Residual Capacity and Repairability of Earthquake-Damaged RC Beam Elements

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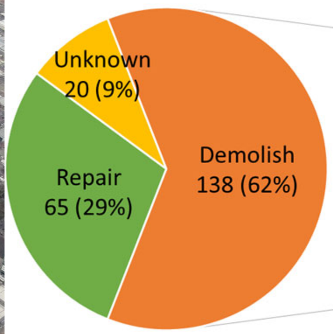
17th US-Japan-NZ Workshop
on the Improvement of Structural Engineering and Resilience

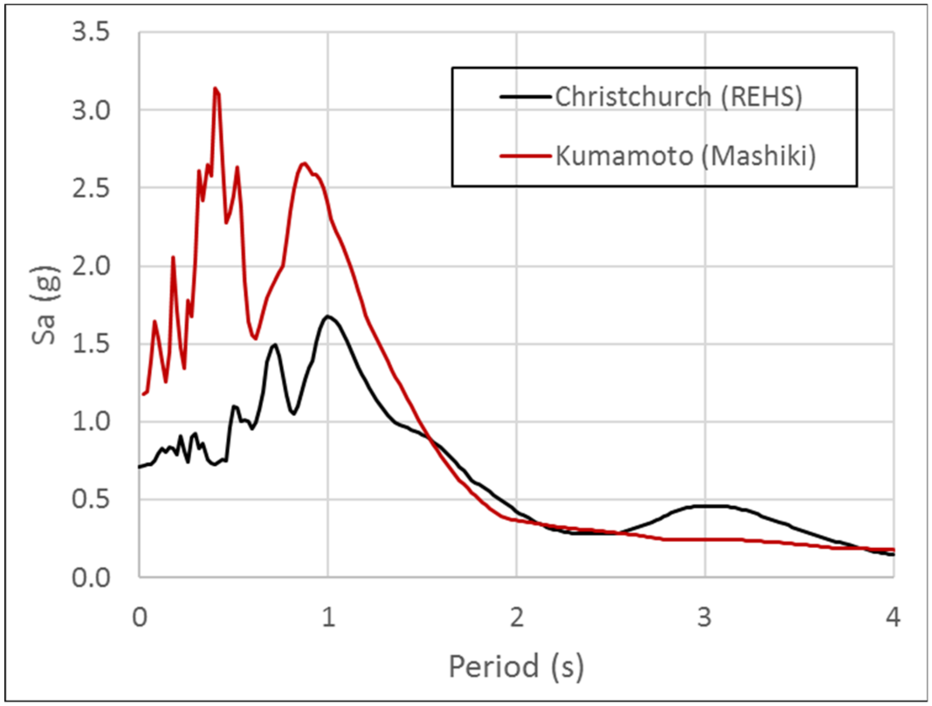
16th US-Japan-NZ Workshop

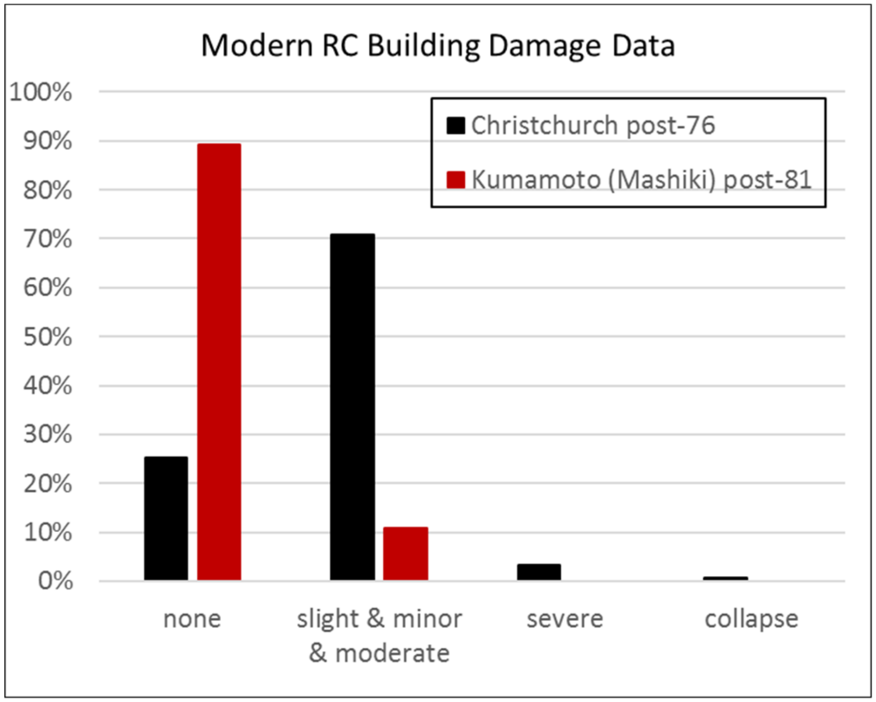
Kumamoto vs Christchurch

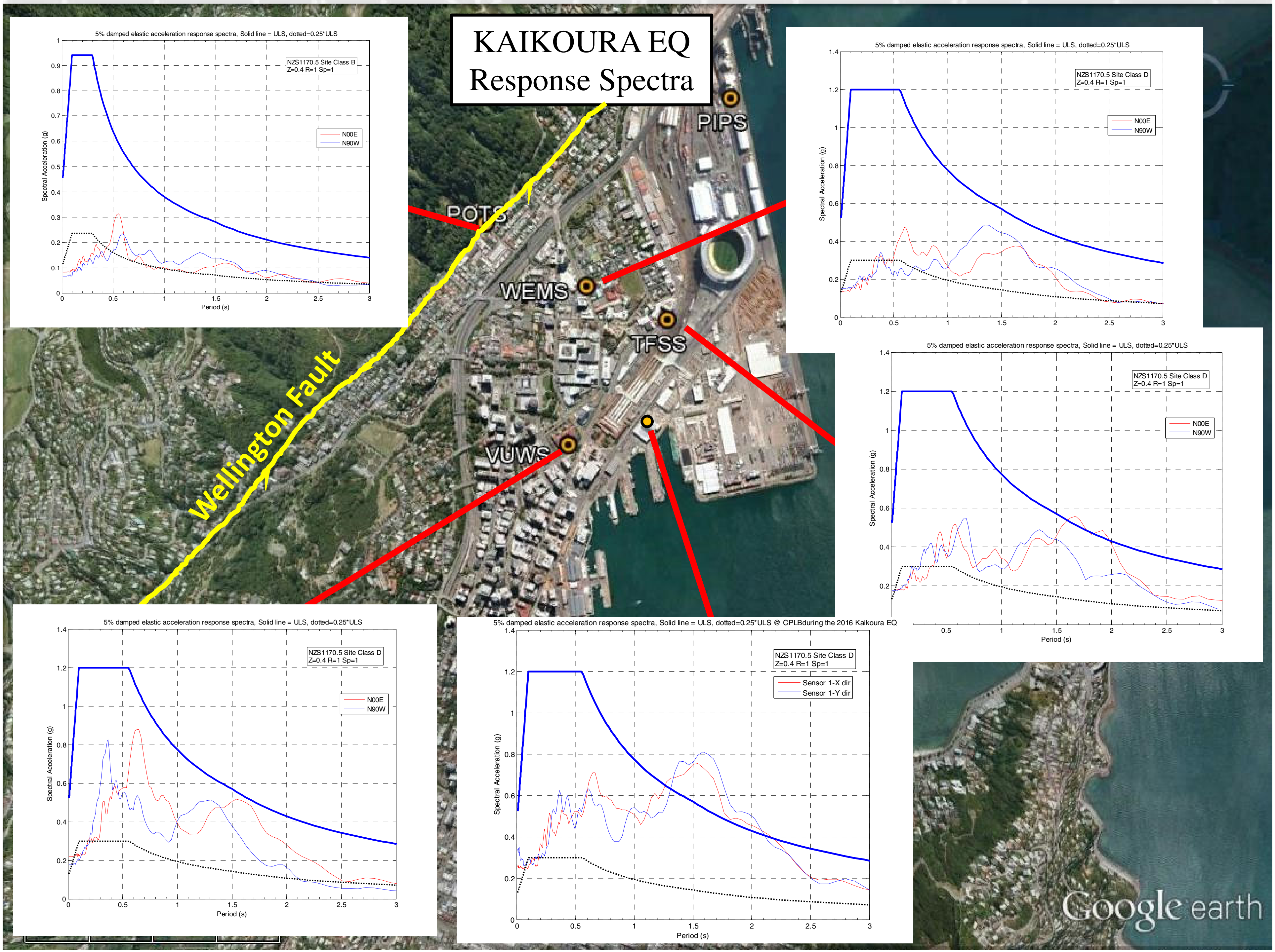
Kumamoto
- Focus on strength and stiffness

Christchurch
- Focus on ductility





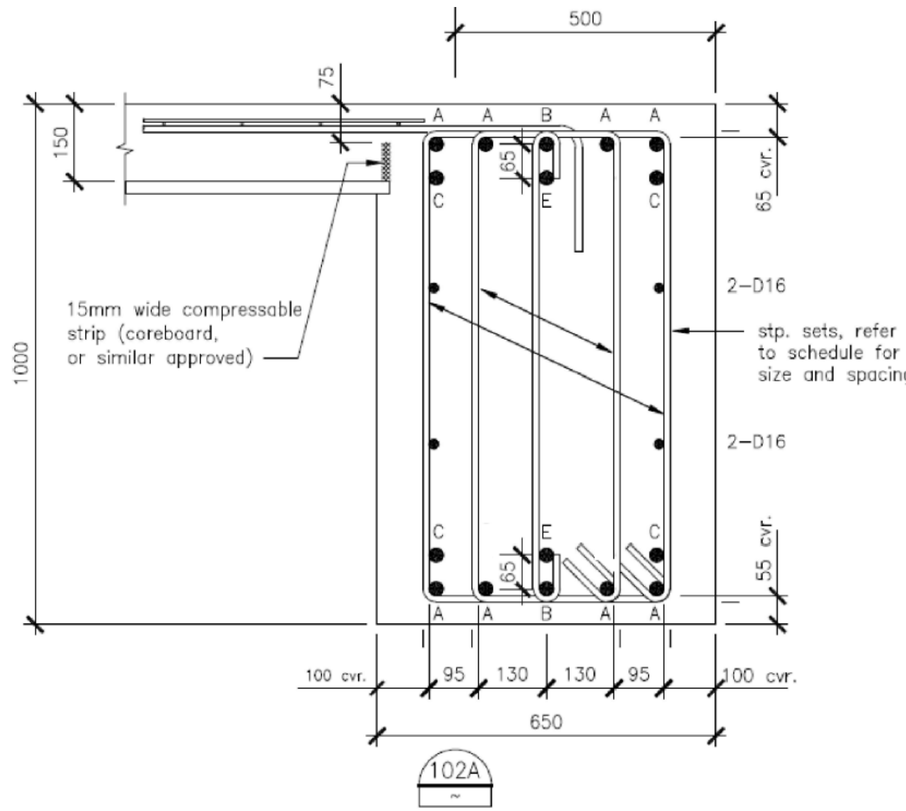




KAIKOURA EQ
Response Spectra
PIPS
POTS
WEMS
TFSS
VUWS
Wellington Fault
5% damped elastic acceleration response spectra, Solid line = ULS, dotted=0.25*ULS
NZS1170.5 Site Class B
Z=0.4 R=1 Sp=1
N00E
N90W
Spectral Acceleration (g)
Period (s)
5% damped elastic acceleration response spectra, Solid line = ULS, dotted=0.25*ULS
NZS1170.5 Site Class D
Z=0.4 R=1 Sp=1
N00E
N90W
Spectral Acceleration (g)
Period (s)
5% damped elastic acceleration response spectra, Solid line = ULS, dotted=0.25*ULS
NZS1170.5 Site Class D
Z=0.4 R=1 Sp=1
N00E
N90W
Spectral Acceleration (g)
Period (s)
5% damped elastic acceleration response spectra, Solid line = ULS, dotted=0.25*ULS
NZS1170.5 Site Class D
Z=0.4 R=1 Sp=1
N00E
N90W
Spectral Acceleration (g)
Period (s)
5% damped elastic acceleration response spectra, Solid line = ULS, dotted=0.25*ULS @ CPLBduring the 2016 Kaikoura EQ
NZS1170.5 Site Class D
Z=0.4 R=1 Sp=1
Sensor 1-X dir
Sensor 1-Y dir
Spectral Acceleration (g)
Period (s)
Google earth

Wellington buildings

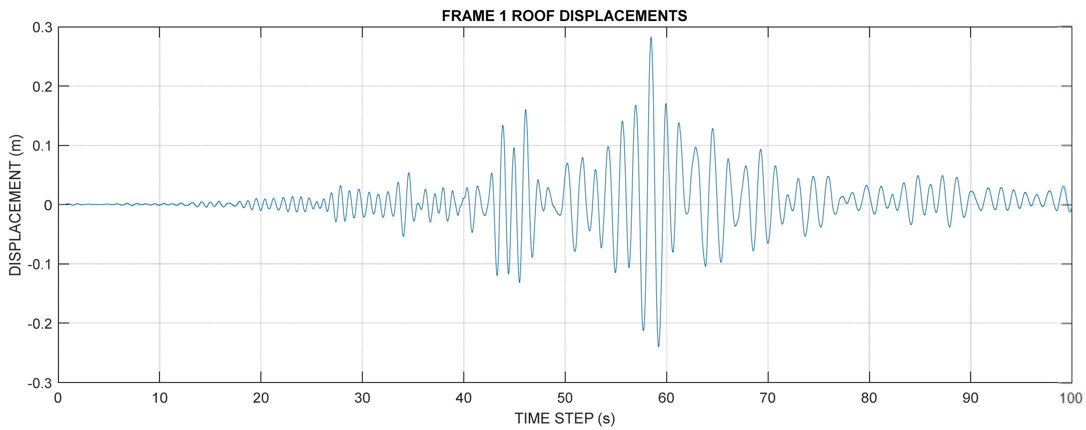
- 14 buildings demolished
  5 decisions pending
- Opportunity!
- RC Perimeter Frame Structure
- Modern Seismic Design Standards
- Precast Flooring System
- 4 Beam-Column Joints Extracted for testing.

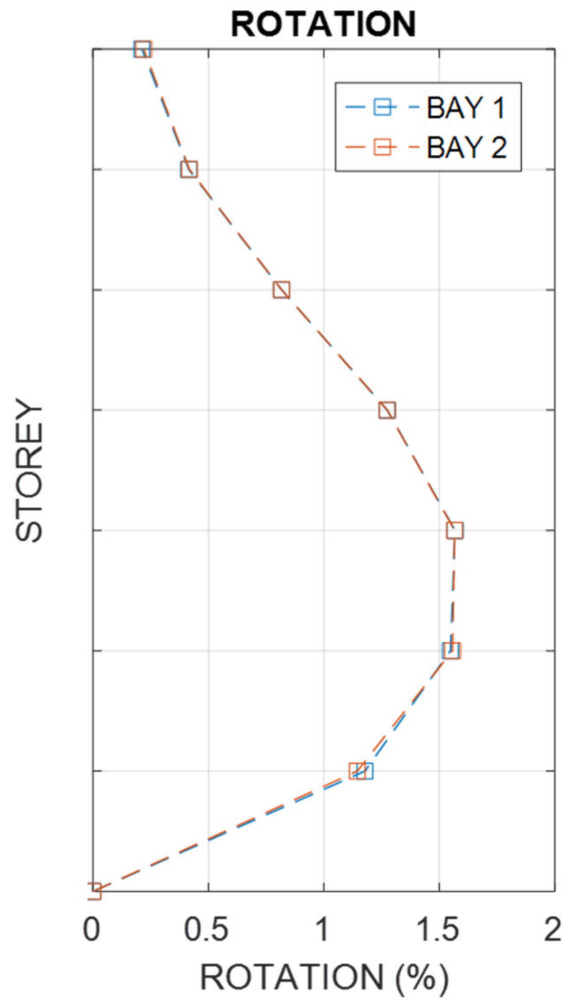


Cross Section of Extracted Units

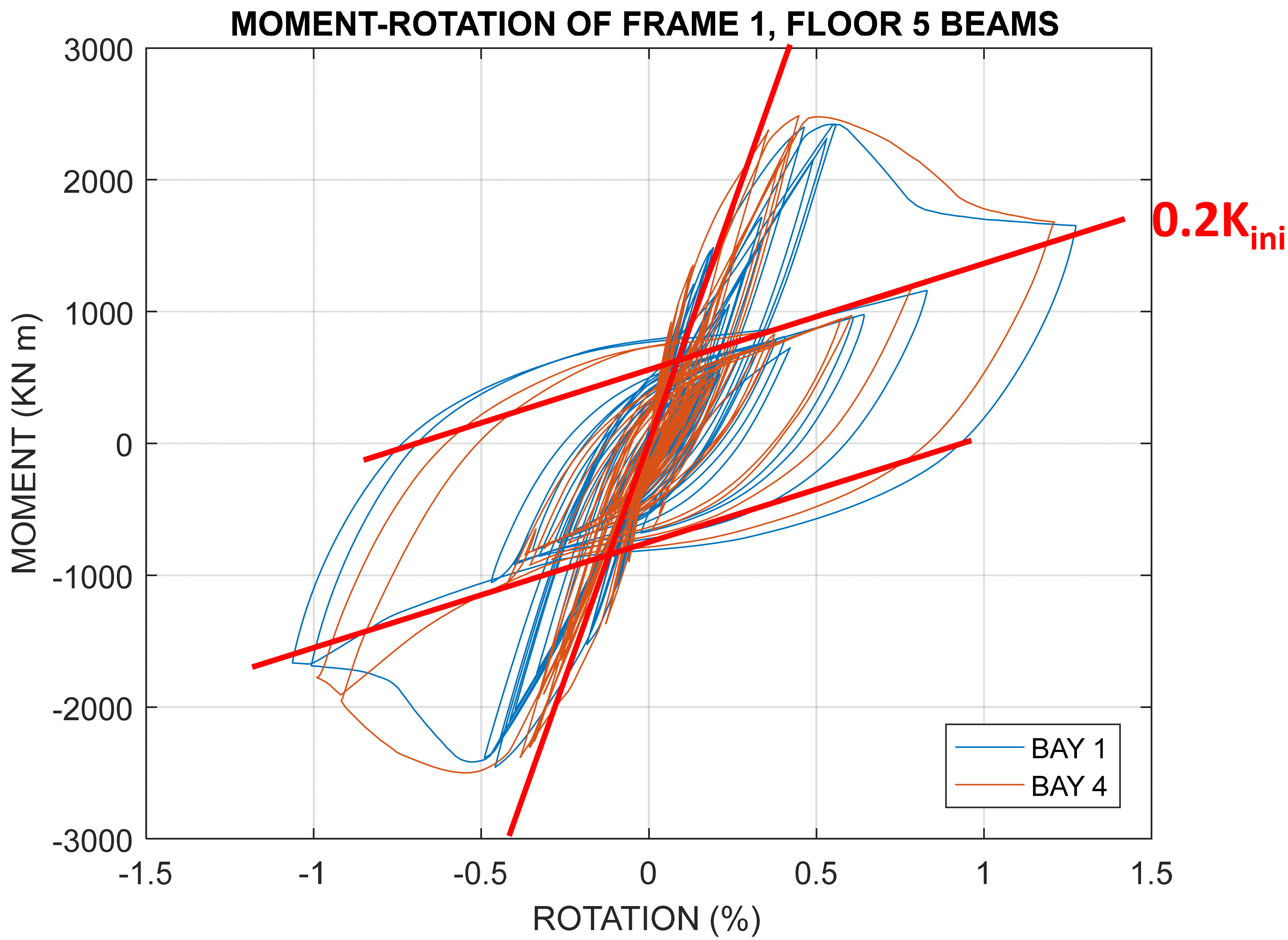
Damage state
– *Beam hinging examples*

Structural Response / Drift demands

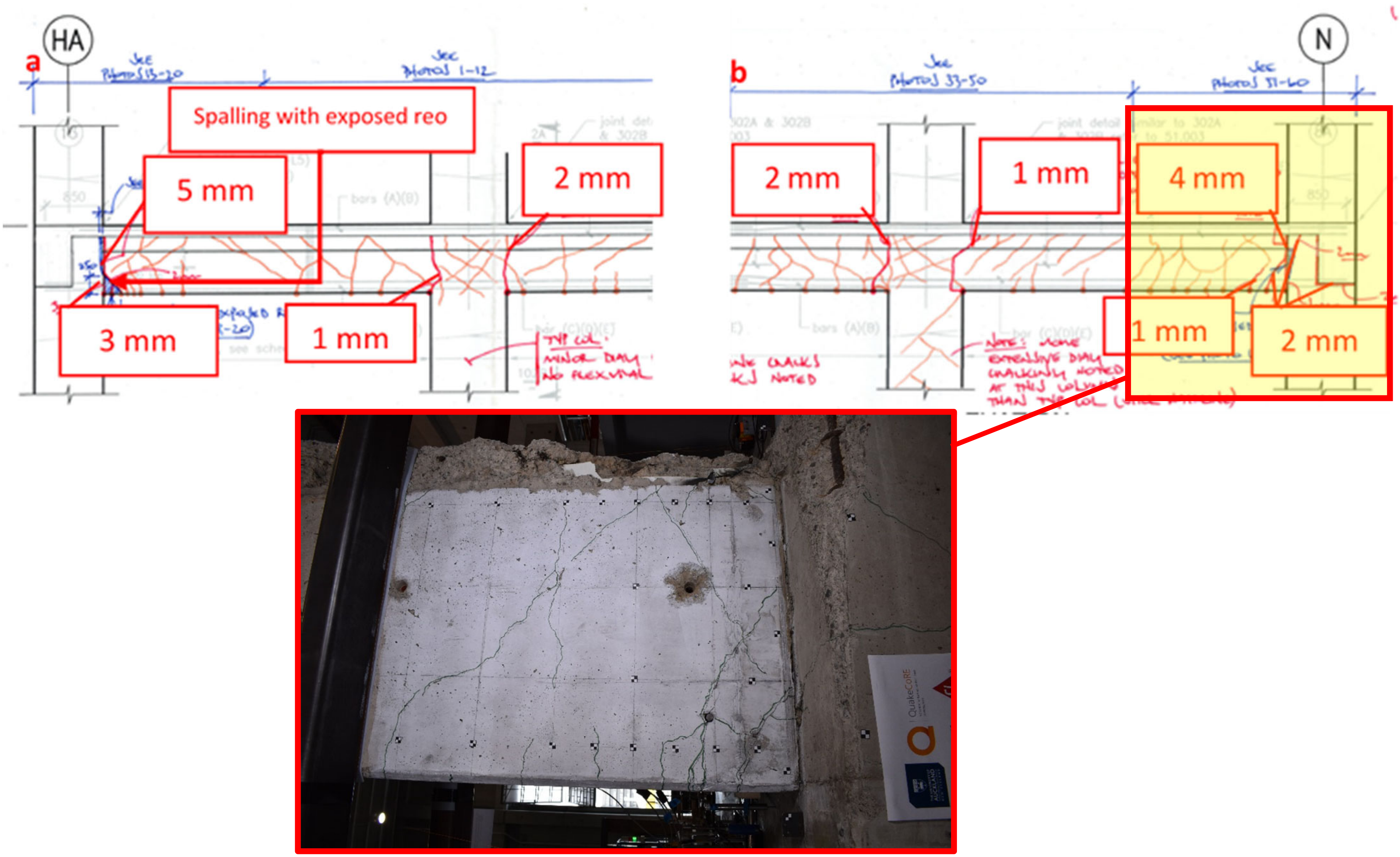




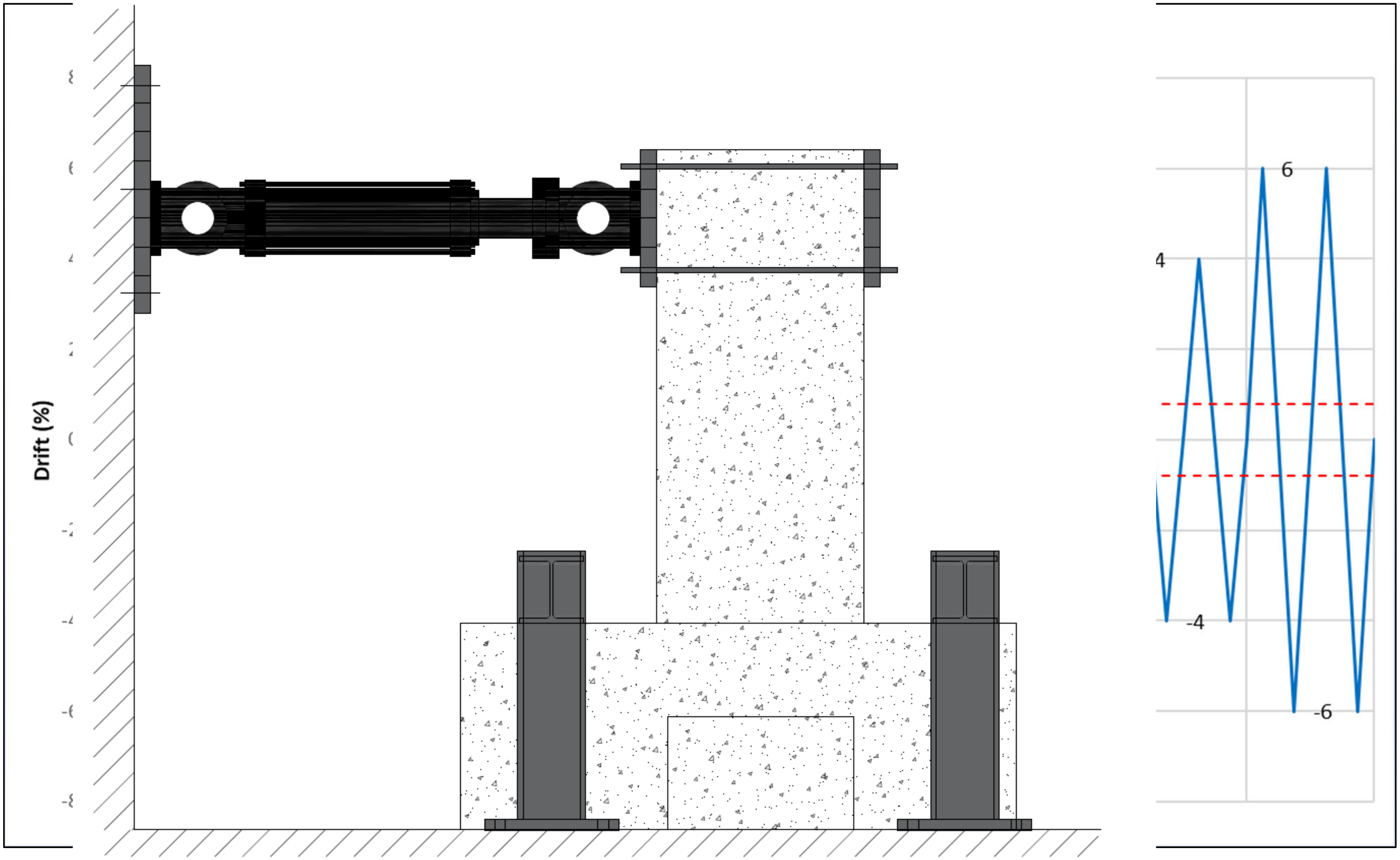
Beam rotation demands



Extracted beams



Test setup



Damage progression

1% Drift / Start

Kaikoura
Demand

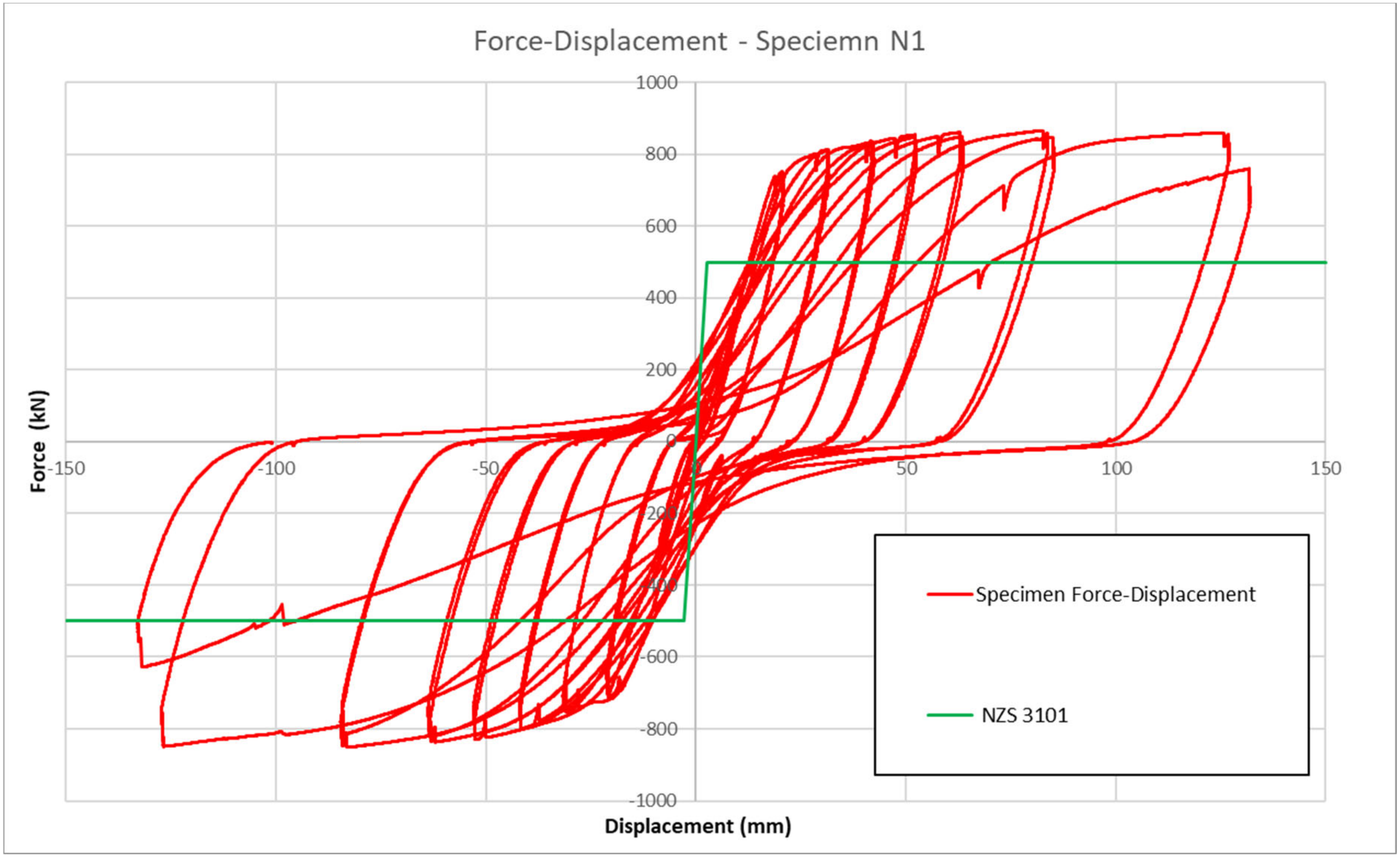
2.5% Drift

Max Crack Width
11 mm
(10 mm residual)

6% Drift

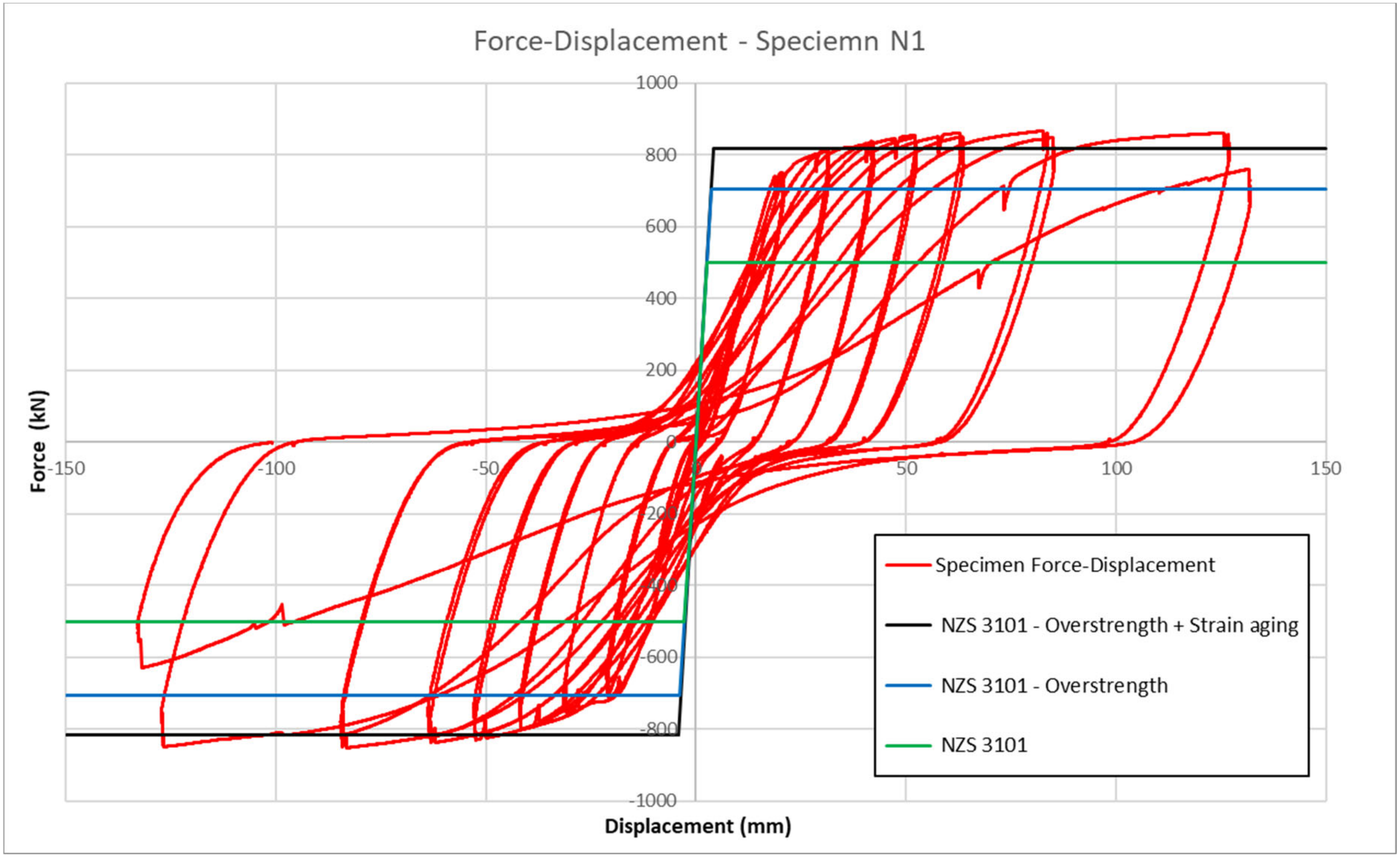
Failure following
opening of
stirrup hooks

Load displacement

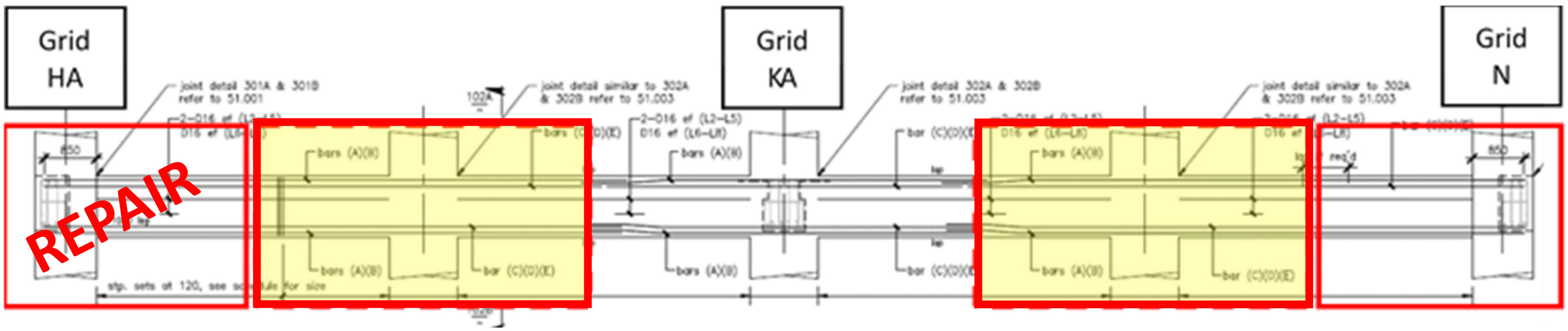


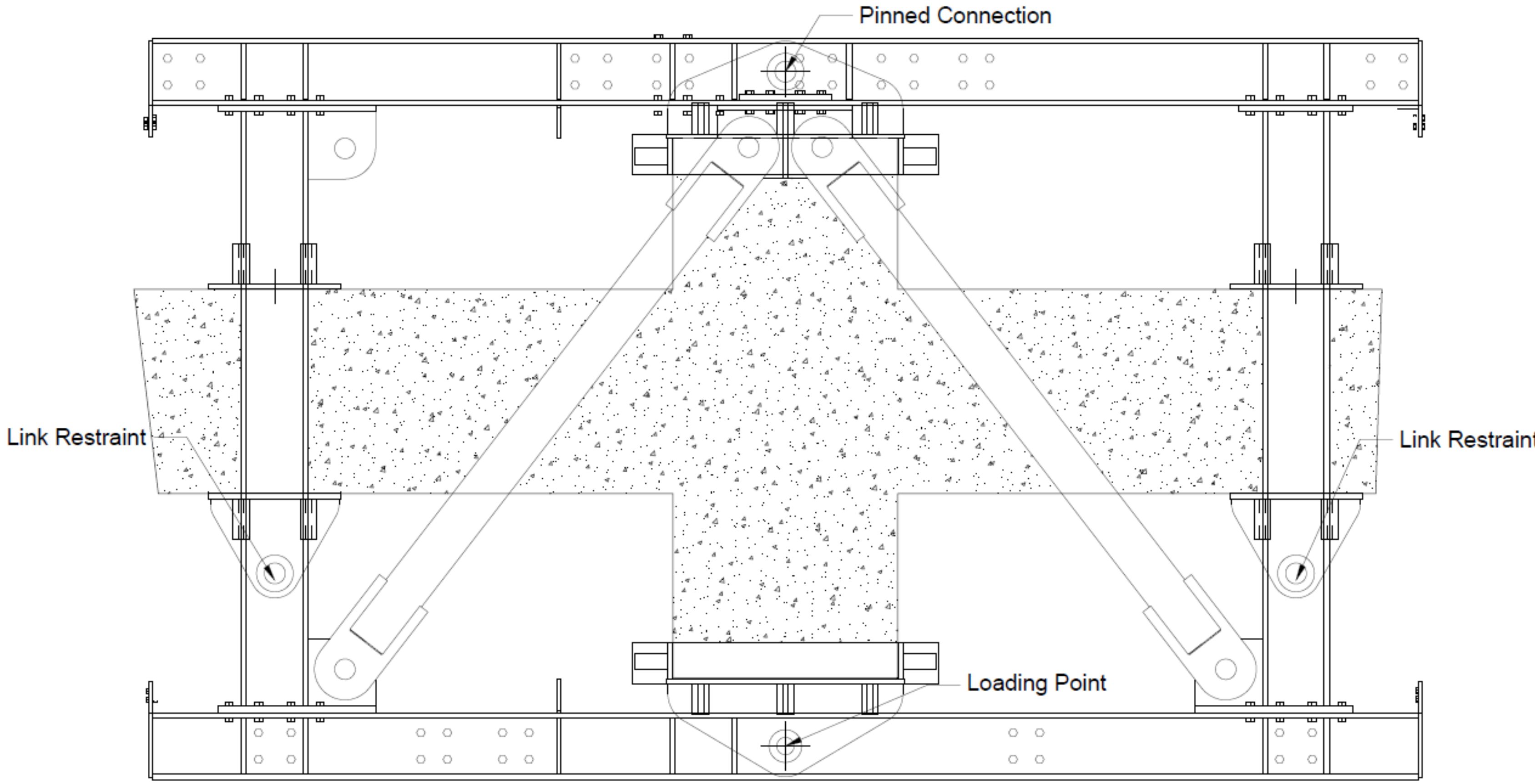
Load displacement

Load displacement

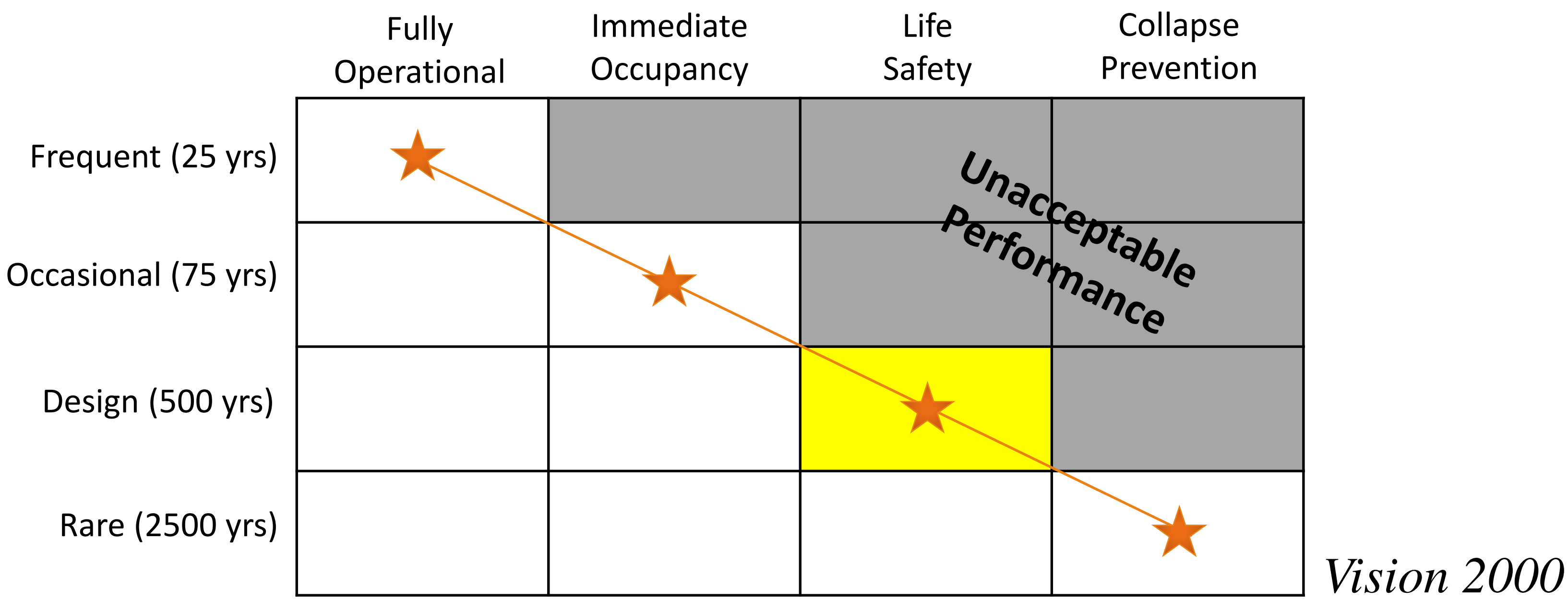


Future tests

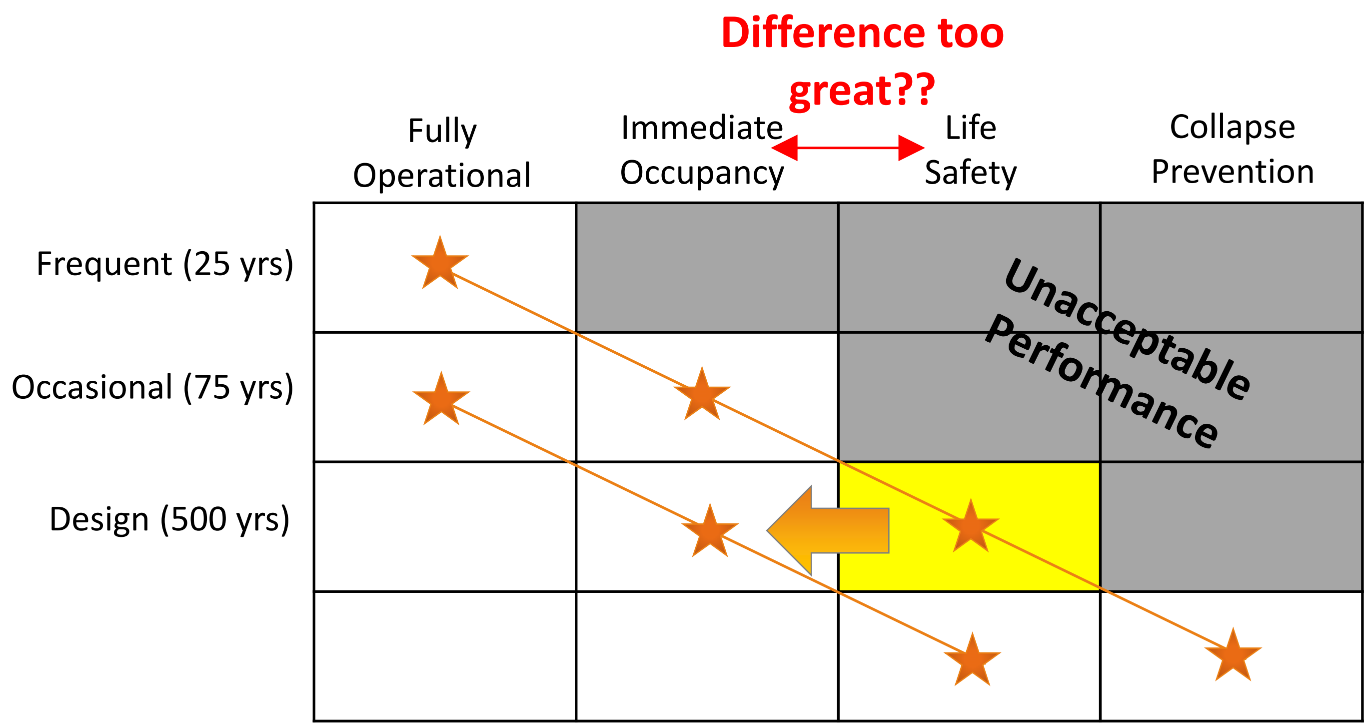




Performance objectives



Performance objectives



Immediate Occupancy	Most operations and functions can resume immediately. Structure safe for occupancy. Essential operations protected, non-essential operations disrupted. Repair required to restore some non-essential services. Damage is light.
Life Safe	Damage is moderate, but structure remains stable. Selected building systems, features, or contents may be protected from damage. Life safety is generally protected. Building may be evacuated following earthquake. Repair possible, but may be economically impractical.

Vision 2000

Performance objectives
- Repairability limit state?

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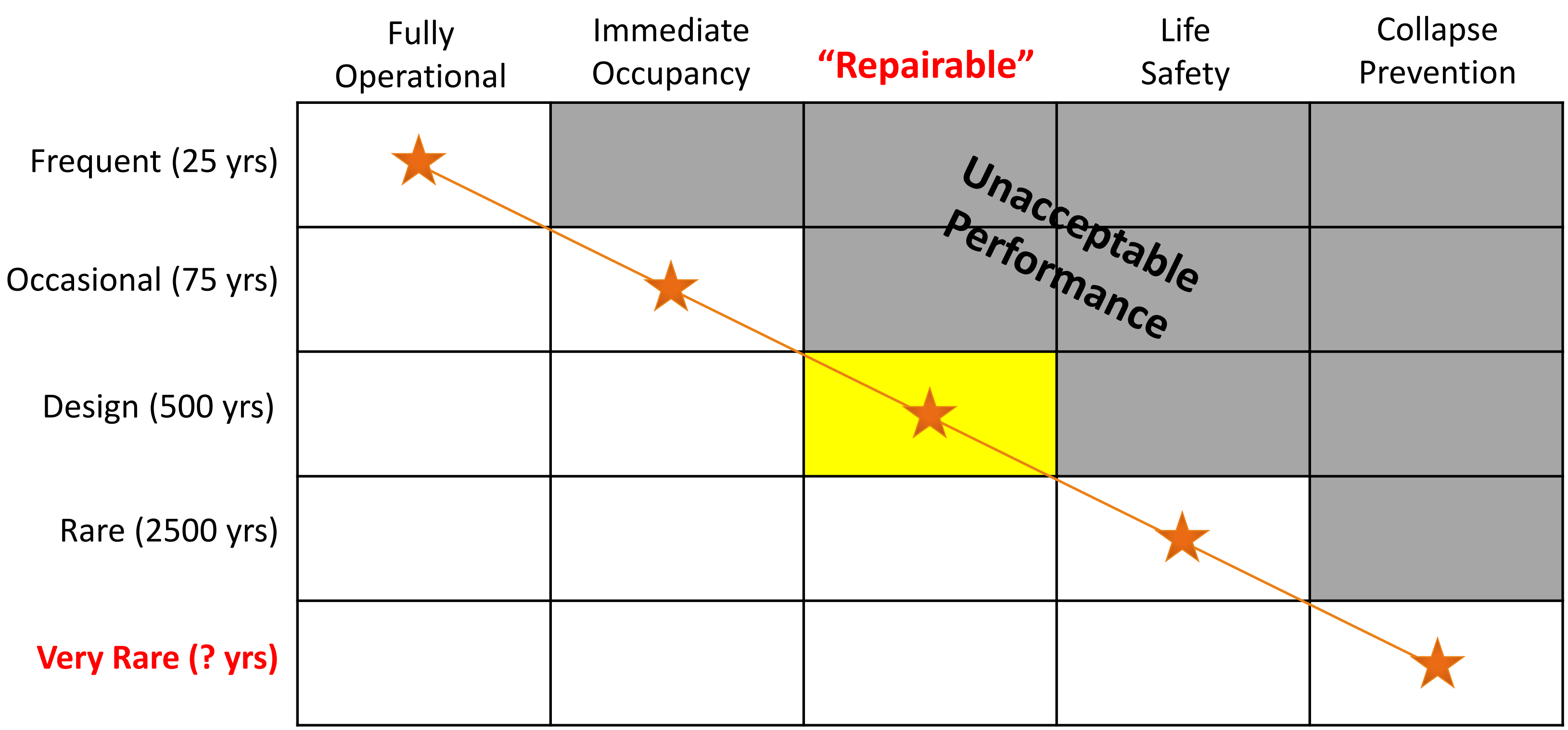

ATC-145 – Post-EQ repair and designing for repairability

Thank you to our funders!

MINISTRY OF BUSINESS, INNOVATION & EMPLOYMENT
HĪKINA WHAKATUTUKI

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NZ Centre for Earthquake Resilience
Te Hiranga Rū

THE UNIVERSITY OF AUCKLAND
Te Whare Wānanga o Tāmaki Makaurau
NEW ZEALAND

Sika®

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Questions?

UC University of Canterbury
The University of Auckland New Zealand
Resilient Organisations
GNS Science
Massey University
Victoria University of Wellington
The University of Waikato
BRANZ

Kaikoura Earthquake - Wellington

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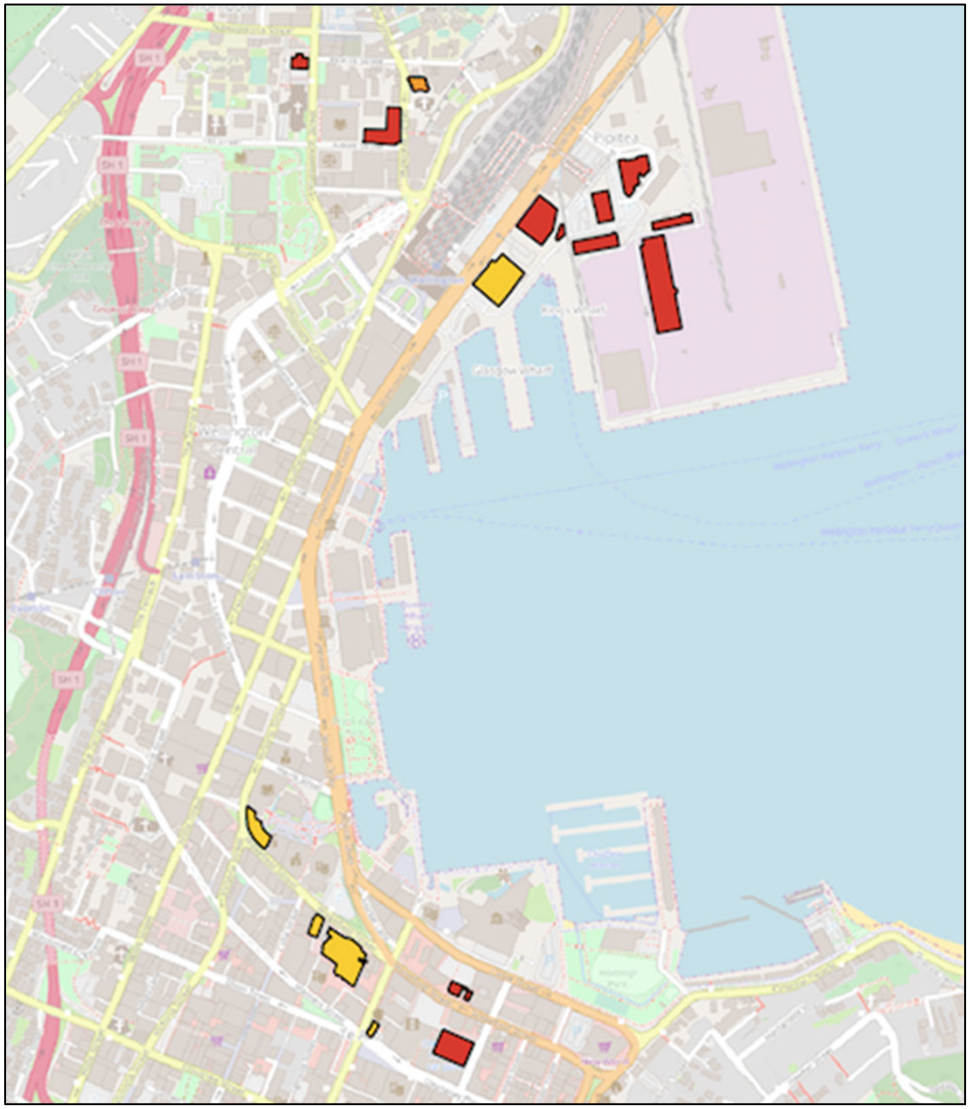
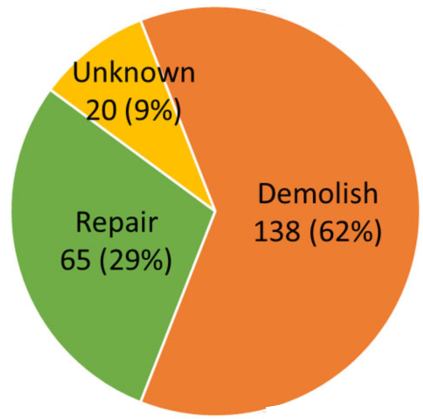


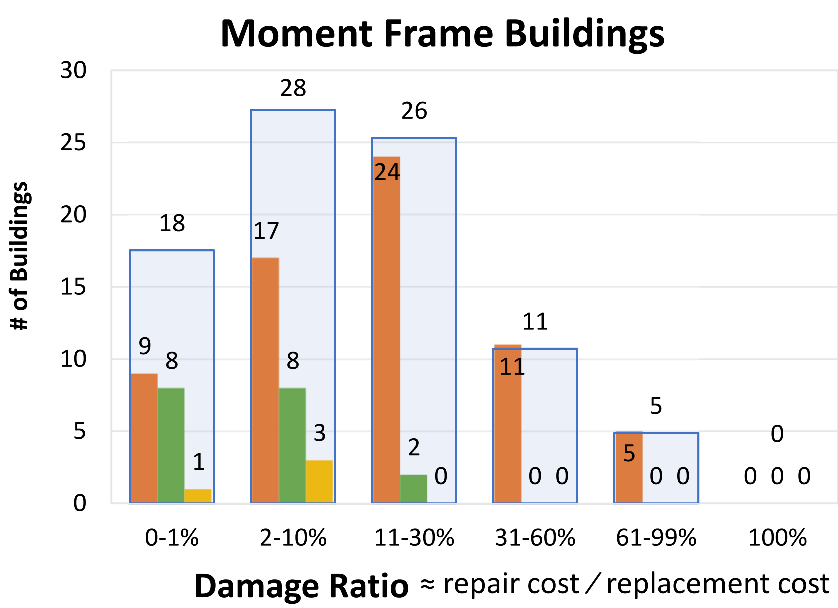
Demolished
Under demolition
Unoccupied

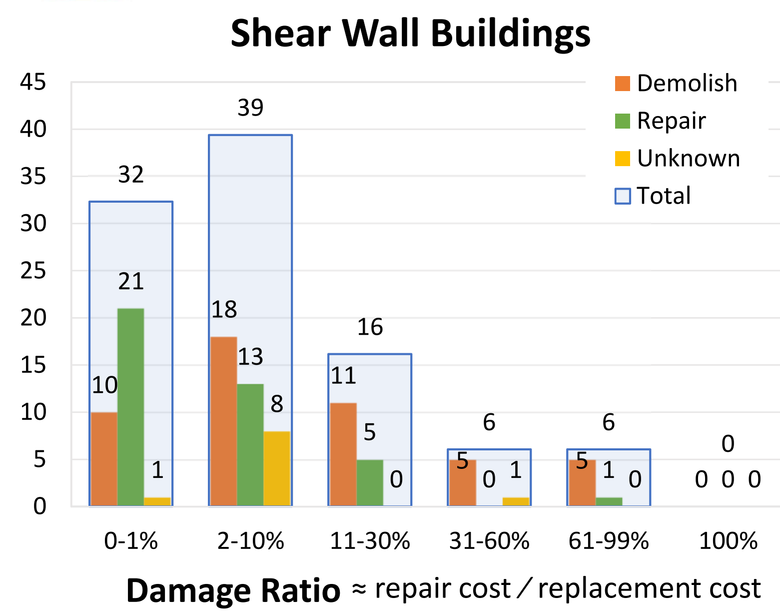
(WCC 2018)

Christchurch Damage Statistics

223 RC Buildings over
2 stories (Kim et al. 2015)

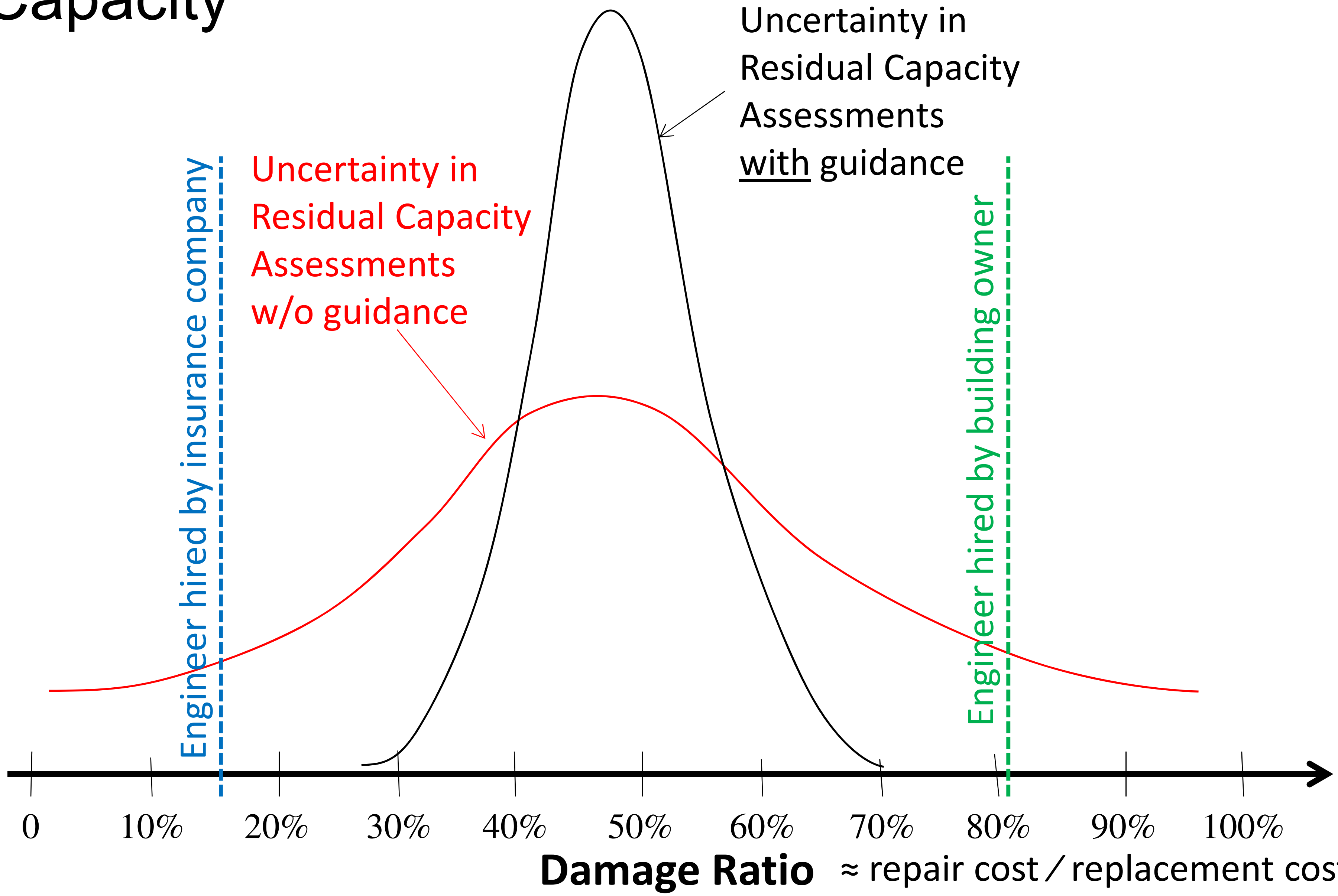






→ Significant number of RC buildings with relatively low damage were demolished.

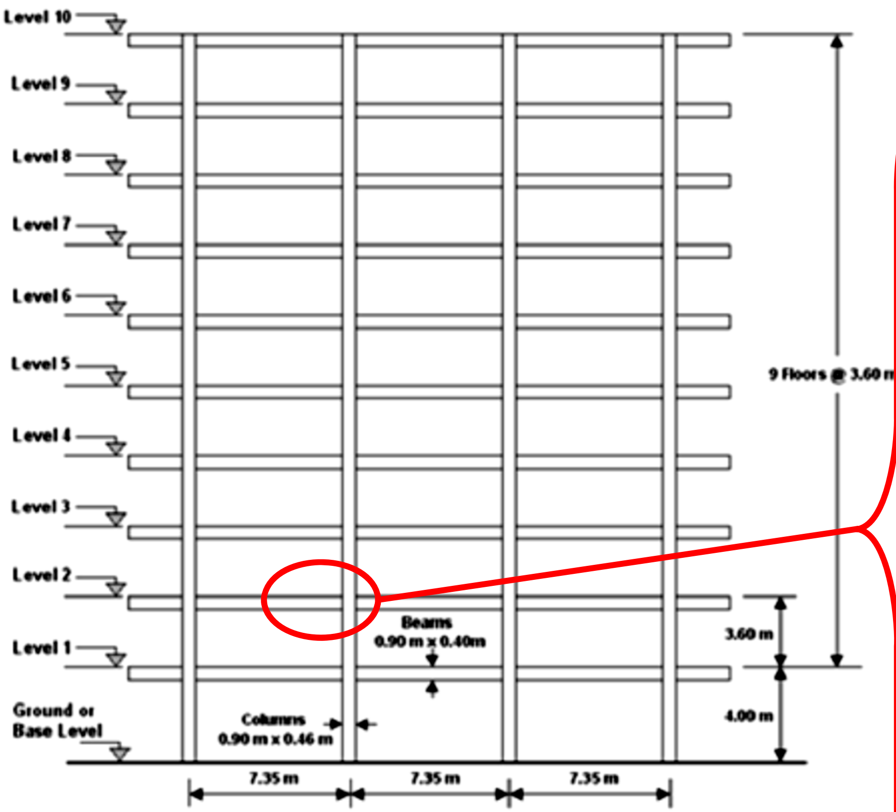
Impact of Uncertainty in Residual Capacity



Residual Capacity Beam Tests

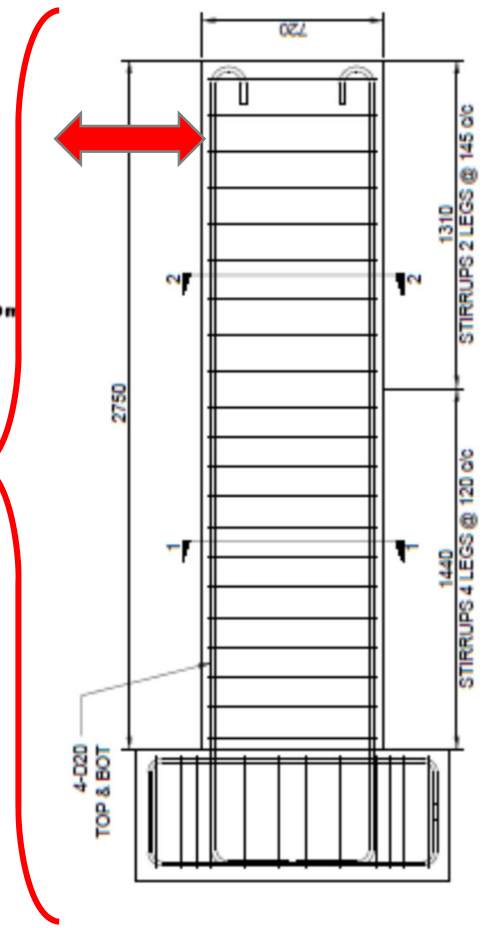
Kai Marder et al

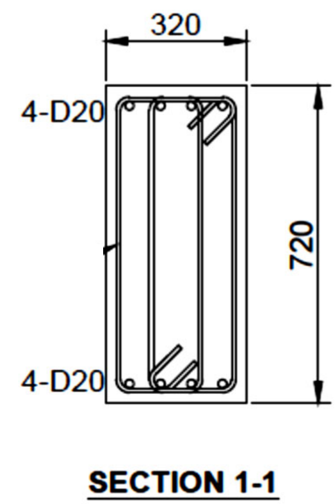
- *To be presented in next session*

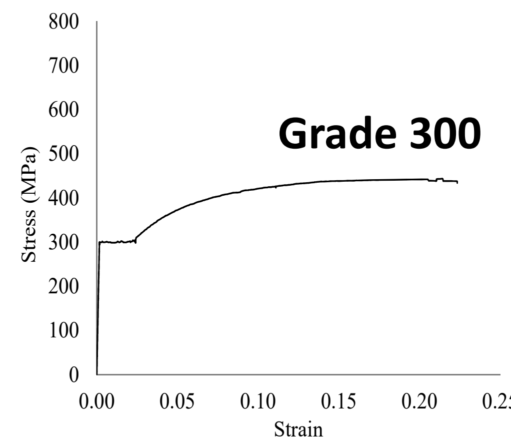


“Red Book” frame building

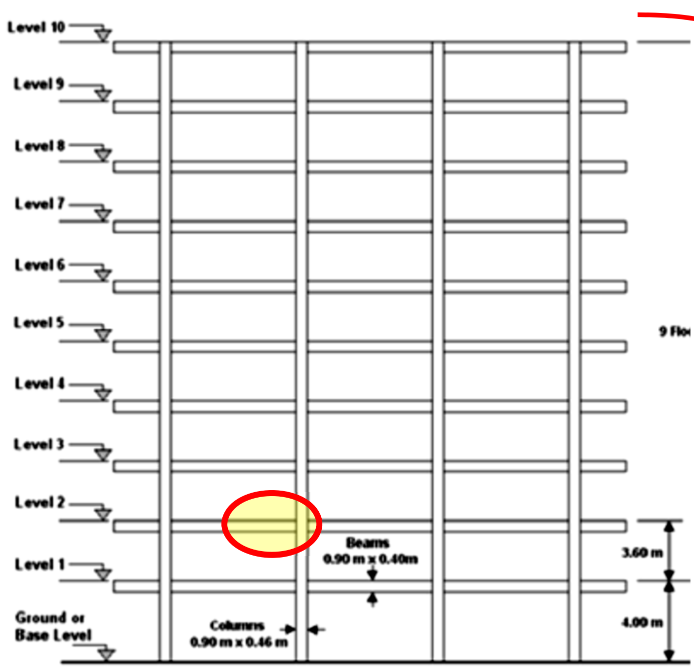
CCANZ, 2008

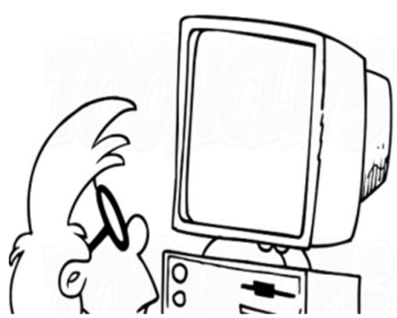


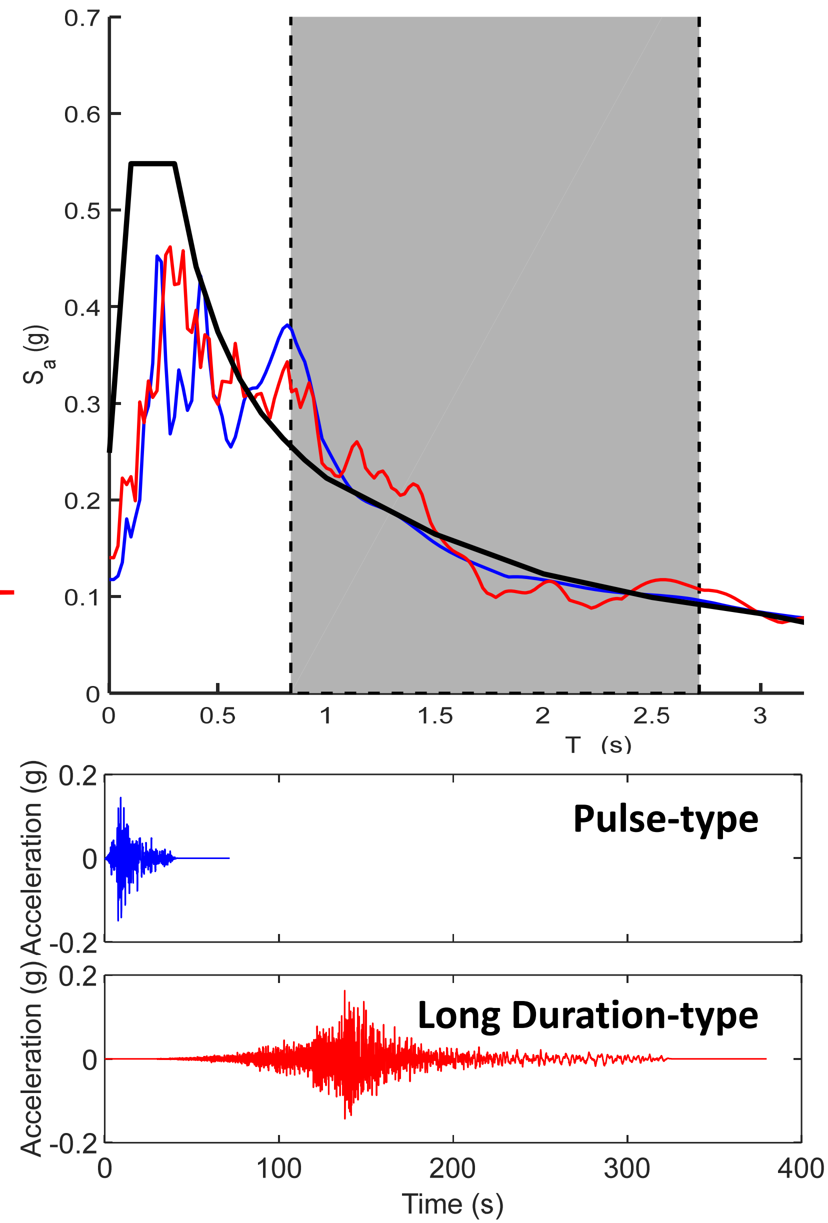




Loading protocol

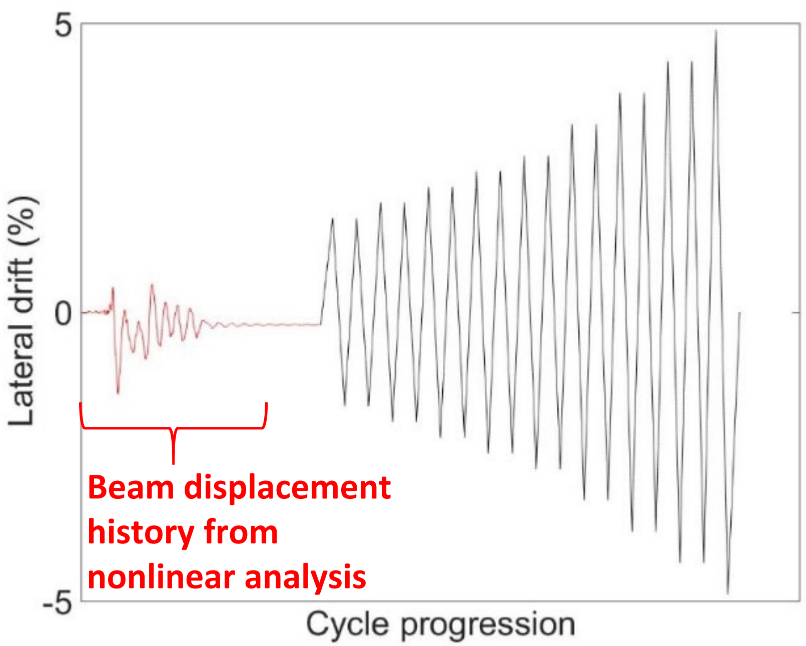




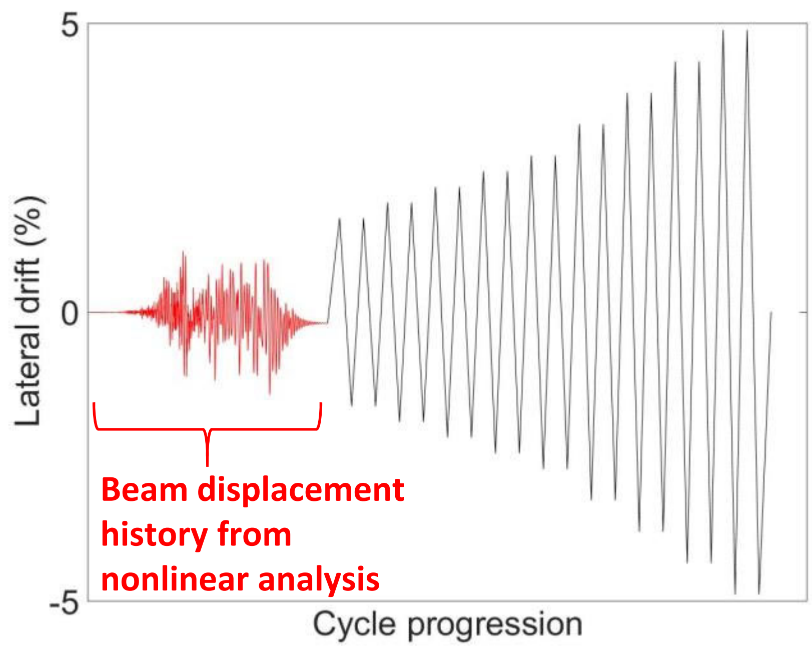


Loading protocol

Pulse-type



Long duration



16 specimens
+ monotonic

Variables:

- Earthquake input
- EQ drift demand
- Loading rate
- Axial restraint*
- Epoxy repair

* See Marder et al next session

CYC
CYC-DYN
CYC-ER
CYC-LER

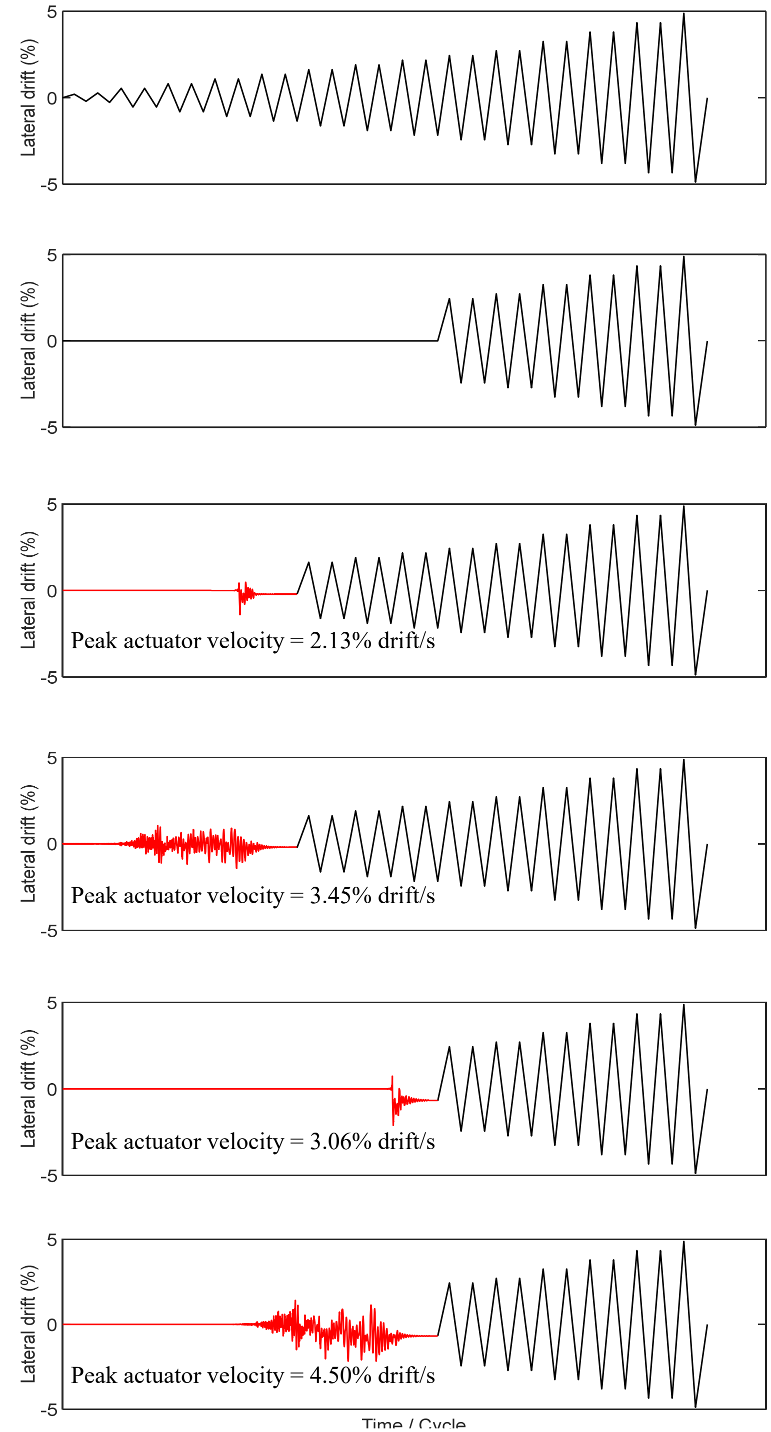
CYC-NOEQ

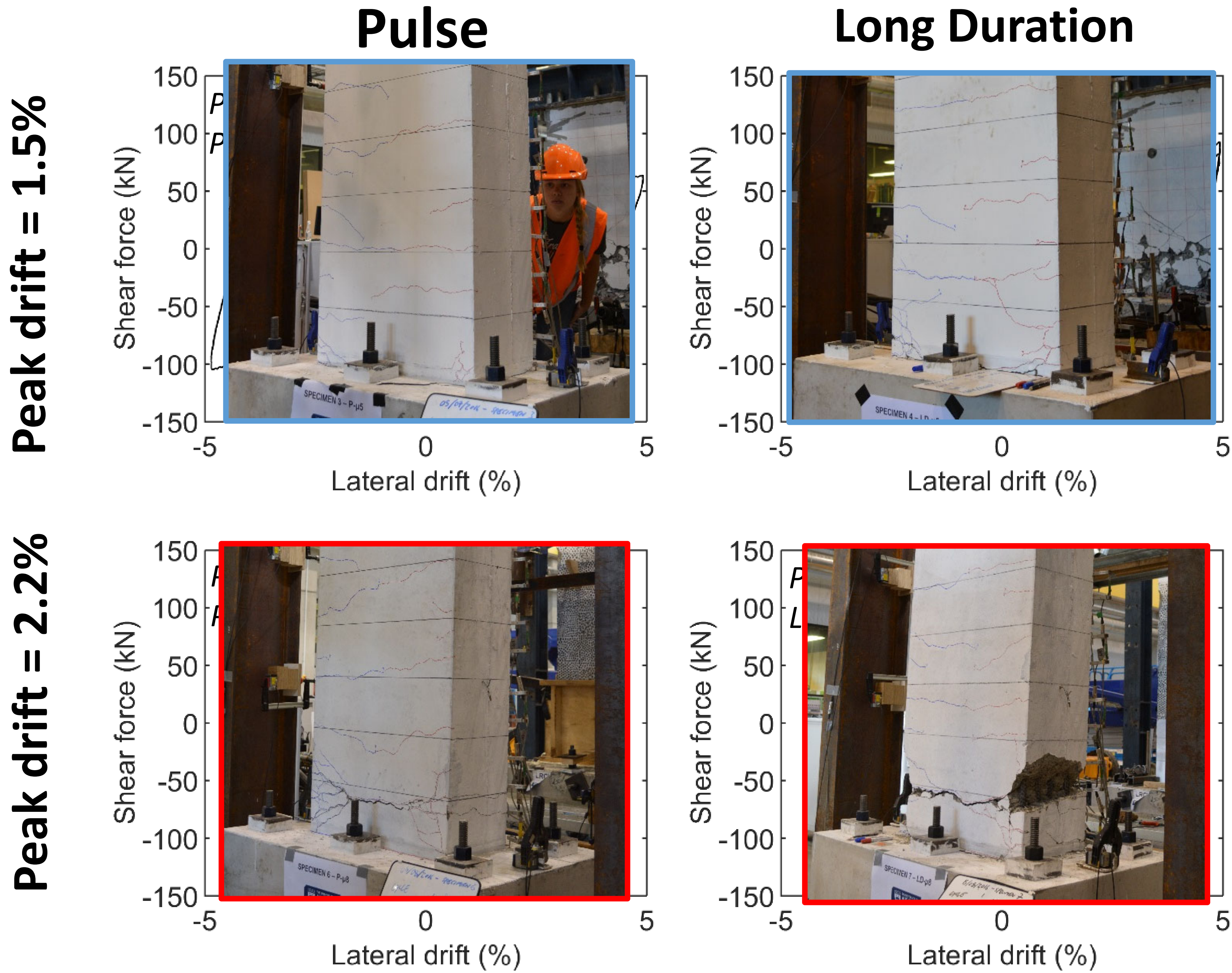
P-1

LD-1
LD-1-R

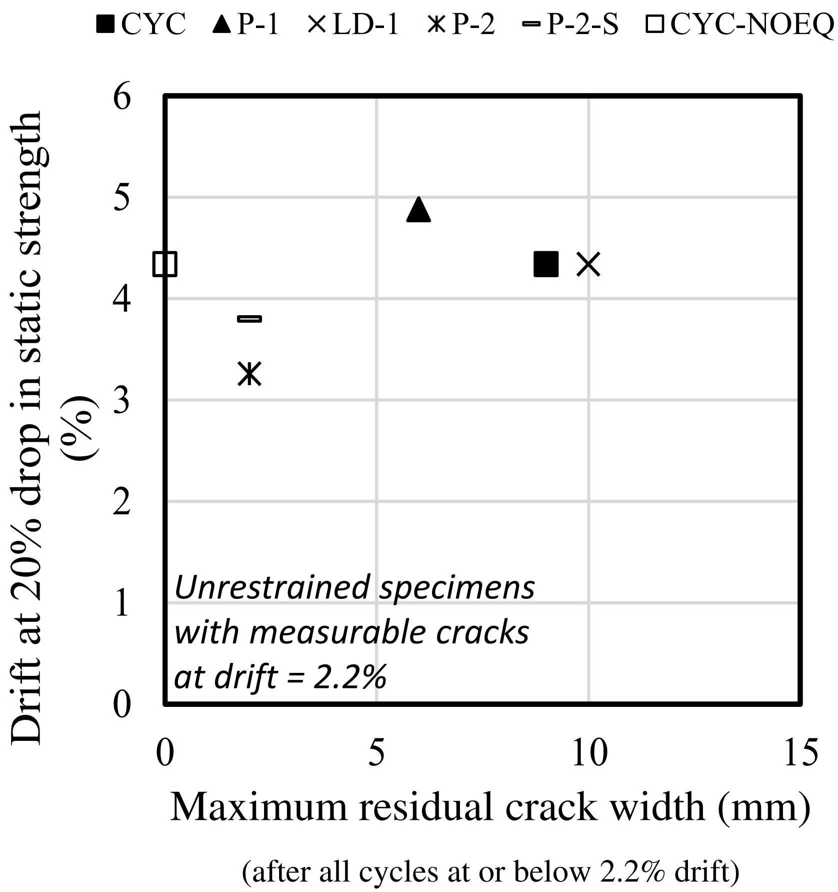
P-2
P-2-S

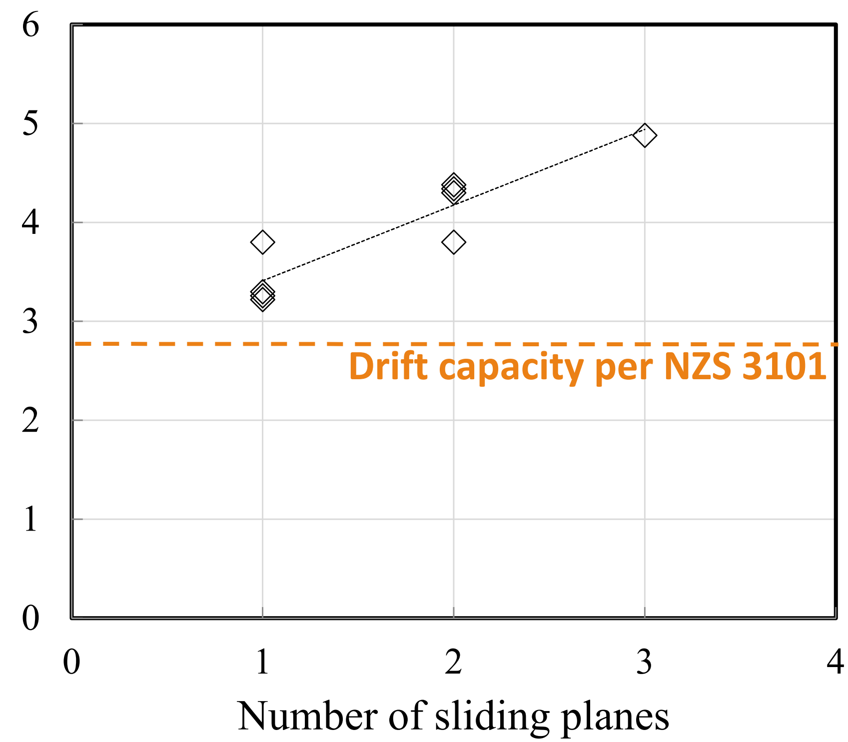
LD-2
LD-2-S
LD-2-R
LD-2-ER
LD-2-LER
LD-2-LER-R




Pulse
Long Duration
Peak drift = 1.5%
Peak drift = 2.2%
Shear force (kN)
150
100
50
0
-50
-100
-150
-5
0
5
Lateral drift (%)
SPECIMEN 3 – P-μ5
SPECIMEN 6 – P-μ8

Damage → Drift capacity?



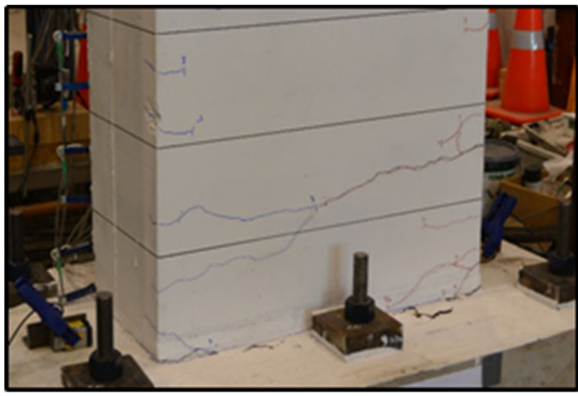


→ No relationship between crack widths and drift capacity.

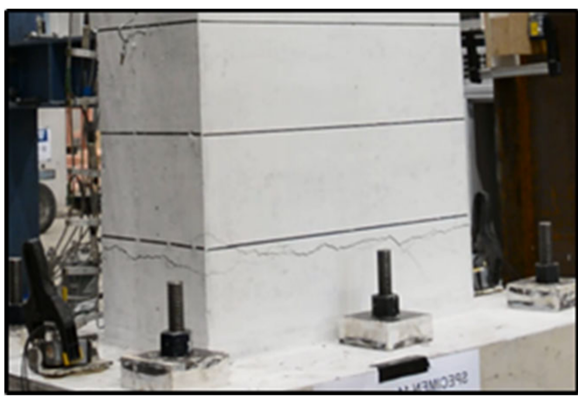
→ Drift capacity correlated with number of sliding planes.

Drift Capacity

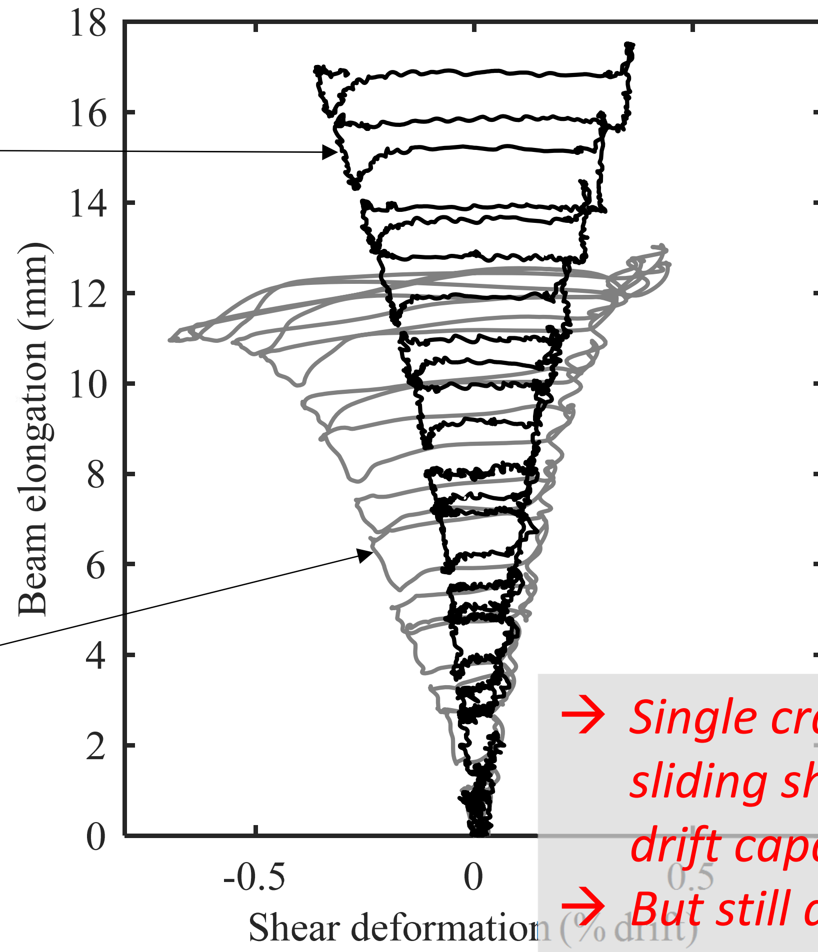
- limited by sliding shear



CYC (multiple sliding planes)



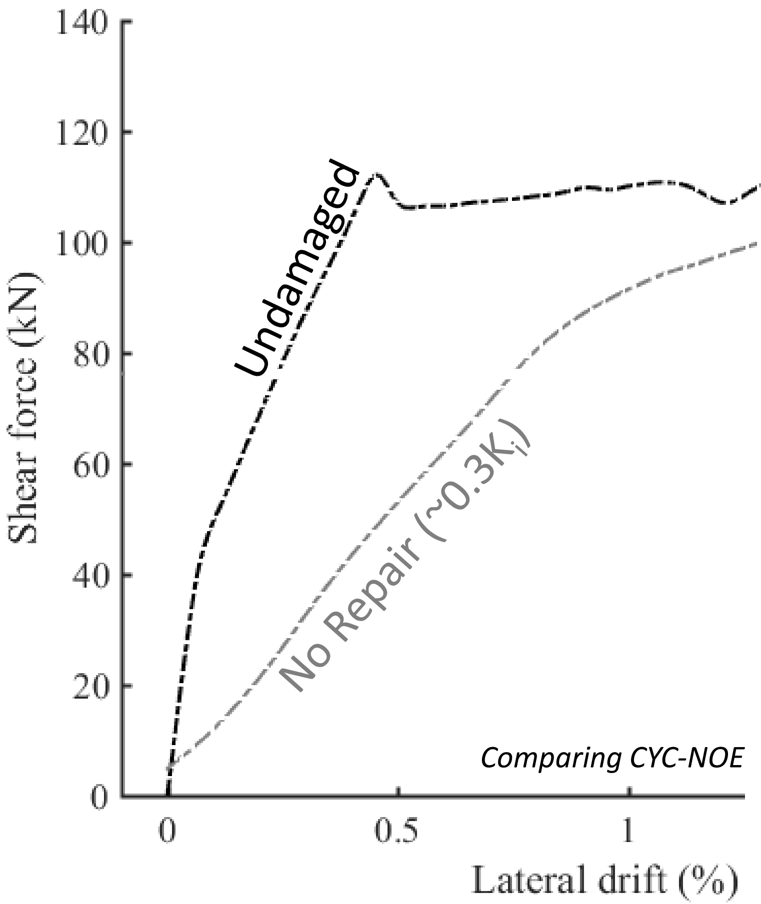
CYC-DYN (single sliding plane)

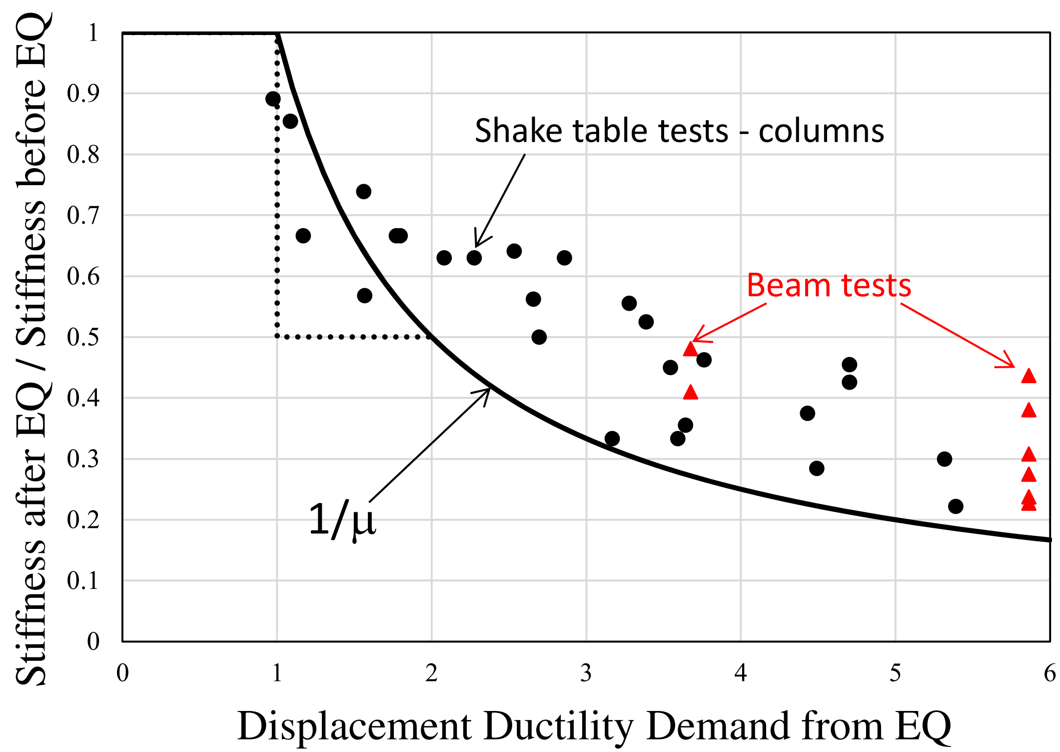


→ *Single crack w = 2-3mm, sliding shear will limit drift capacity.*

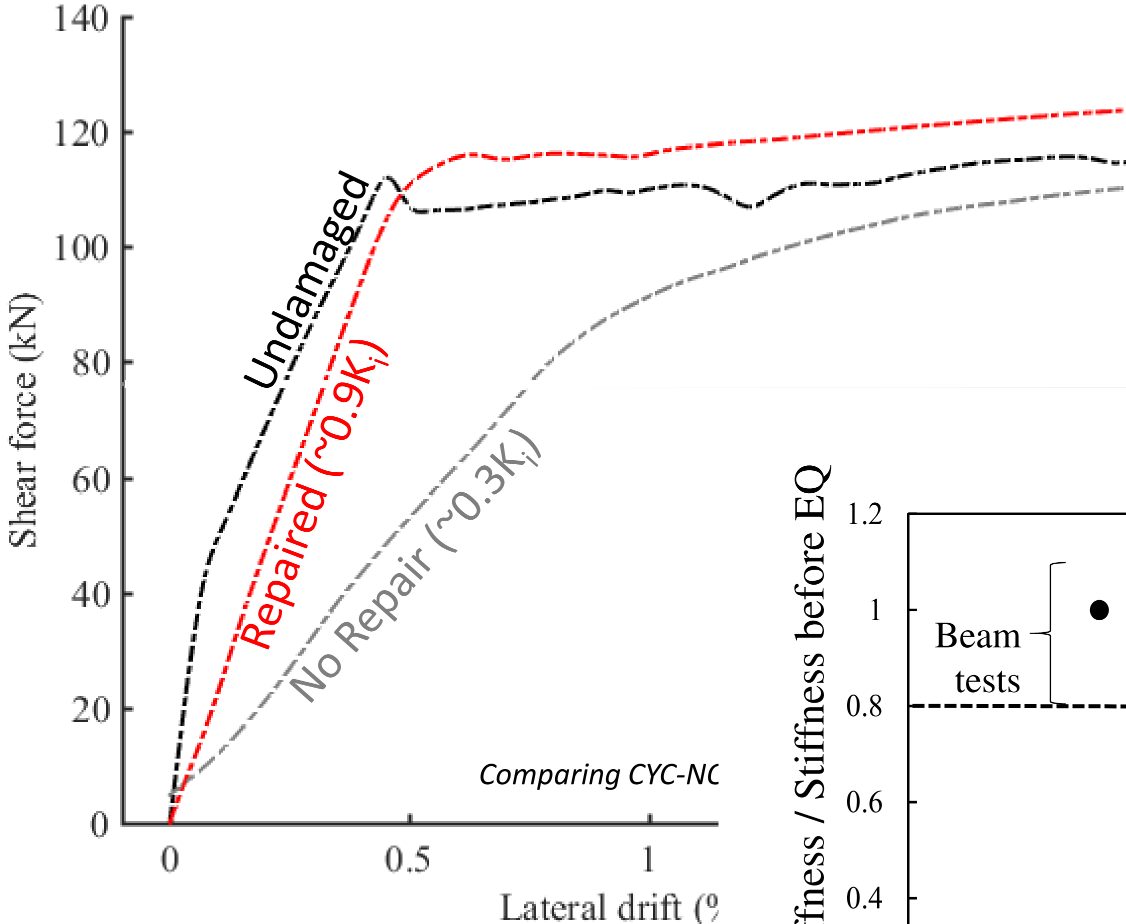
→ *But still above NZS 3101 drift capacity.*

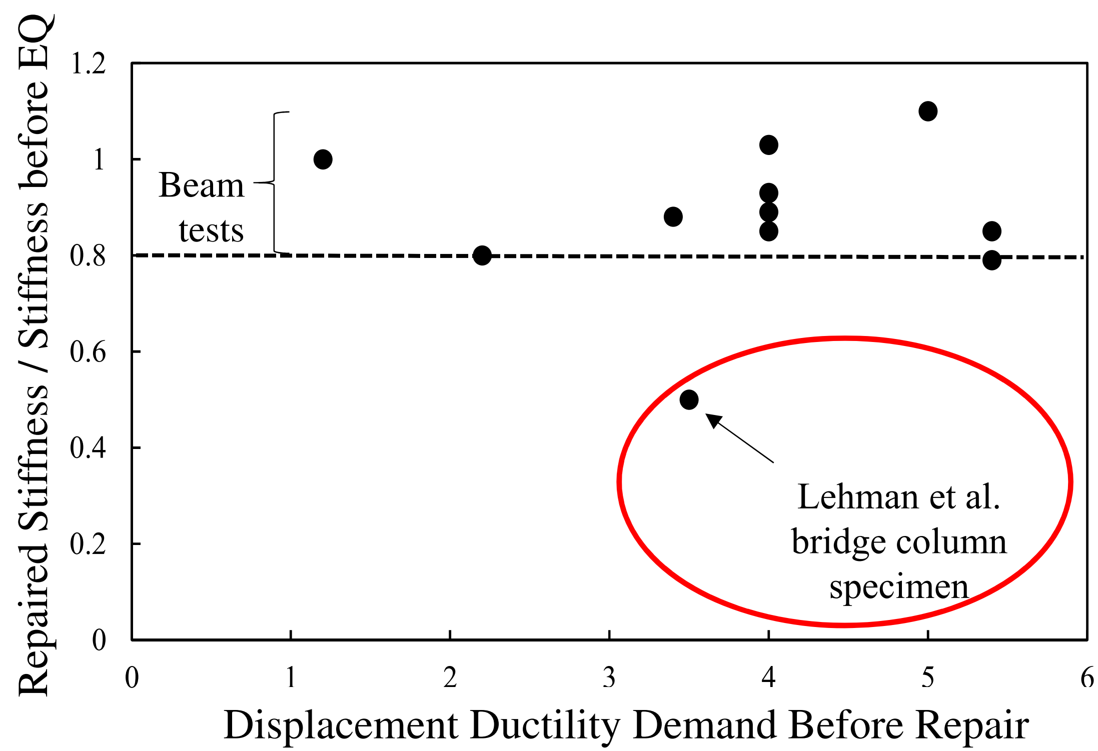
Stiffness - unrepaired





Stiffness – epoxy repair





Capacity - epoxy repair

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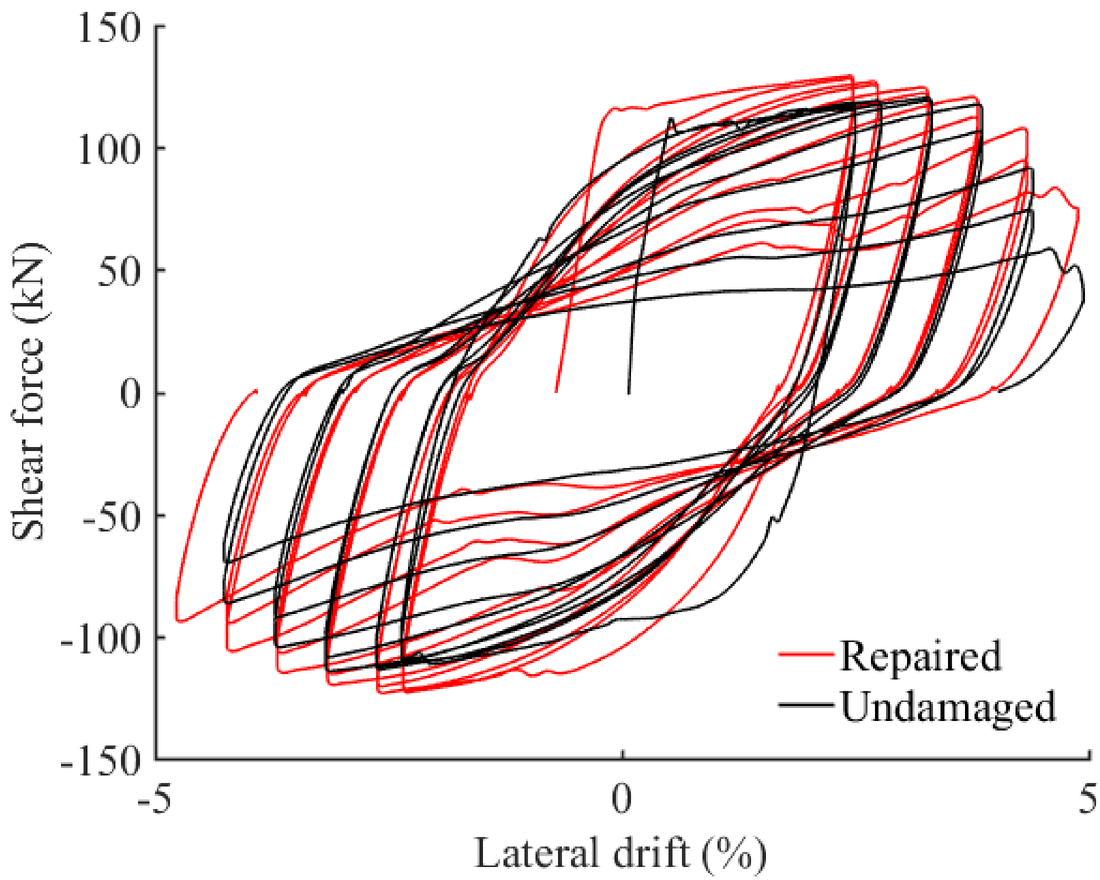
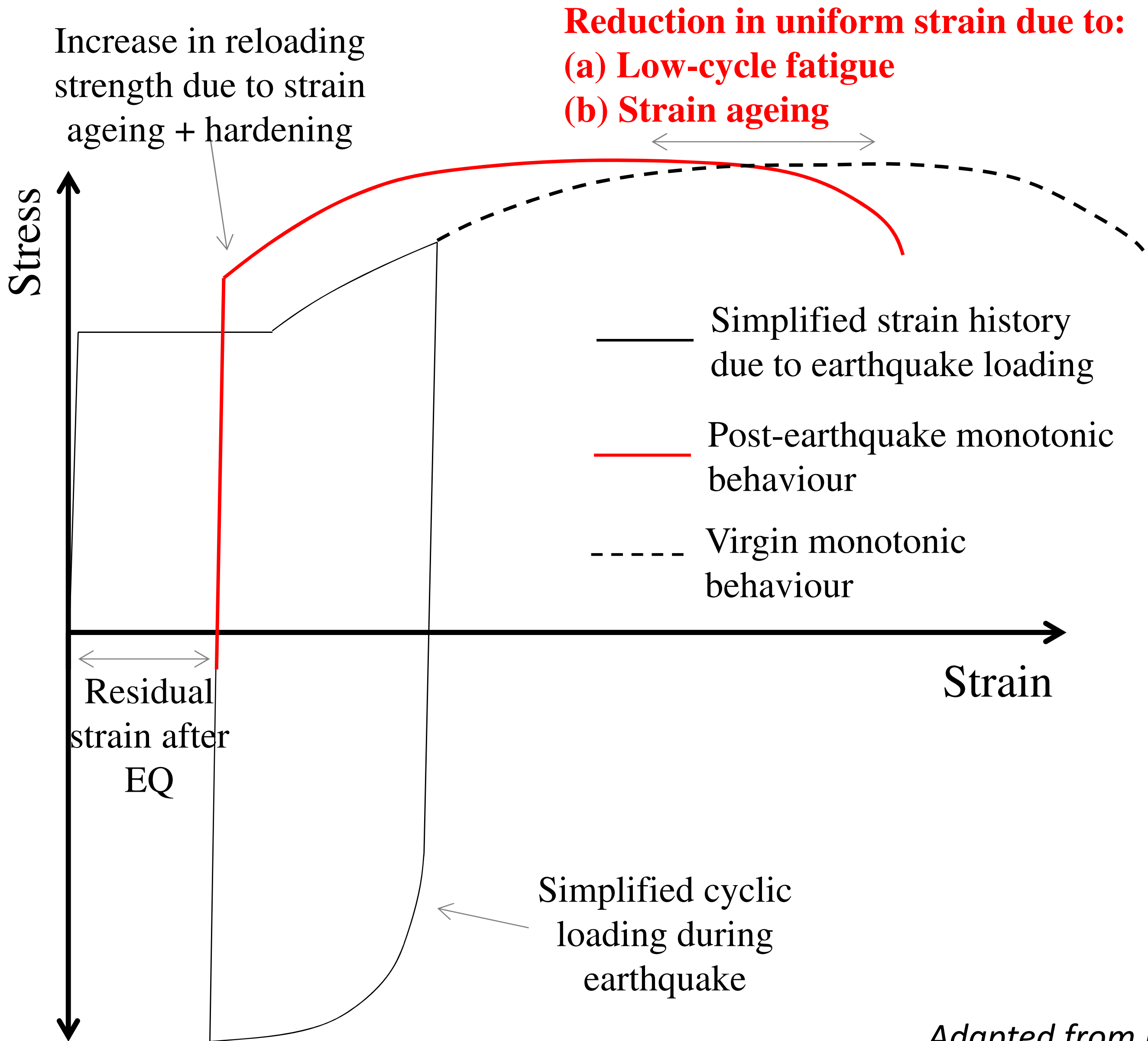


Strength: Repaired > Undamaged

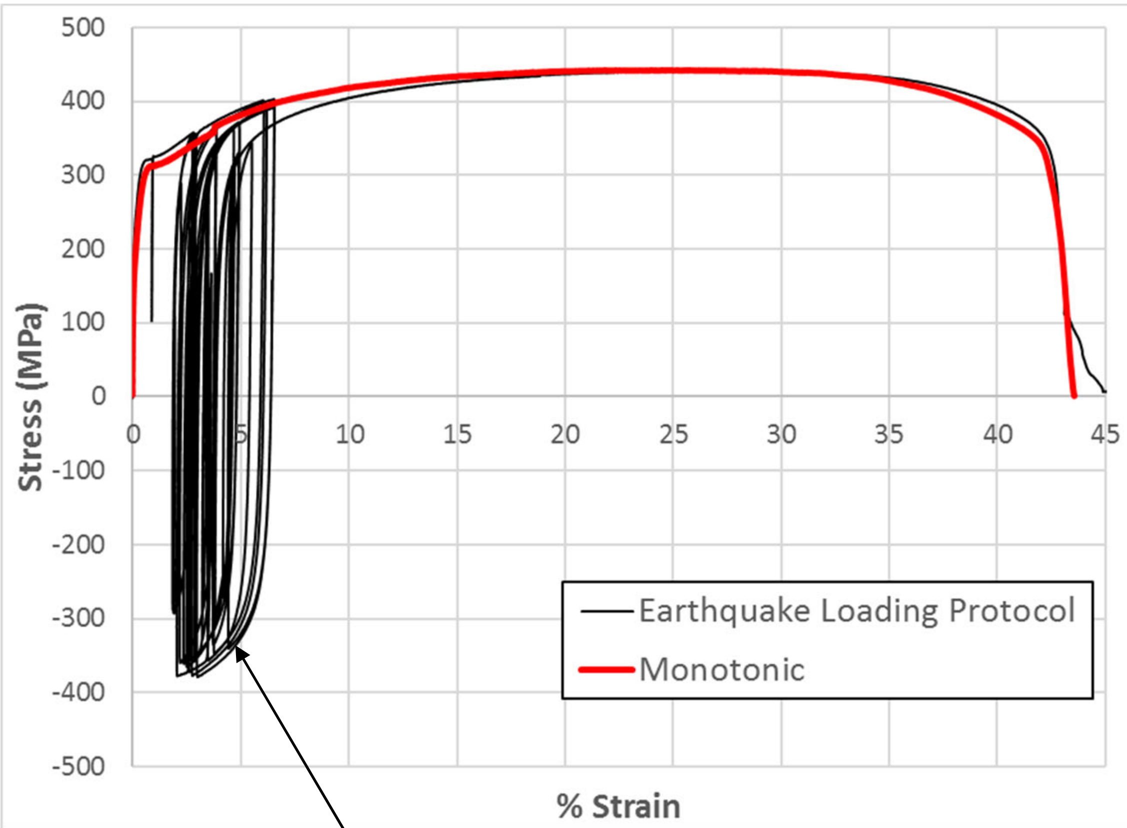
Drift capacity: Repaired ~ Undamaged

Reduction in steel strain capacity



Adapted from Pussegoda (1978)

Reduction in steel strain capacity
-Low-cycle fatigue



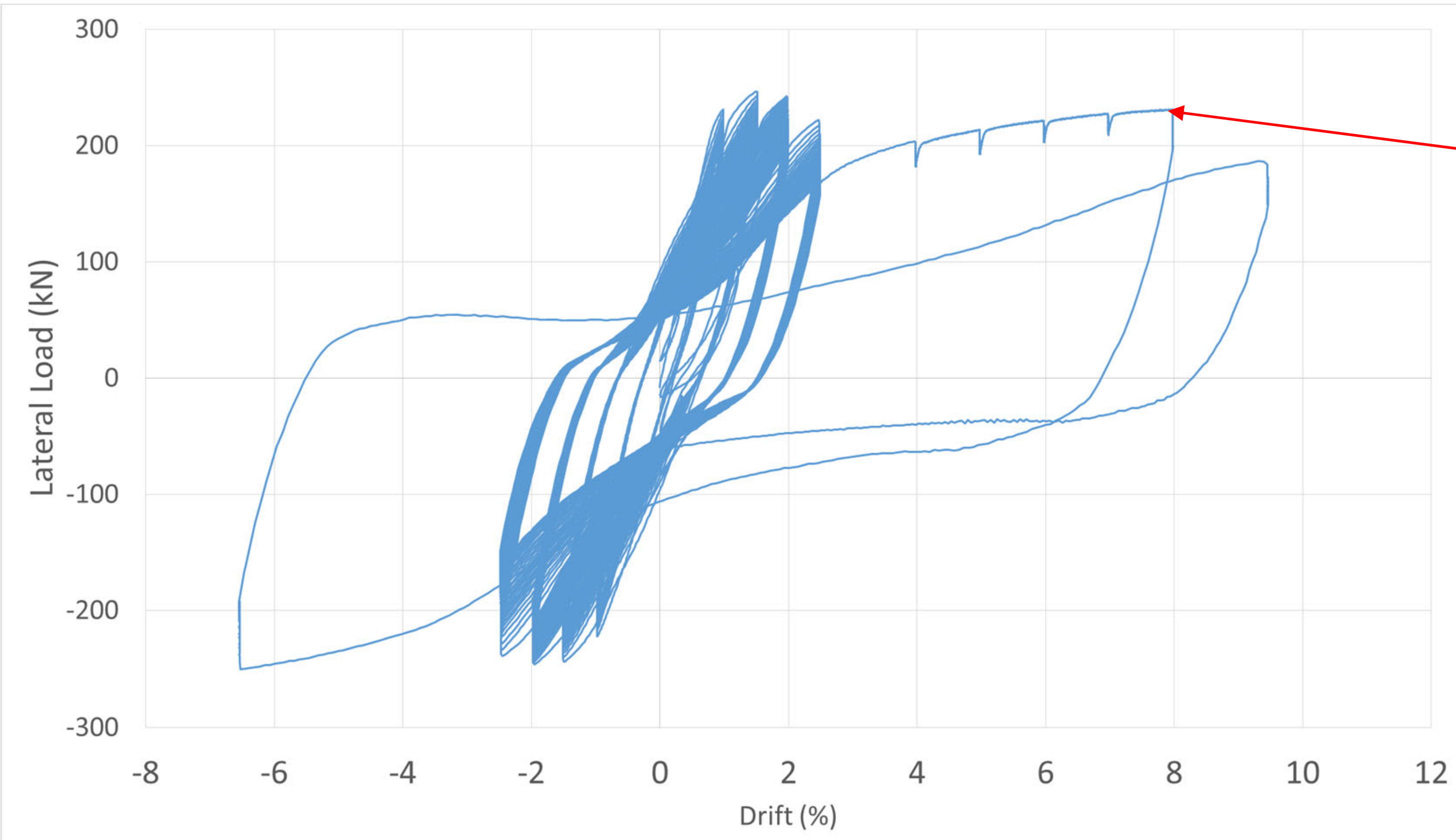
Strain demands from bar from long-duration beam test scaled to 6% max strain

Marder (2018)

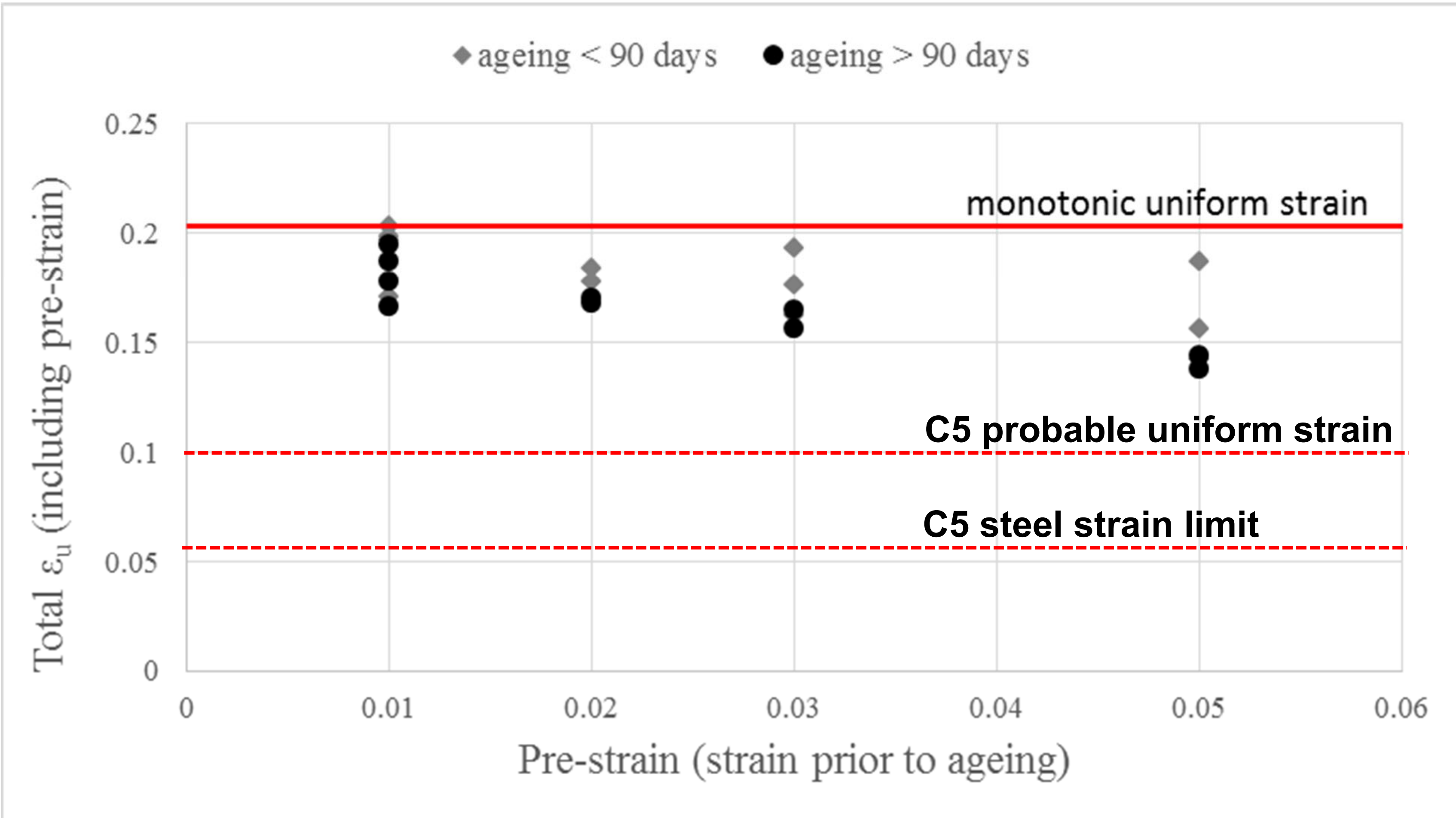
Reduction in steel strain capacity
-Low-cycle fatigue (beam test)

Tayo Opabola et al

- *To be presented in next session*

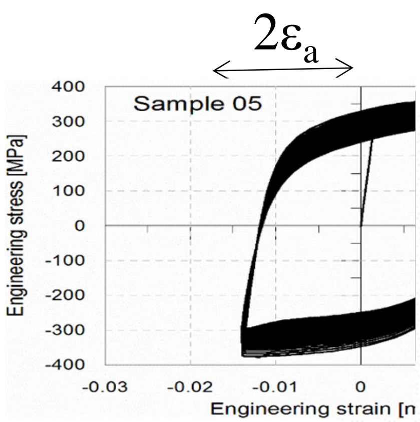


Reduction in steel strain capacity
- *Strain ageing*

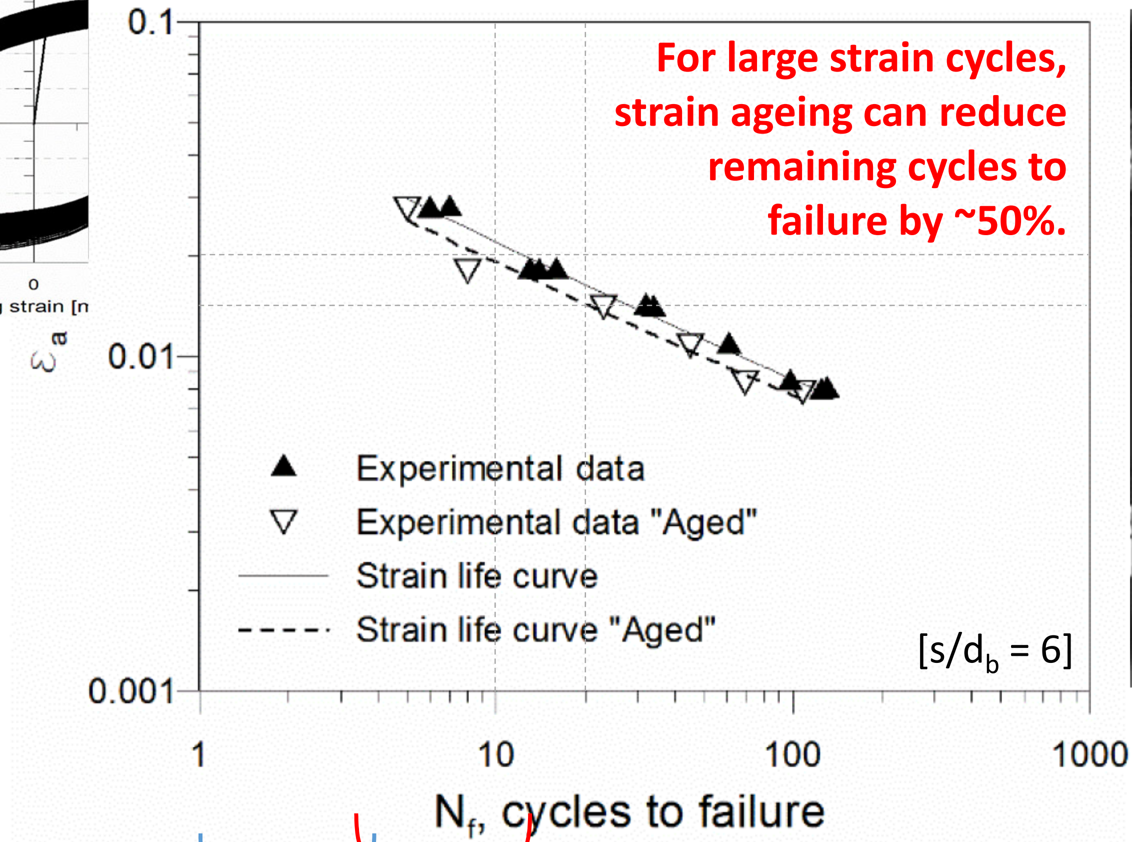


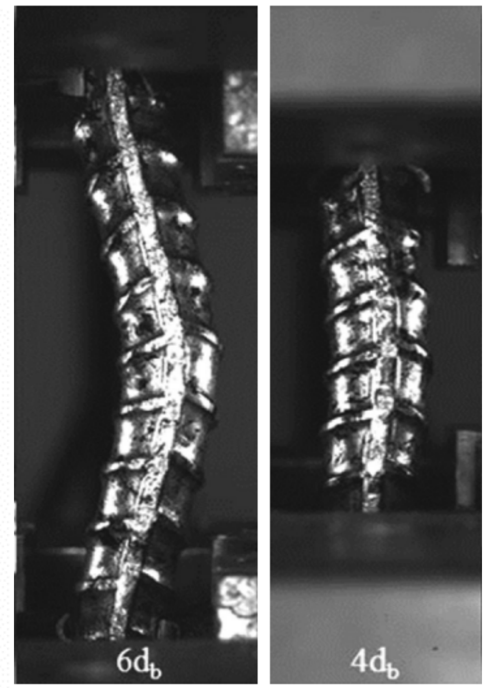
Data: Restrepo-Posada et al (1994) and Loporcaro et al (2016)

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



Loporcaro (2017)





Ghannoum and Slavin (2016)

Typ. pulse GM

Typ. subduction or other long duration GM??

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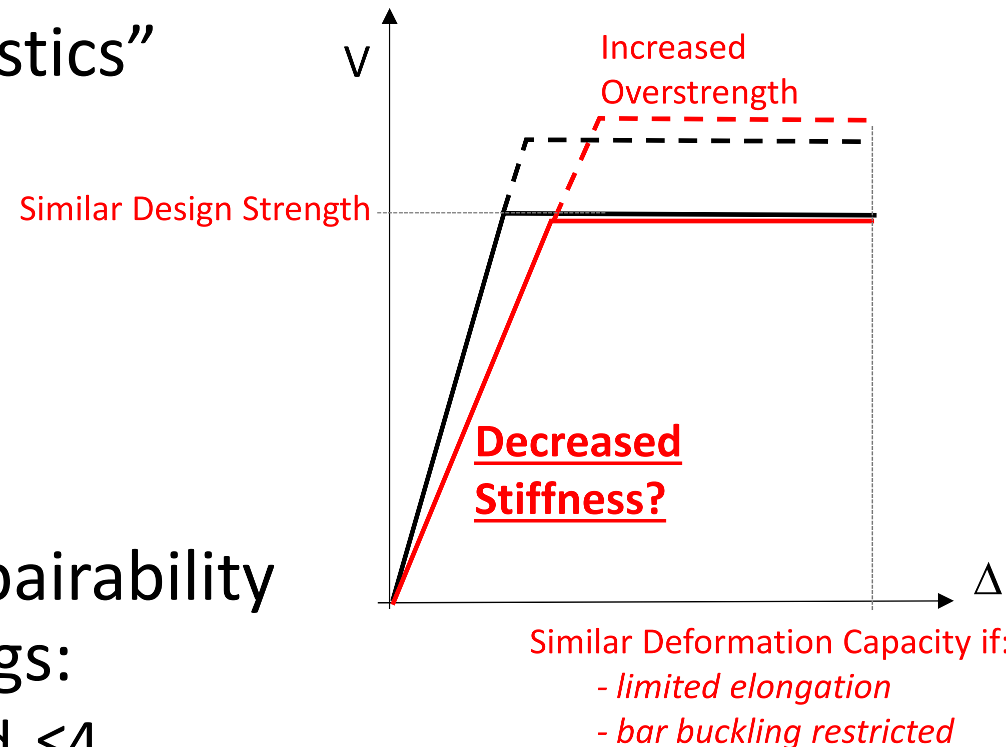
Repairability Limit State

Definition:

- Maintain "original design performance characteristics" after repair.
  - ➢Strength
  - ➢Drift capacity
  - ➢Stiffness

Epoxy repair:



- Simple steps toward repairability in conventional buildings:
  - ➢Restrict bar buckling: $s/d_b \leq 4$
  - ➢Reduce ductility/drift → lower elongation and floor damage
  - ➢Use CIP floors

Repairability Limit State
- Future challenges

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- Component
  - Cycles and effective strain levels for different earthquake (sequences) and structures.
  - Low-cycle fatigue + strain ageing tests for $s/d_b = 4$
  - Stiffness of repaired columns and walls
  - Different repair methodologies

- Whole-of-building performance
  - Interaction and deformation compatibility with floors
  - What systems are more or less repairable?
  - Much more…


> 60% of Multi-story Reinforced Concrete Buildings Demolished
Photo courtesy of W. Kam