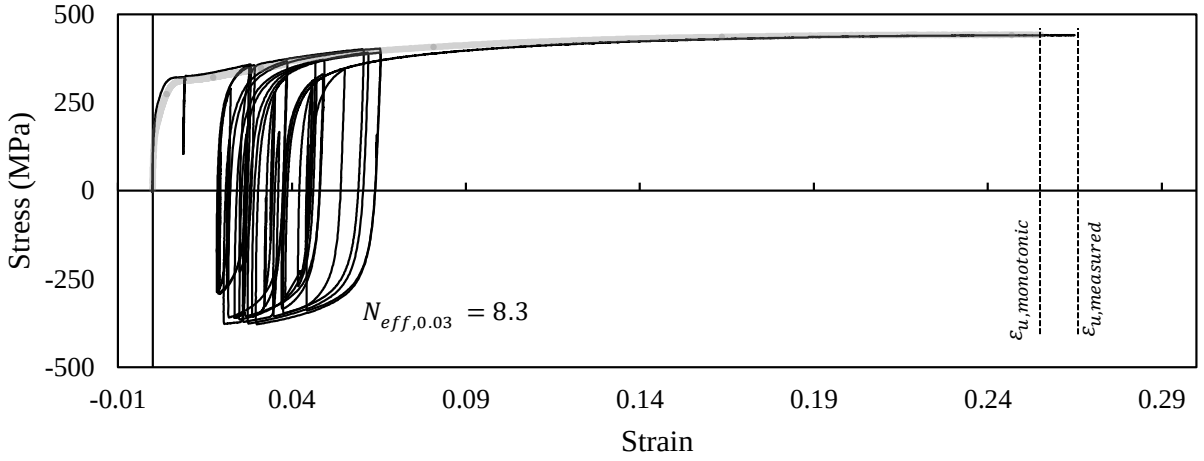
What about low-cycle fatigue?

Strain history measured on beam specimen during long duration earthquake loading

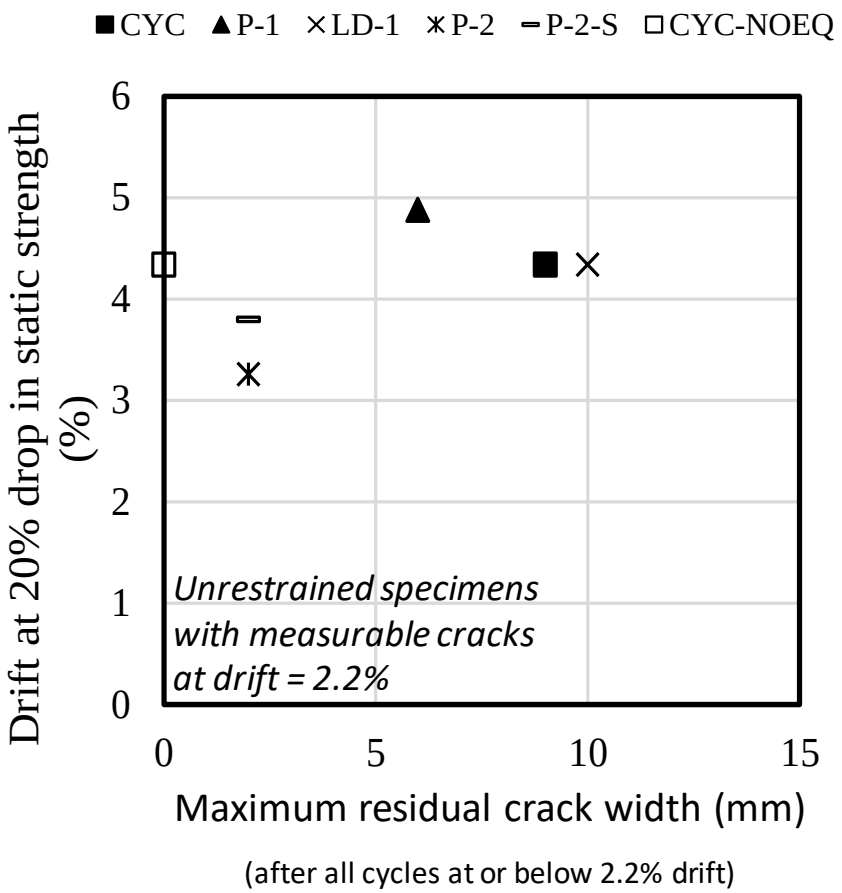


$4d_b$ clear span testing (300E)

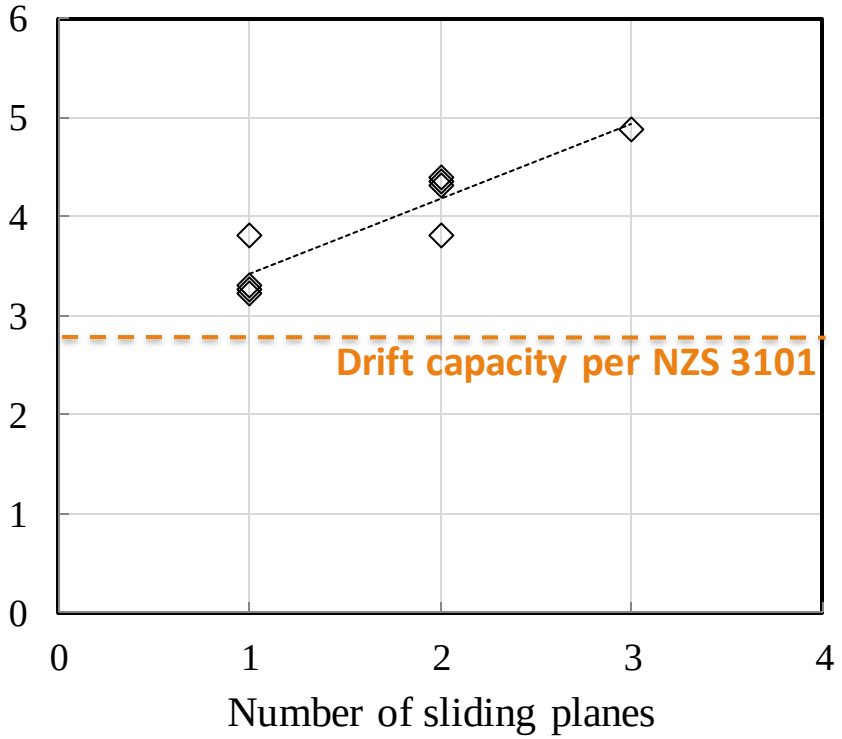




Damage → Drift capacity?

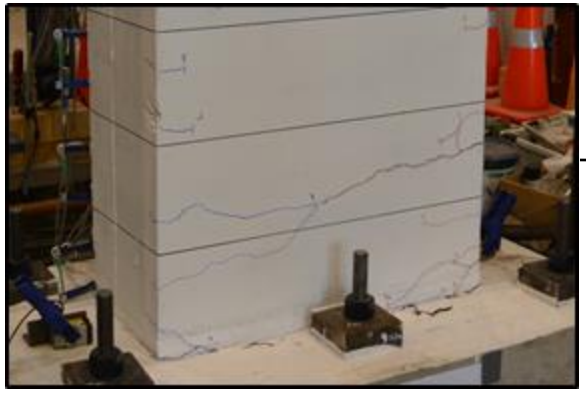


→ *No relationship between crack widths and drift capacity.*

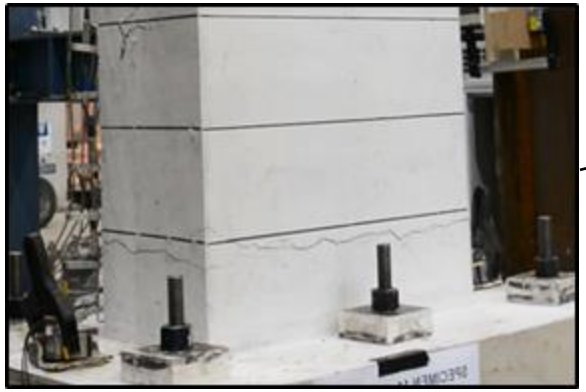


→ *Drift capacity correlated with number of sliding planes.*

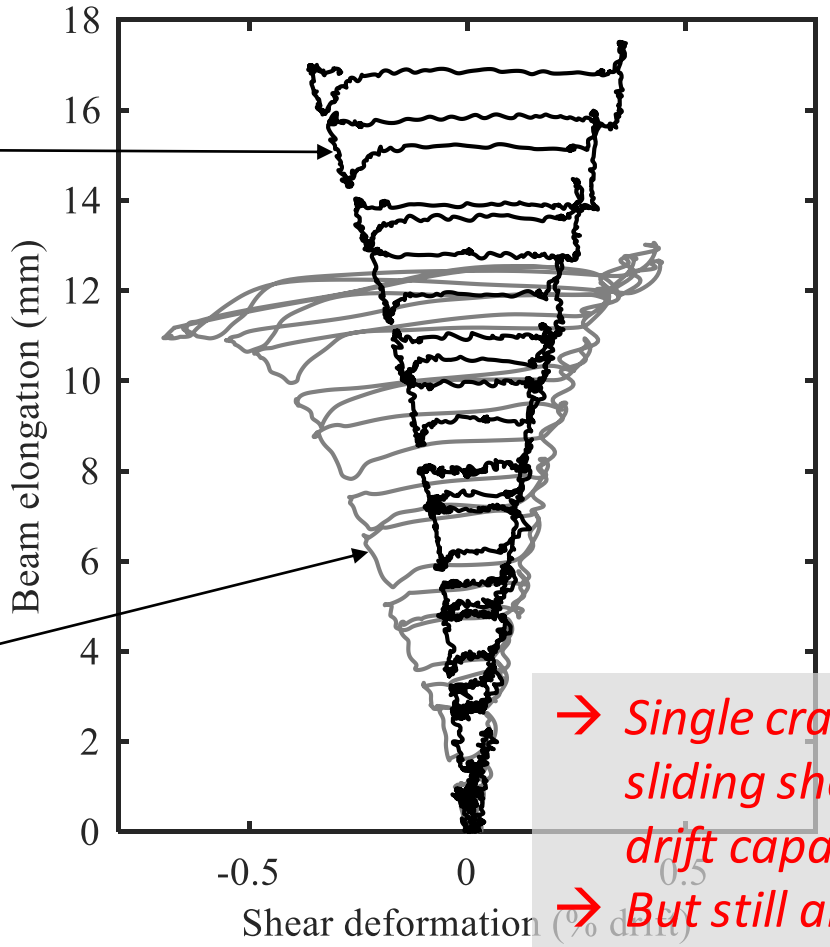
Drift Capacity
- limited by sliding shear



CYC (multiple sliding planes)



CYC-DYN (single sliding plane)



→ *Single crack w = 2-3mm, sliding shear will limit drift capacity.*

→ *But still above NZS 3101 drift capacity.*