QuakeCoRE
NZ Centre for Earthquake Resilience

# Residual capacity of earthquake-damaged concrete buildings

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**University of Auckland, New Zealand**
**QuakeCoRE Director**

2-3 Oct 2017
Anil K Chopra Symposium

UC University of Canterbury
The University of Auckland New Zealand
Resilient Organisations
GNS Science
Massey University
Te Whare Wānanga o te Ūpoko o te Ika a Māui Victoria University of Wellington
The University of Waikato
BRANZ

# Prof Anil Chopra

– *making challenging topics seem easy*

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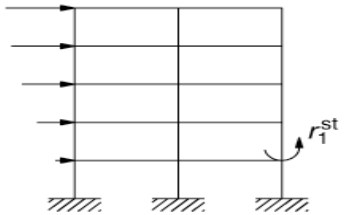
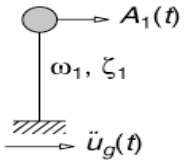
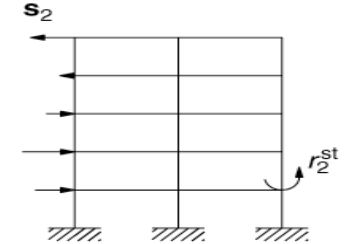
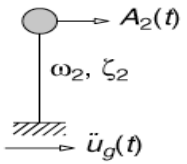
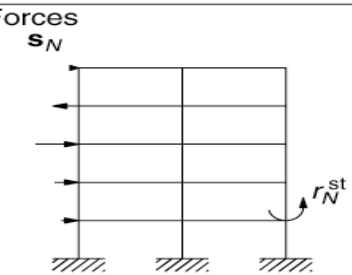
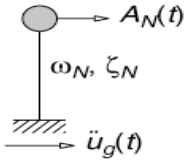
| Mode | Static Analysis of Structure | Dynamic Analysis of SDF System | Modal Contribution to Dynamic Response |
|---|---|---|---|
| 1 | Forces $\mathbf{s}_1$   |   | $r_1(t) = r_1^{st} A_1(t)$ |
| 2 | Forces $\mathbf{s}_2$   |   | $r_2(t) = r_2^{st} A_2(t)$ |
| • | • • | • • | • • |
| $N$ | Forces $\mathbf{s}_N$   |   | $r_N(t) = r_N^{st} A_N(t)$ |
| Total response | | | $r(t) = \sum_{n=1}^{N} r_n(t)$ |

**2010-11 Christchurch NZ:**
**Losses $40B NZD = 20% GDP**

***> 60% of Multi-story Reinforced Concrete Buildings Demolished***

*Photo courtesy of W. Kam*

# Christchurch Damage Statistics

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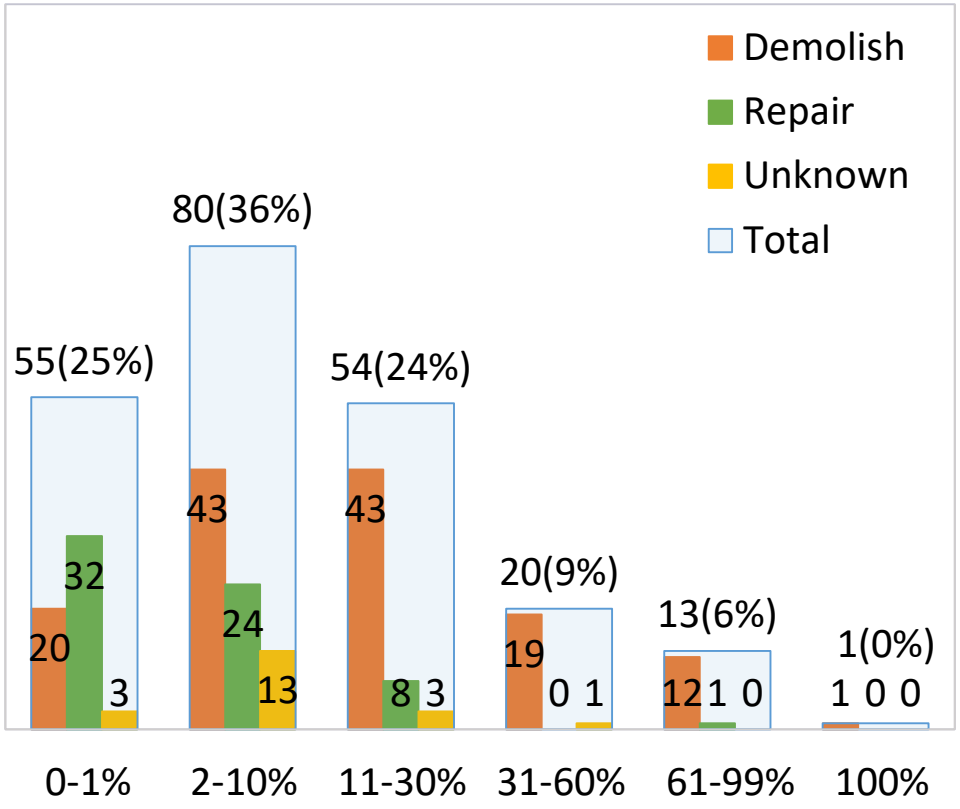
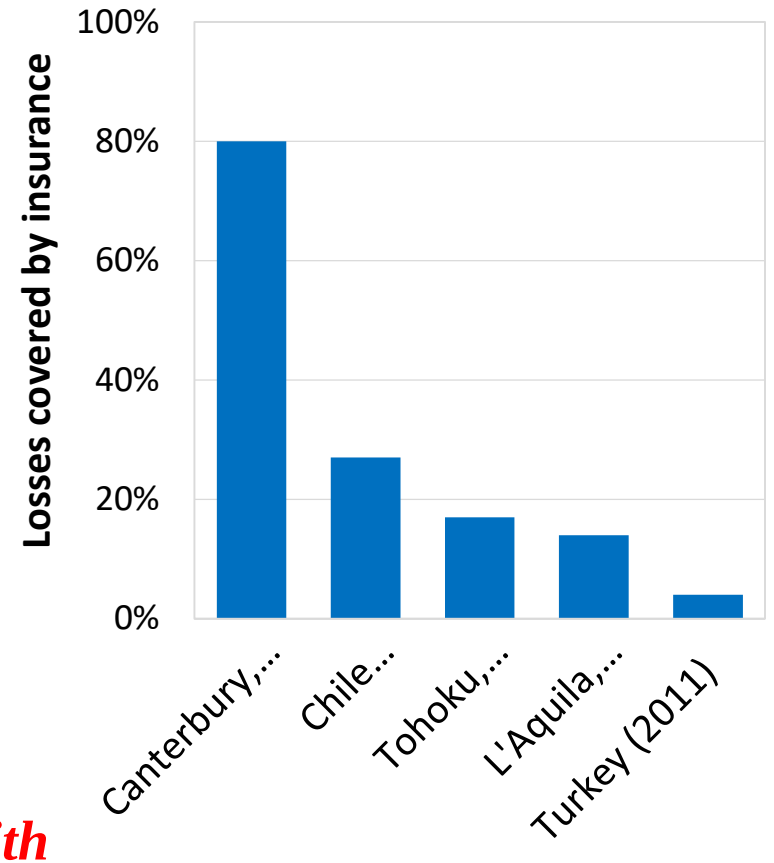
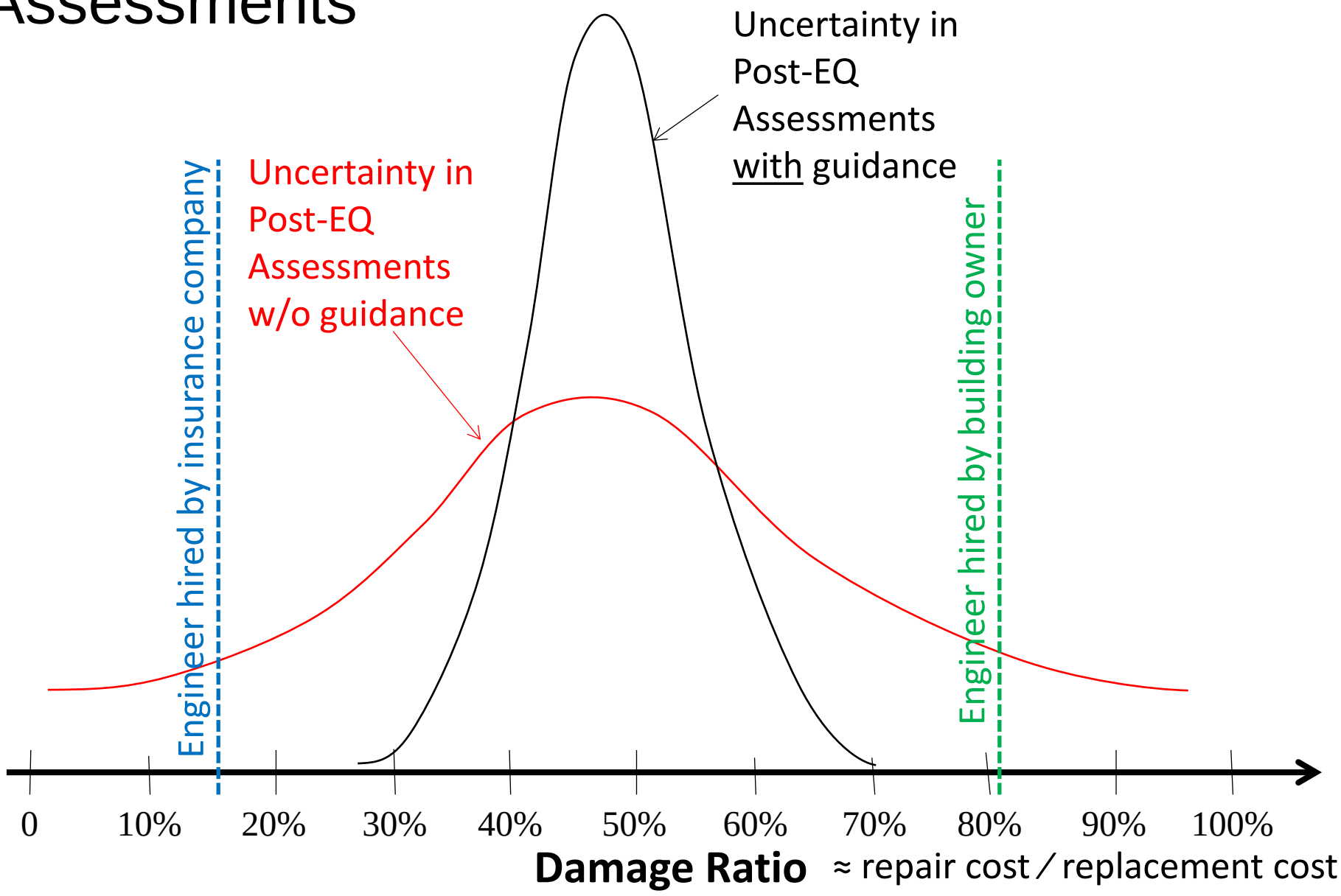
**Damage Ratio** ≈ repair cost / replacement cost (visual estimate)




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

# Impact of Uncertainty in Post-EQ Assessments



# 14 Nov 2016
# M7.8 Kaikoura Earthquake

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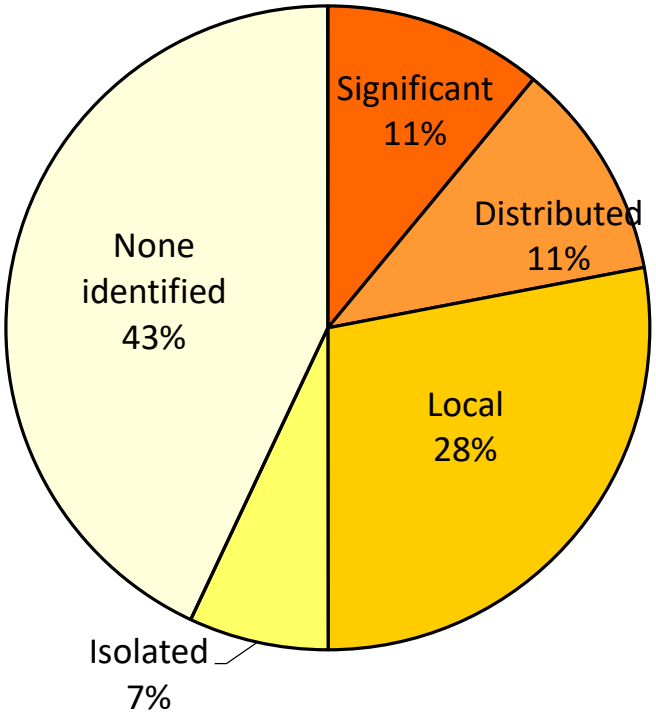
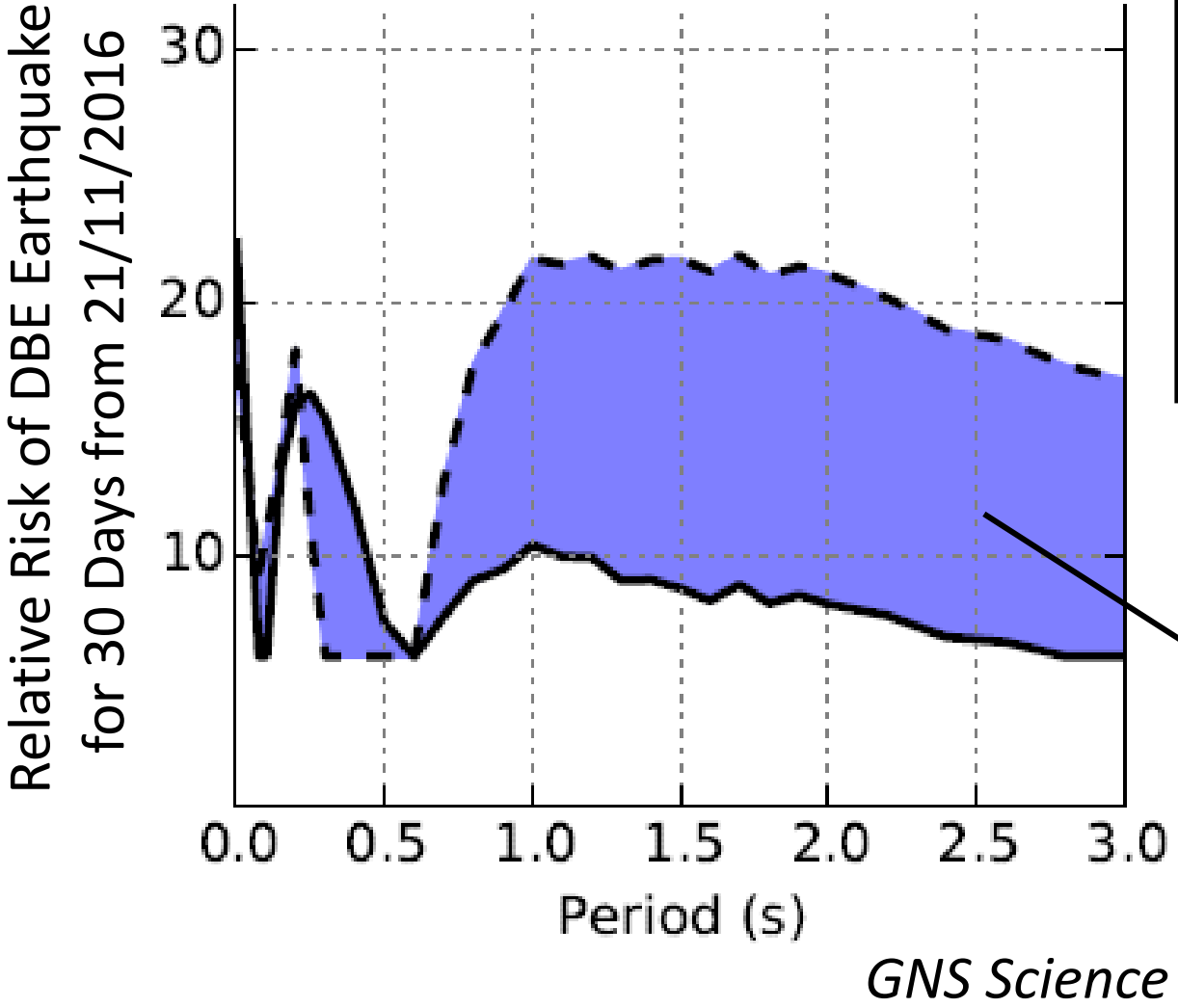
**Summary of Damage**
*(72 Buildings)*





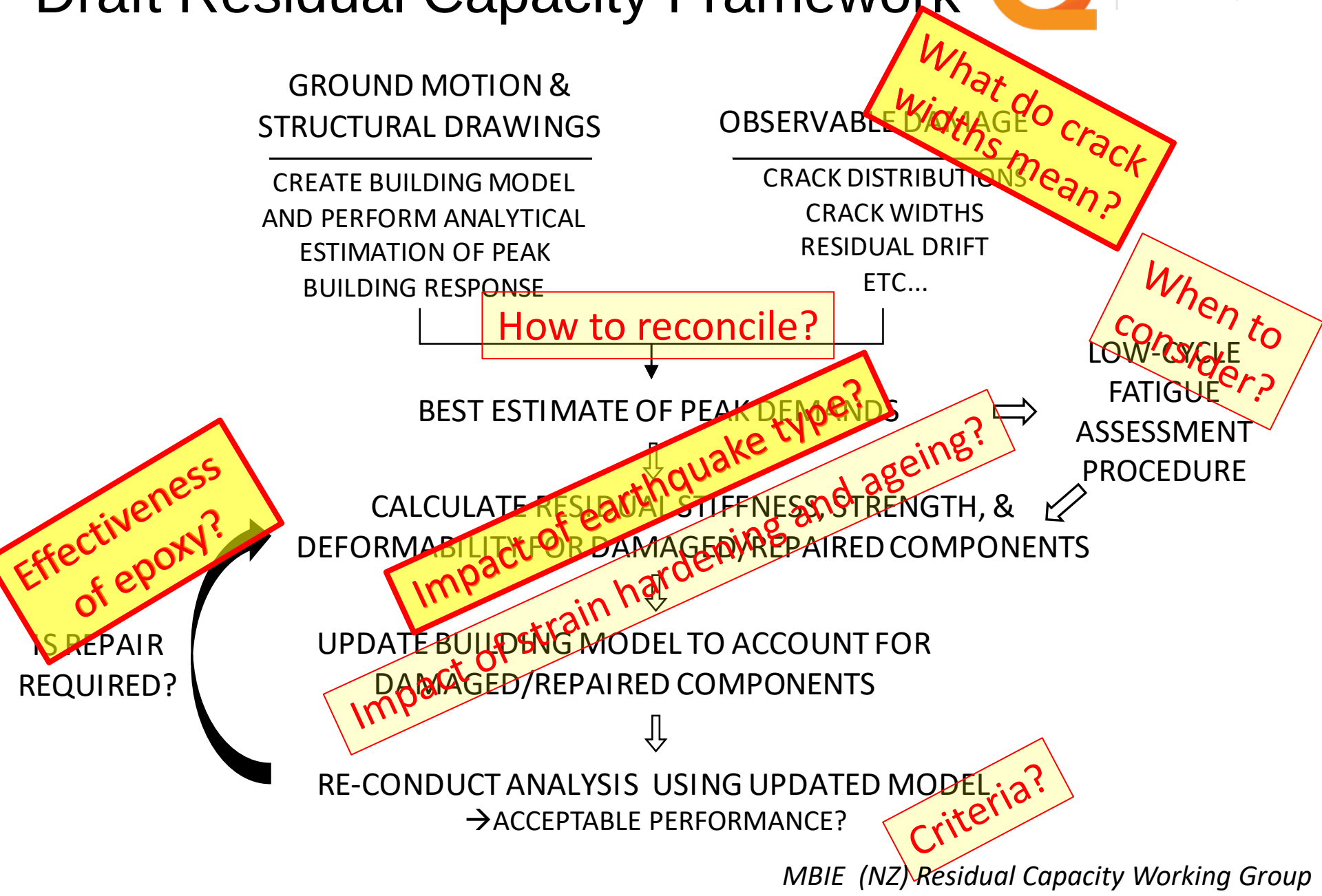
# 14 Nov 2016
# M7.8 Kaikoura Earthquake




*GNS Science*

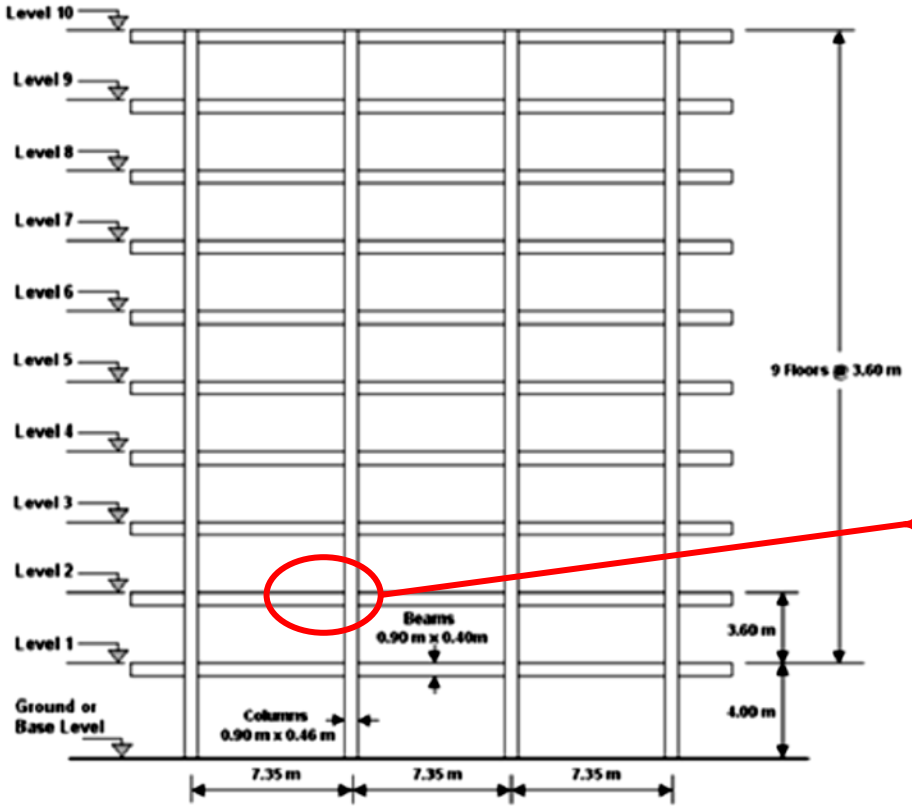
10-20 times more likely to experience DBE than before EQ!

# Draft Residual Capacity Framework



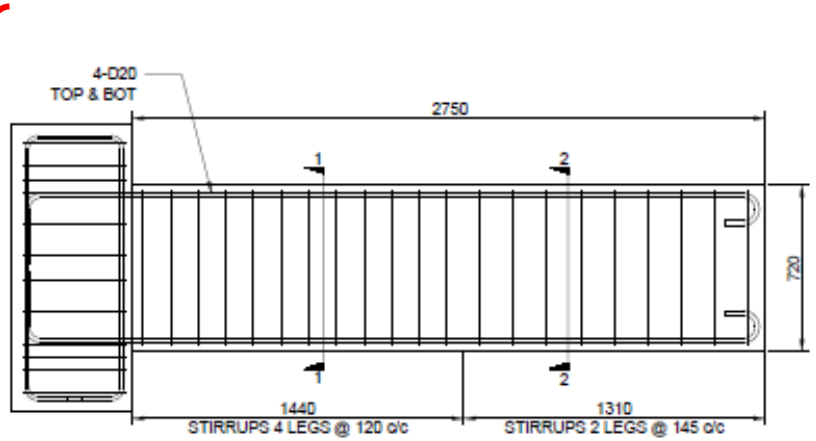

*MBIE (NZ) Residual Capacity Working Group*

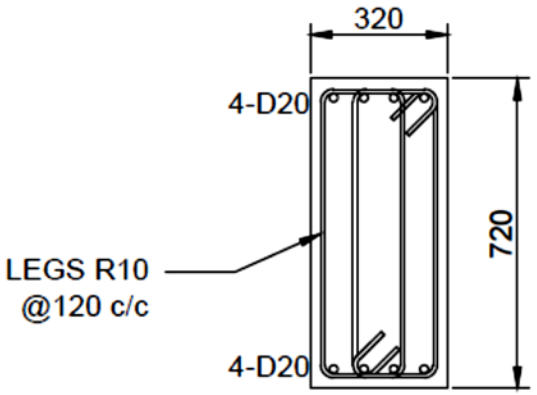
# Test design – Specimen selection




"Red Book" frame building

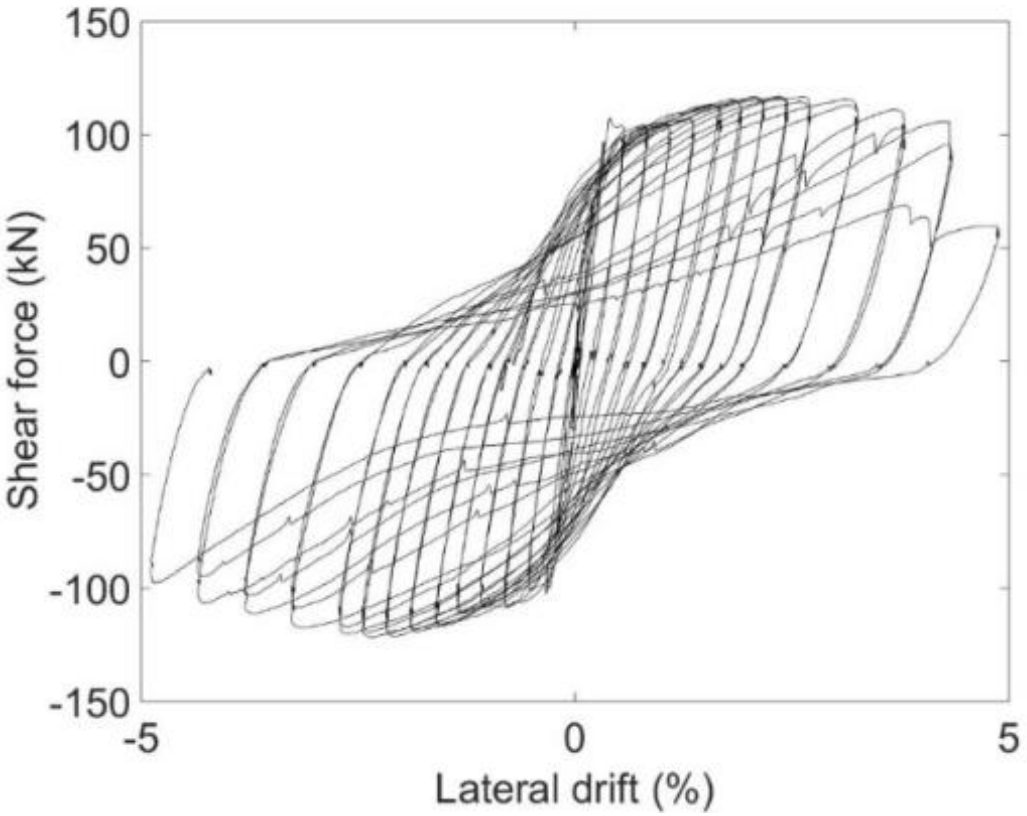
CCANZ, 2008



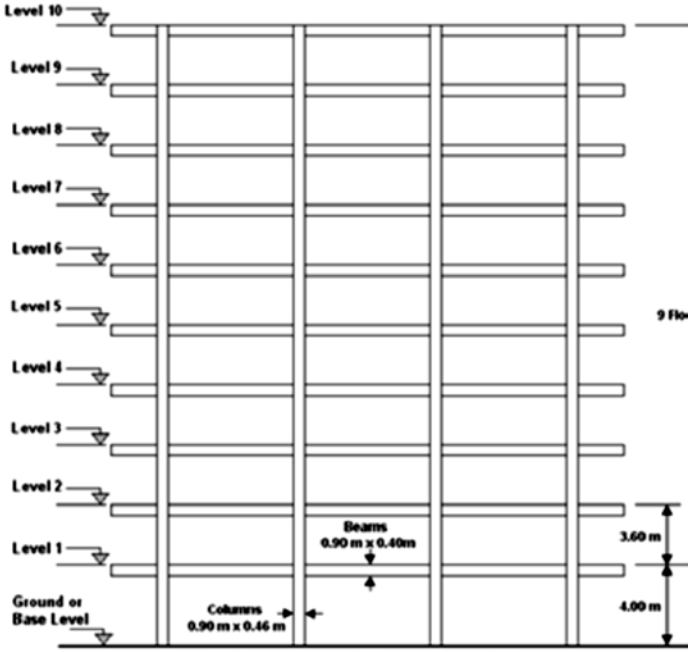



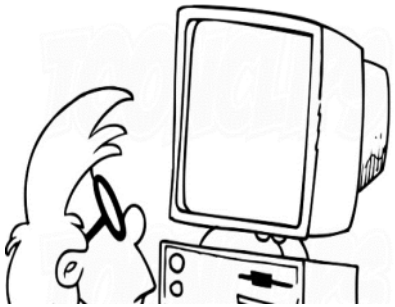

**SECTION 1-1**

# Test design – baseline tests

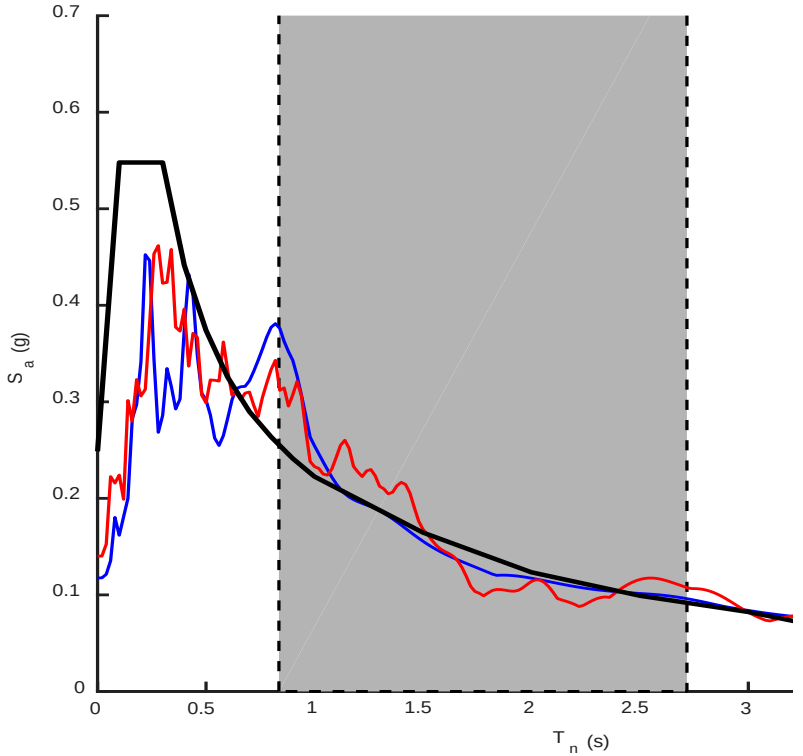


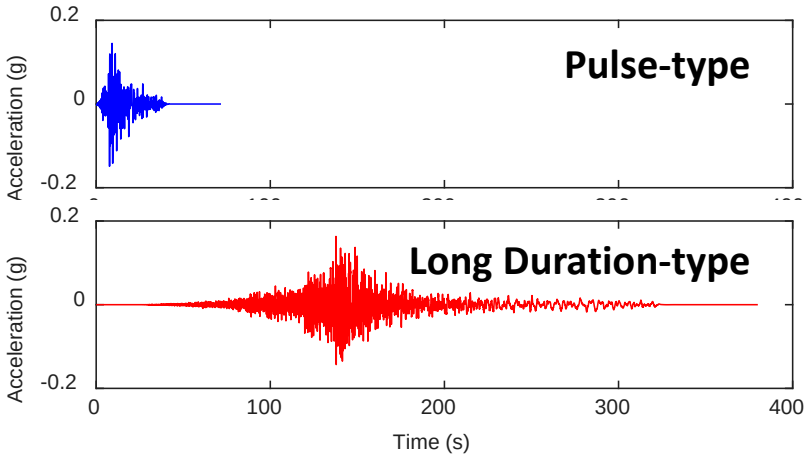
# Test design – Loading protocol



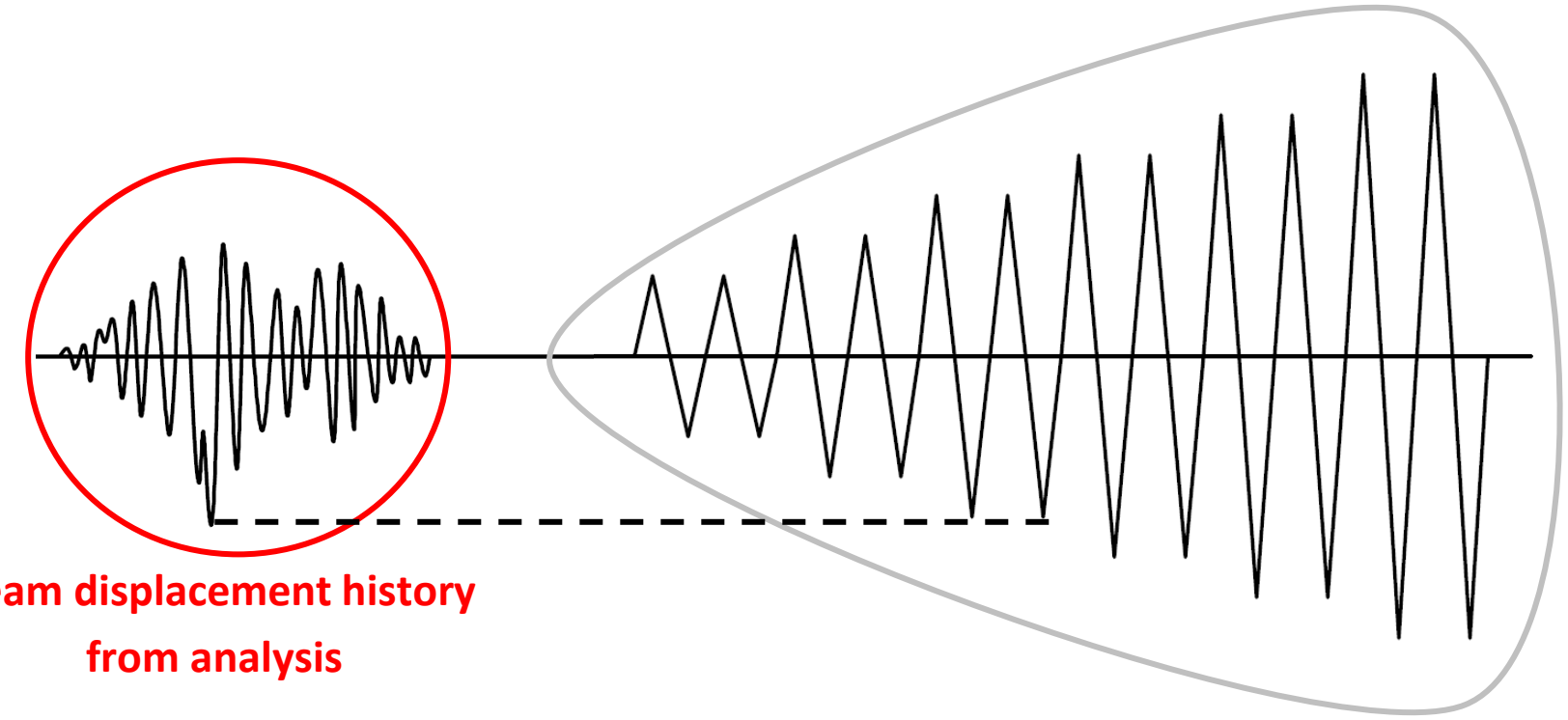



OpenSees



# Test design – Loading protocol

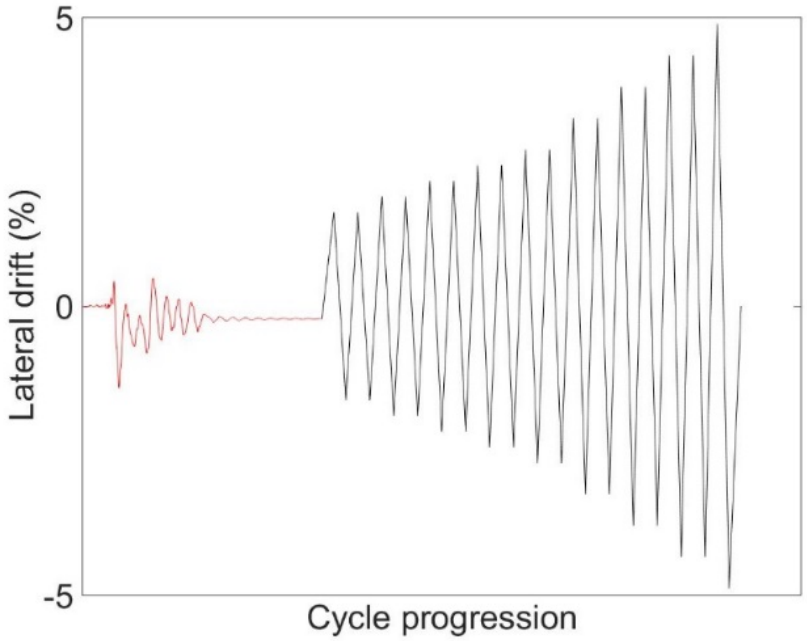


**Beam displacement history from analysis**

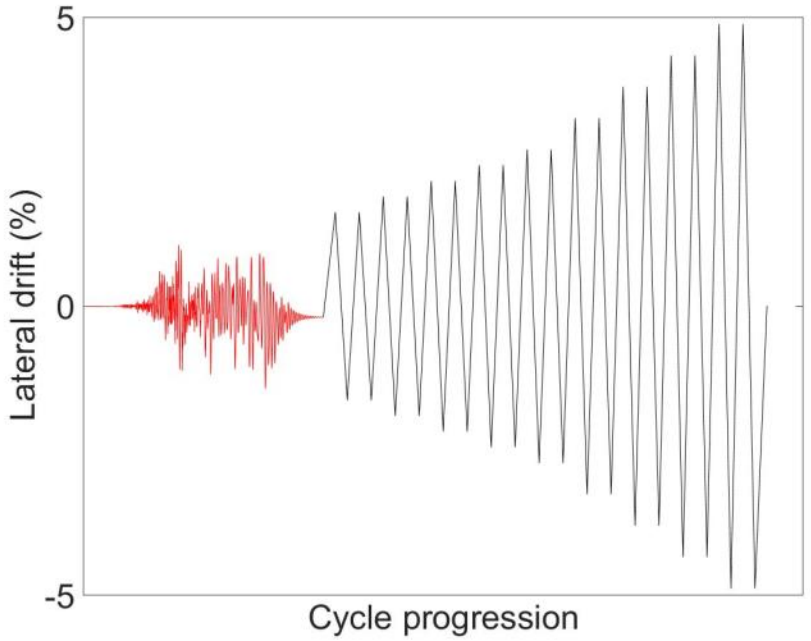
**Static cyclic loading protocol**

# Test design – Loading protocol

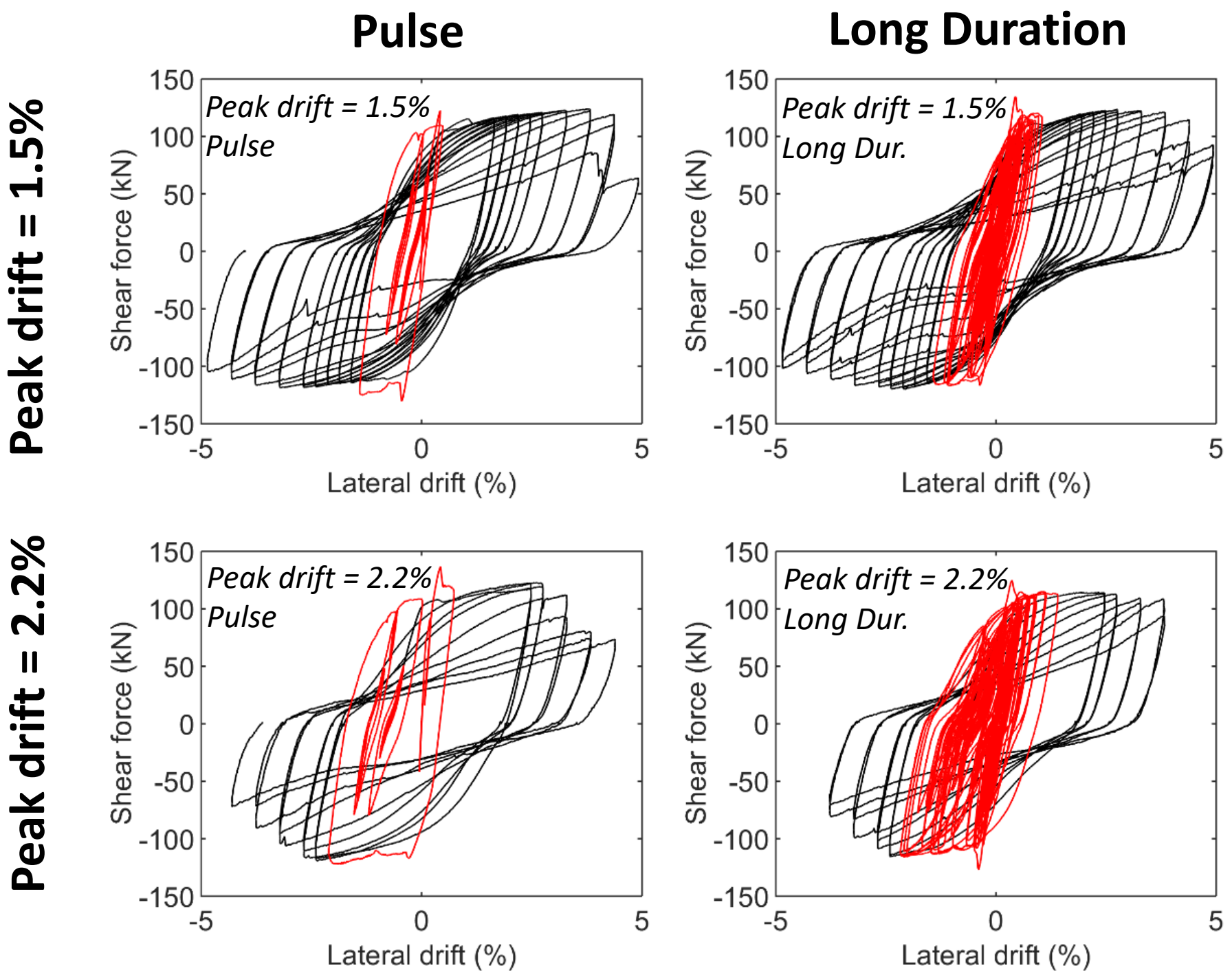
**Pulse-type**




**Long duration**

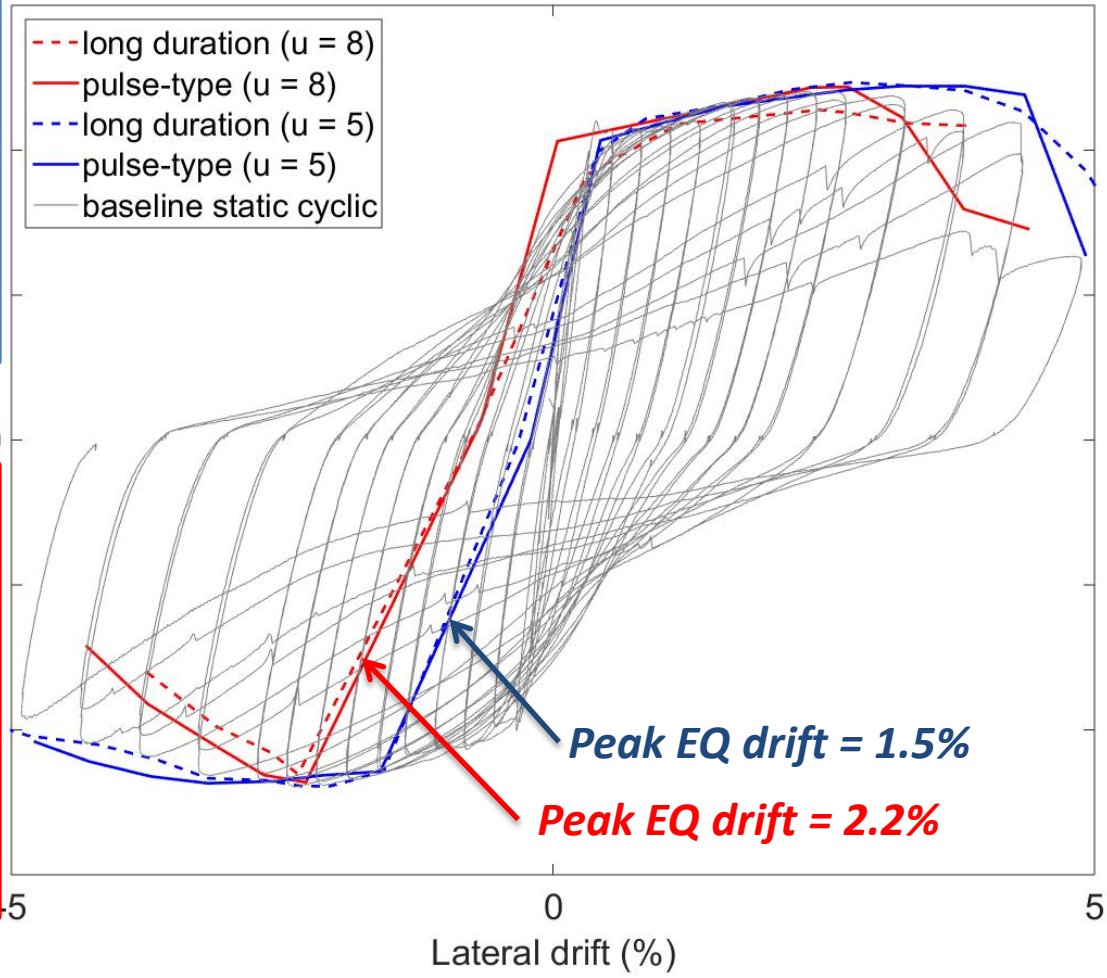



**Static cyclic loading protocol with lower level cycles removed**

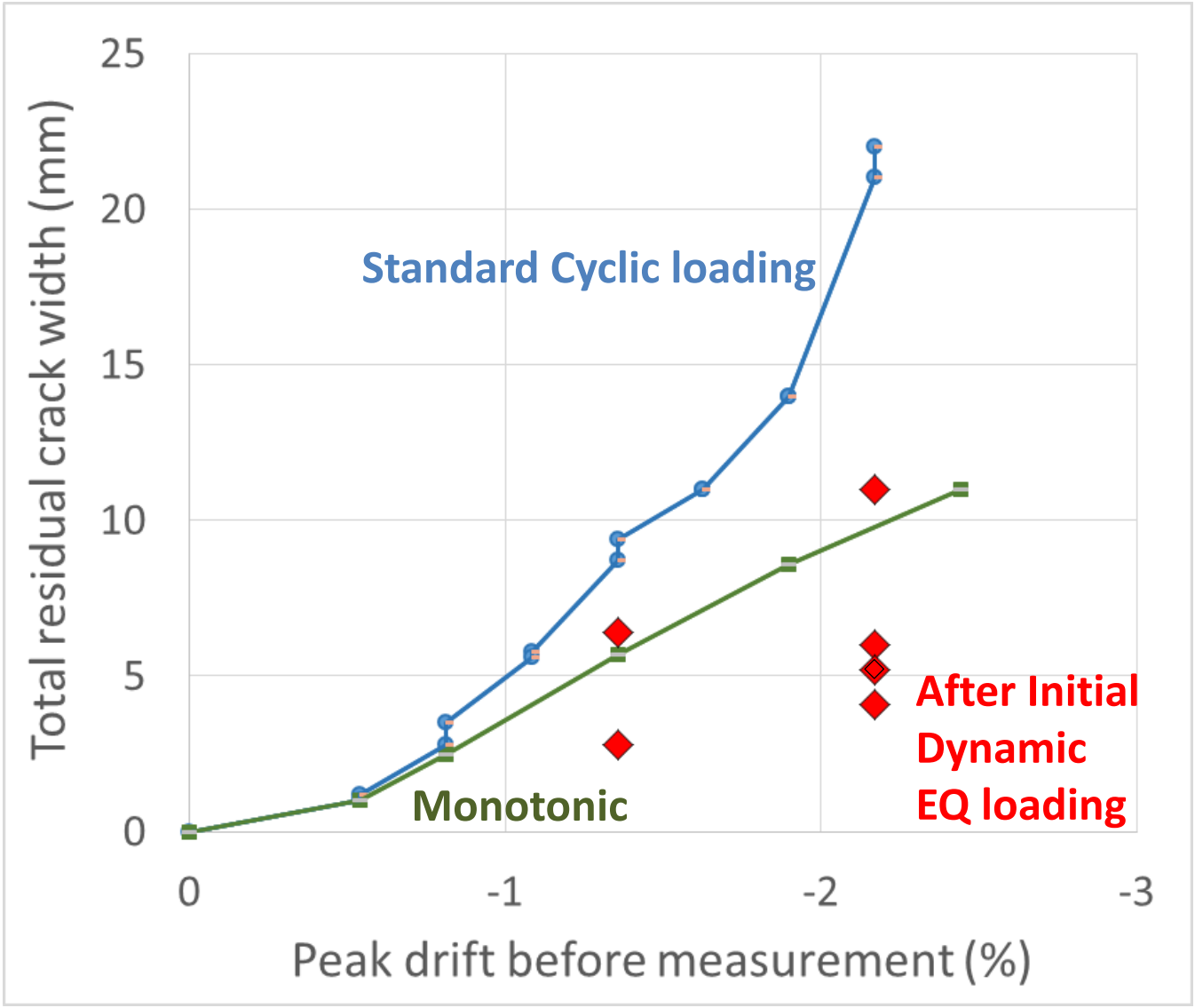

Pulse
Long Duration
Peak drift = 1.5%
Peak drift = 2.2%
Peak drift = 1.5%
Pulse
Peak drift = 1.5%
Long Dur.
Peak drift = 2.2%
Pulse
Peak drift = 2.2%
Long Dur.
Shear force (kN)
Lateral drift (%)
150
100
50
0
-50
-100
-150
-5
0
5

# Effect of loading characteristics

## Post-EQ backbone curves



# What do crack widths mean?



# Extent of damage – better measure?

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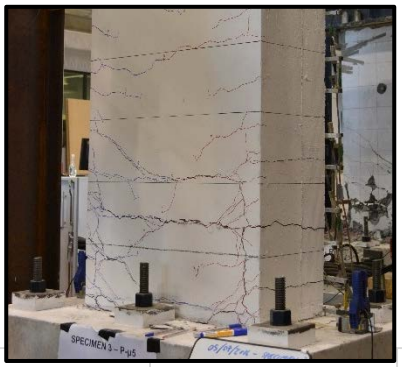
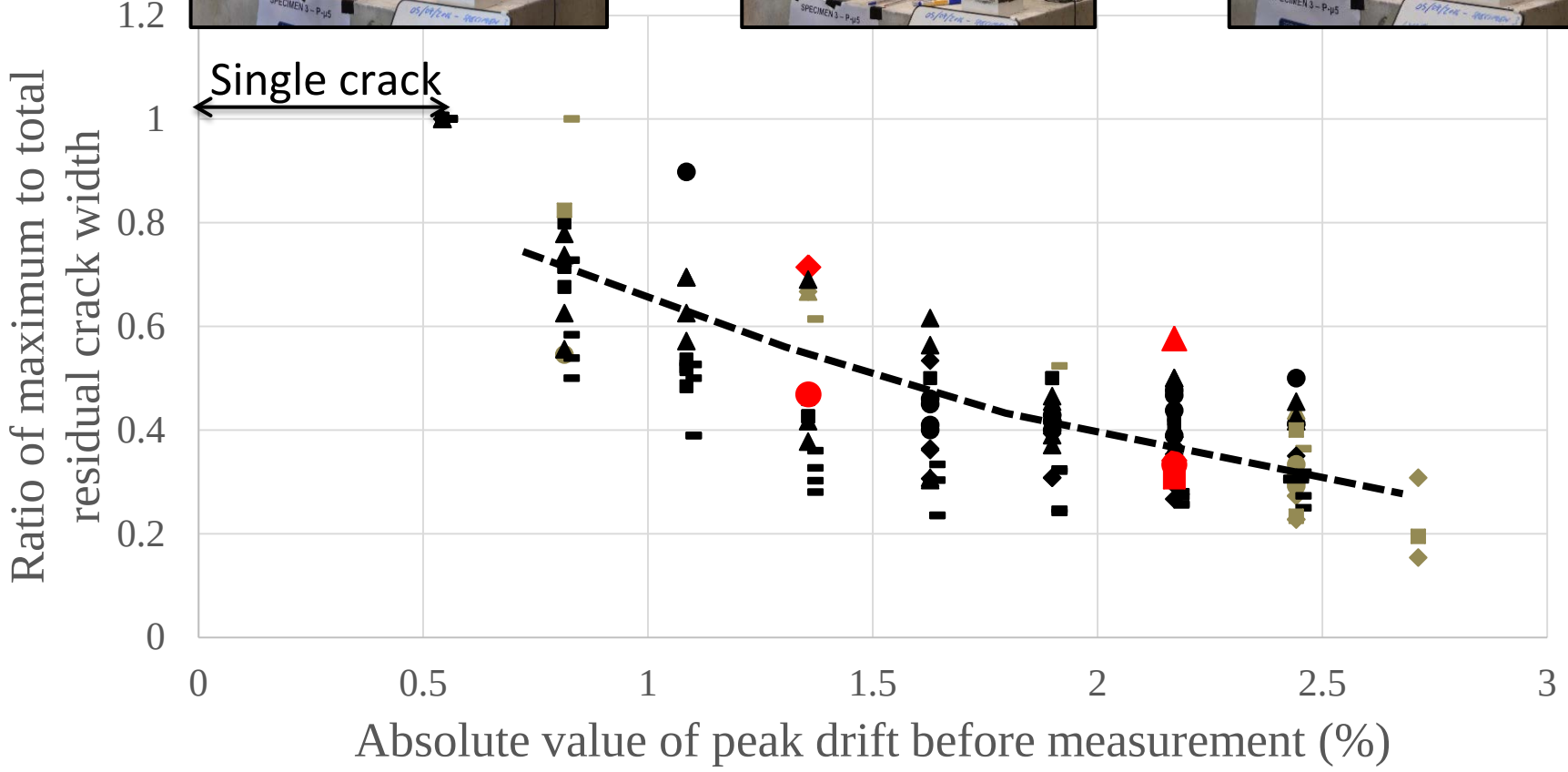
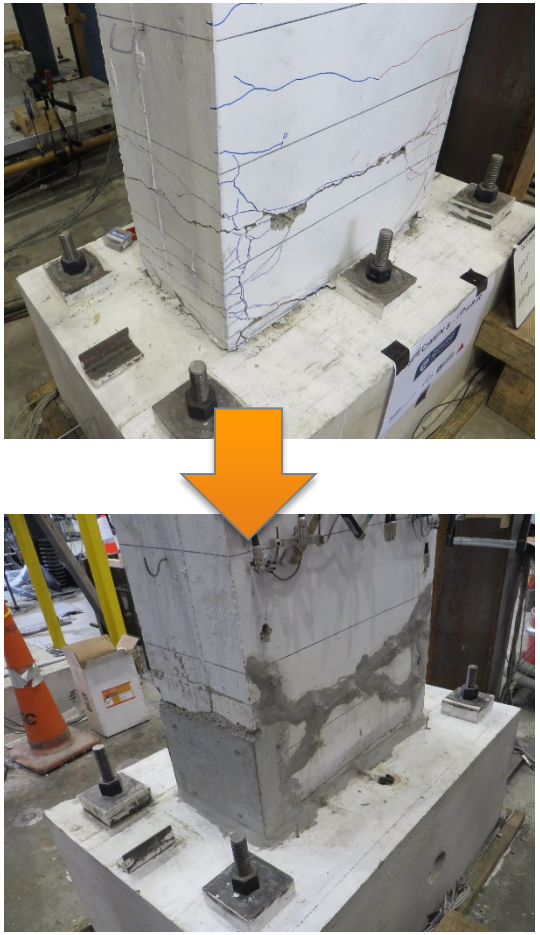
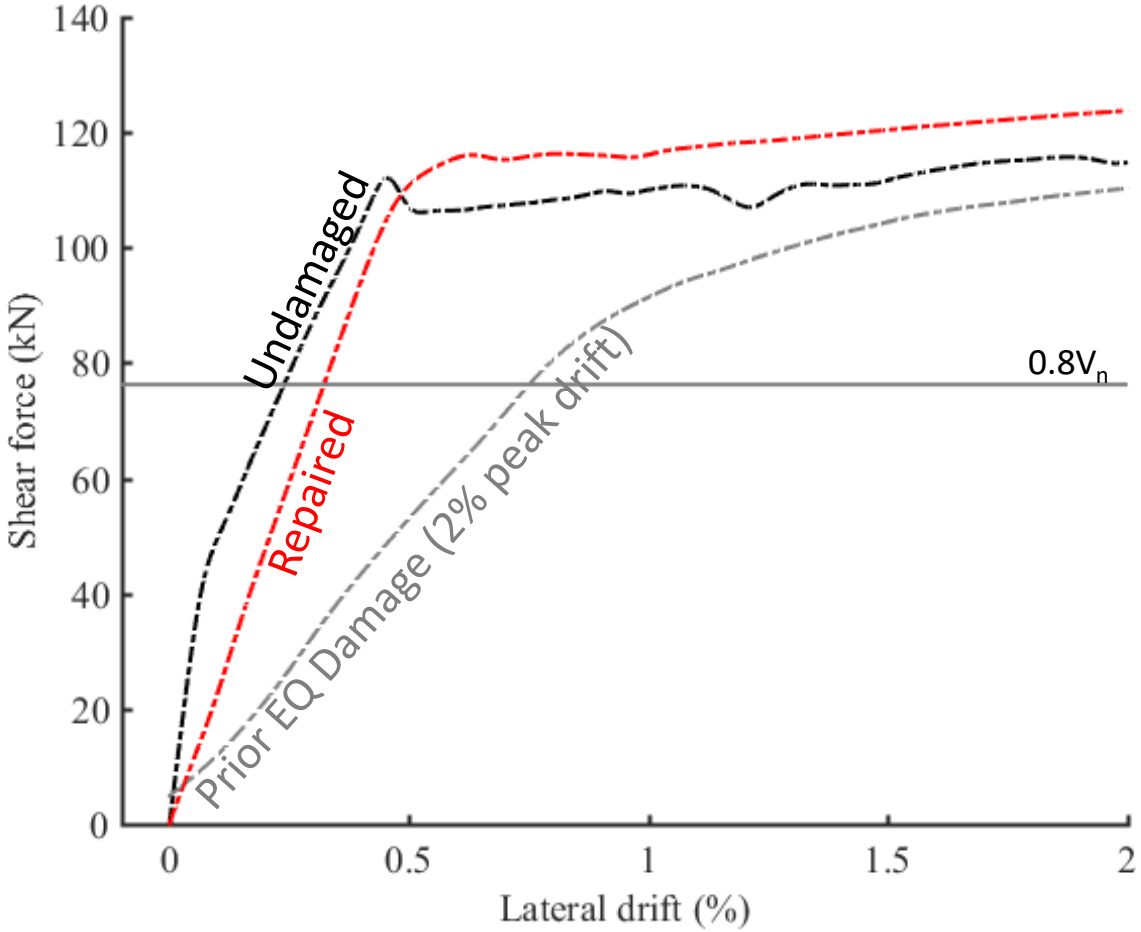




# Epoxy repair – effectiveness?

LD-2-R






**Strength**: Repaired > Undamaged

**Drift capacity**: Repaired ~ Undamaged

**Stiffness:** Repaired ~ 0.7-0.9 Undamaged

# Damaged/Repaired building period?

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*Damaged buildings?*

*Repaired buildings?*

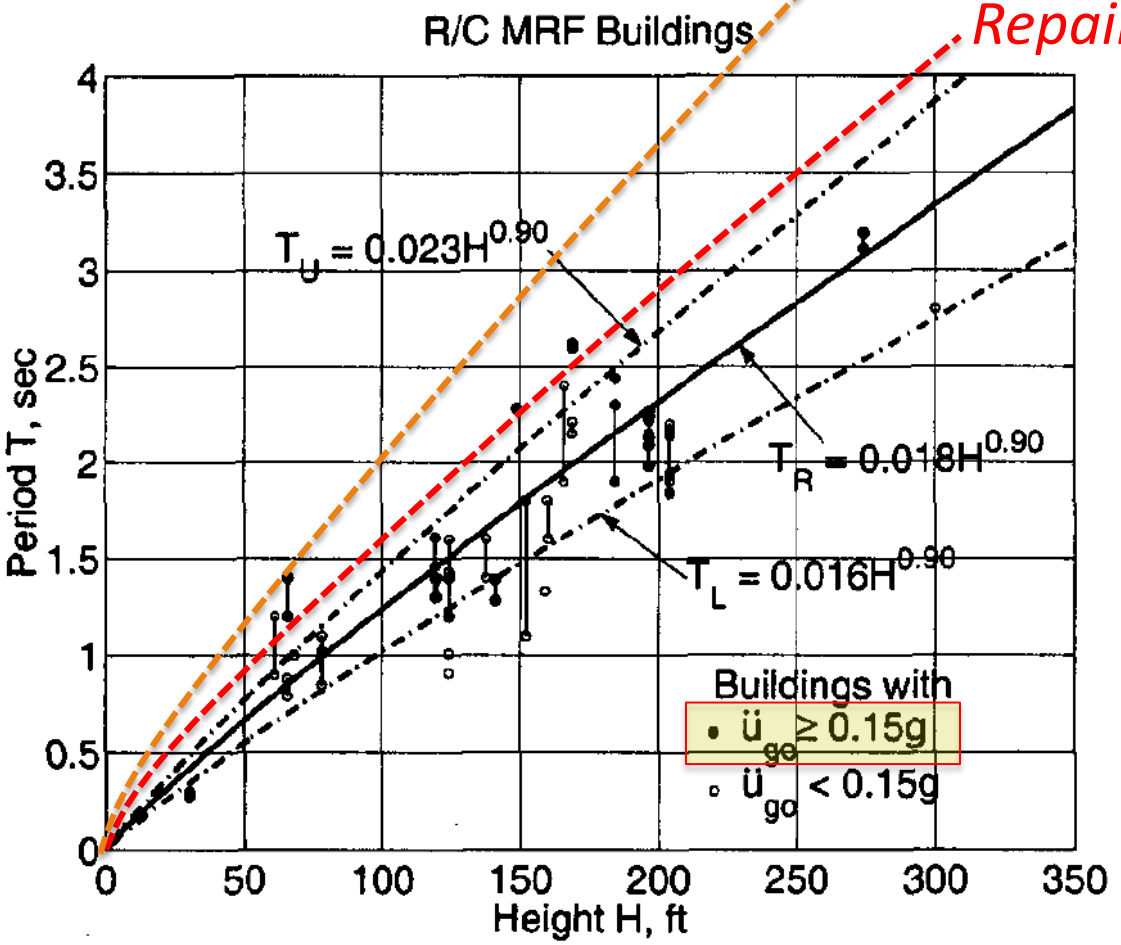


**Figure 3.** Results of regression analysis for R/C MRF buildings

*Chopra and Goel, 2000*

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- ✓ Resilience and recovery requires an understanding of residual capacity.
- ✓ Consider a “rapairability limit state” in design of new buildings?

# Thank you!

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# A case for a Repairability limit state?

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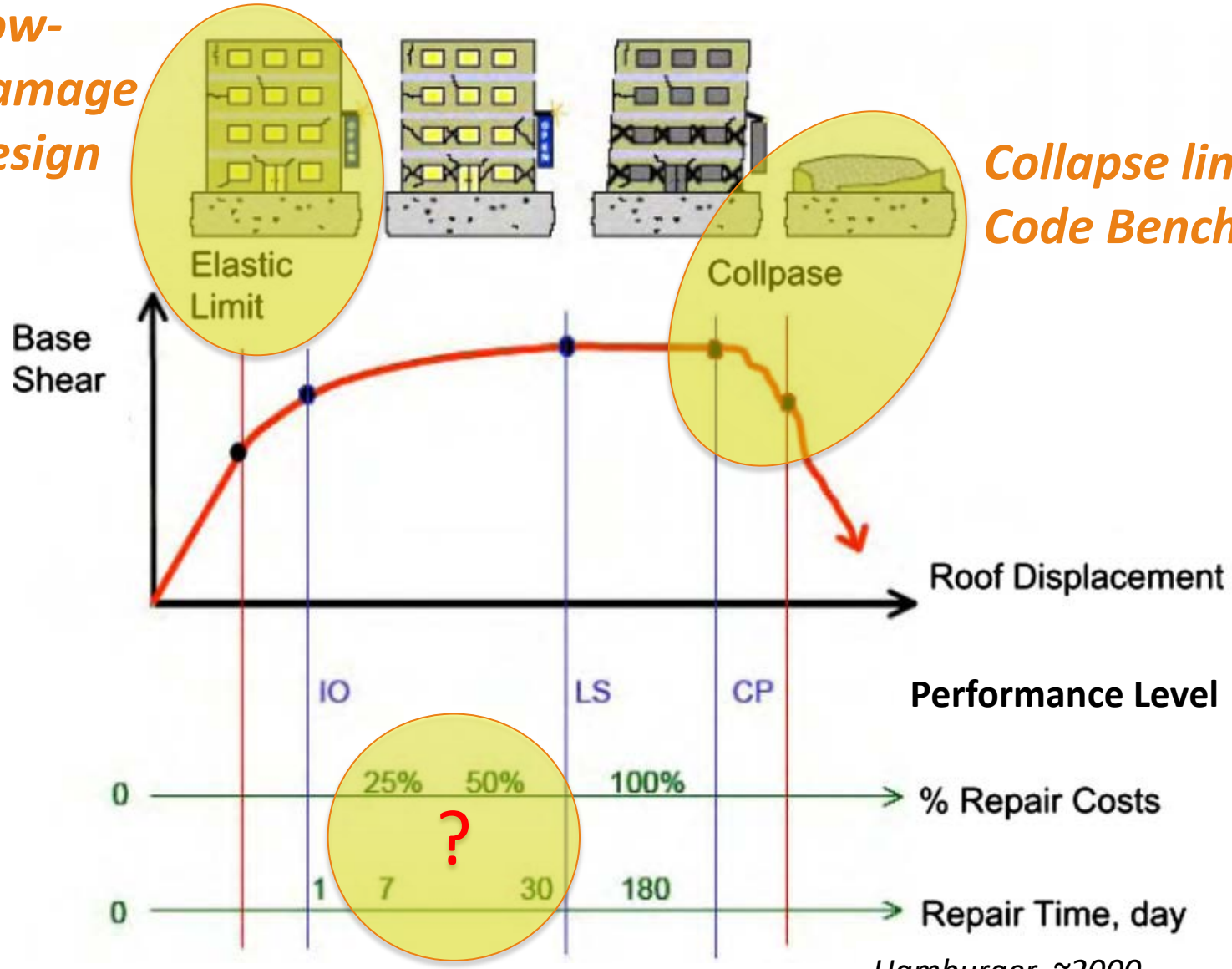
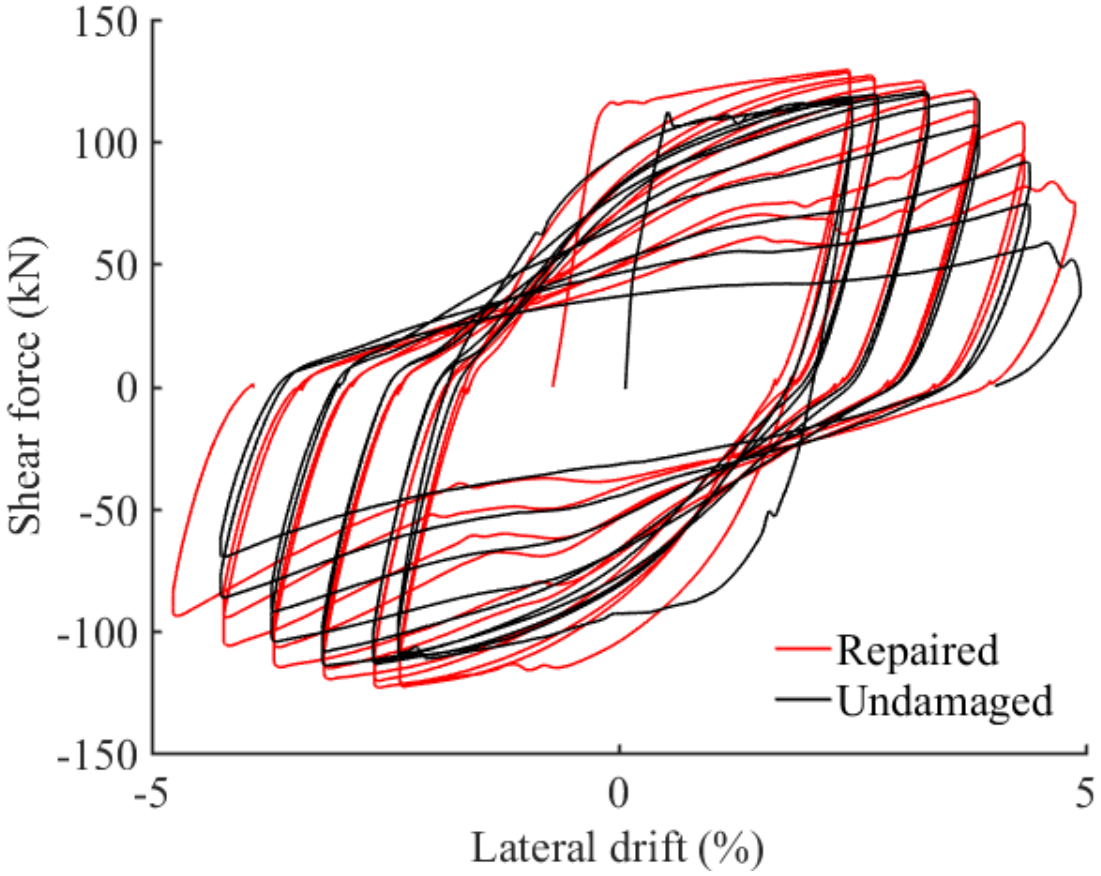
***Low-damage design***

***Collapse limit state: Code Benchmark***




*Hamburger, ~2000*


150
100
50
0
-50
-100
-150
Shear force (kN)
-5
0
5
Lateral drift (%)
Repaired
Undamaged

# Beam elongation

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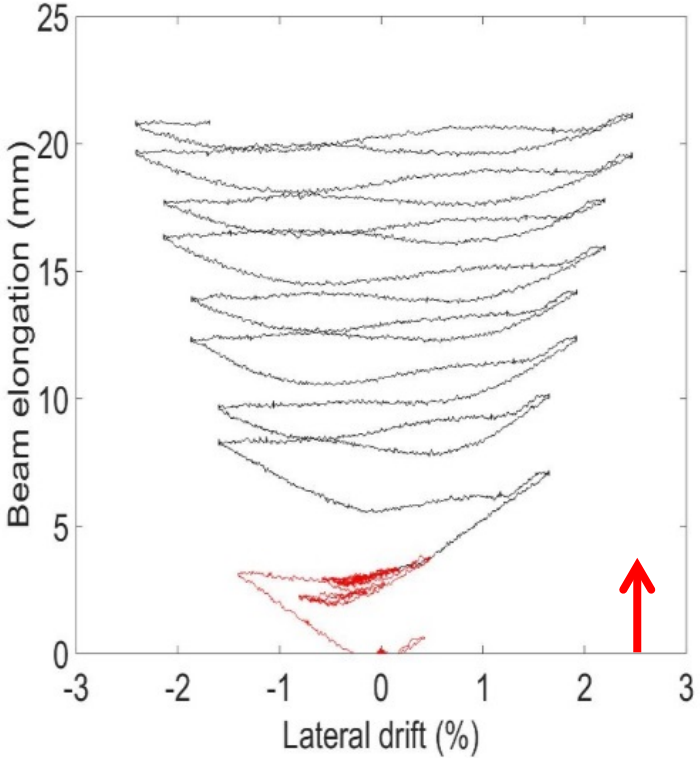
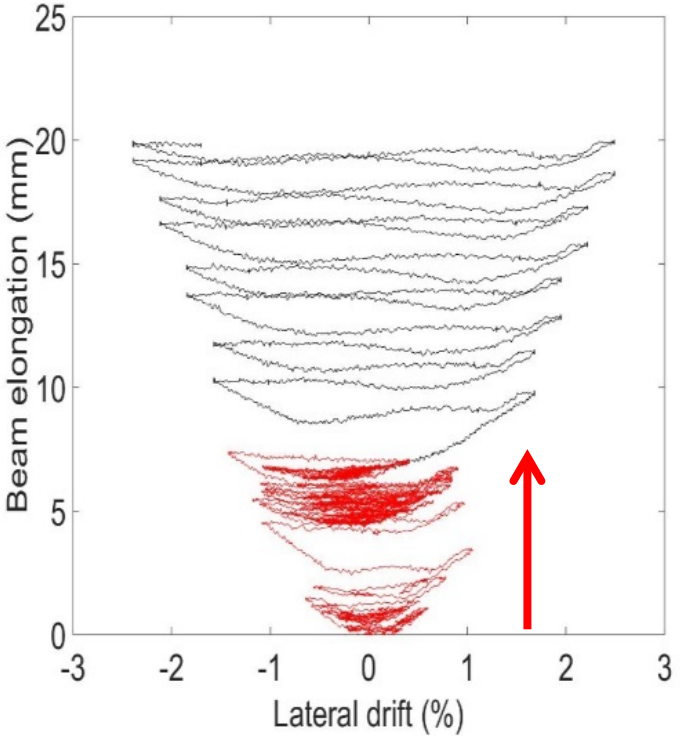
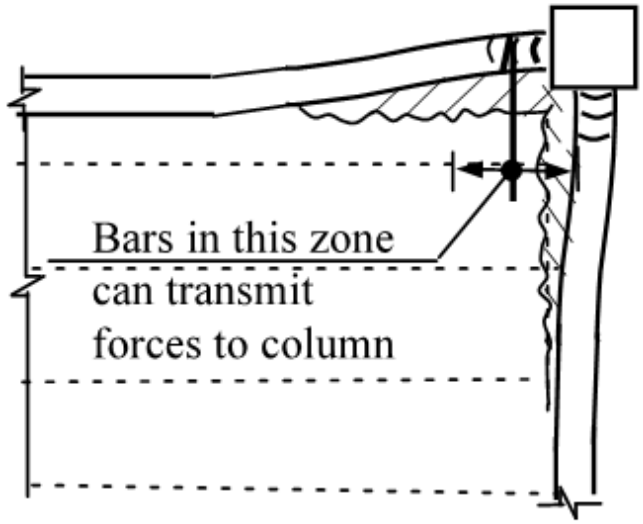
**Pulse-type**



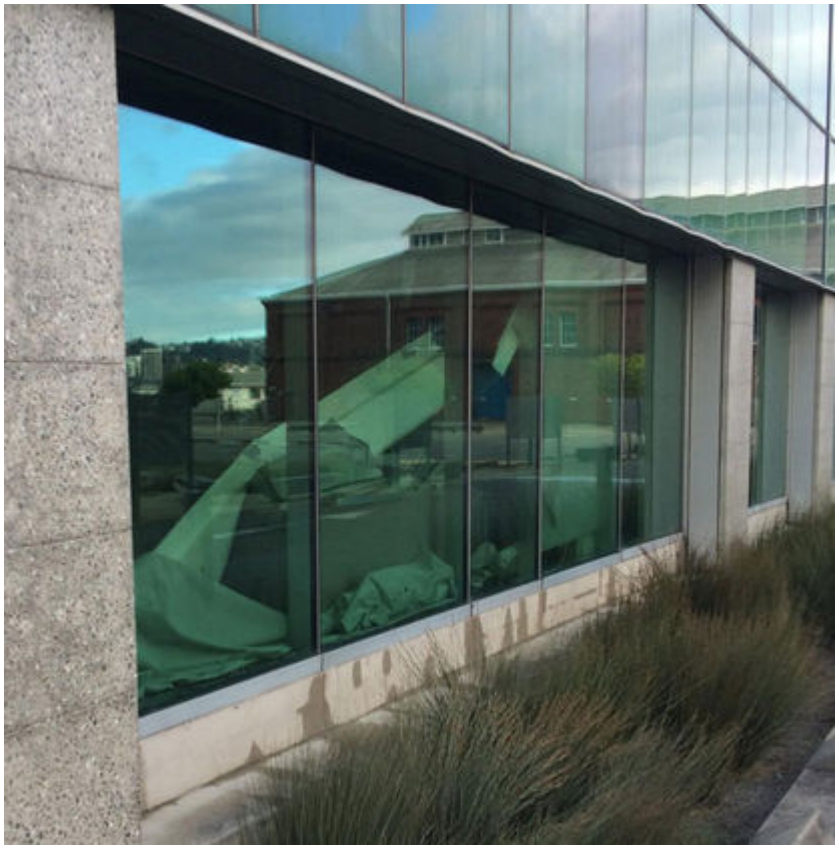

**Long duration**



# Beam elongation
# - 14 Nov Kaikoura Earthquake




(b) Slab reinforcement close to column may resist tension or compression

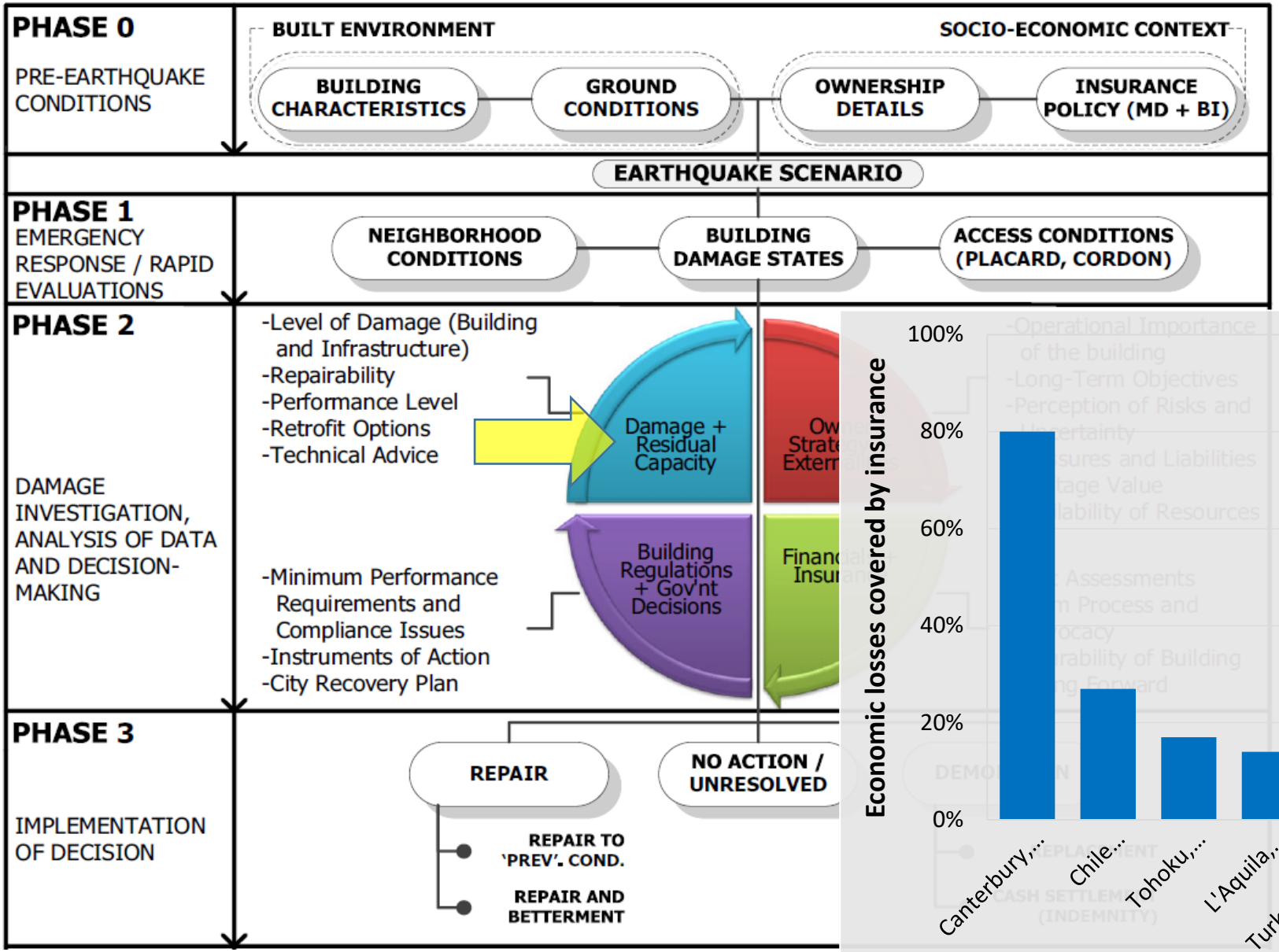


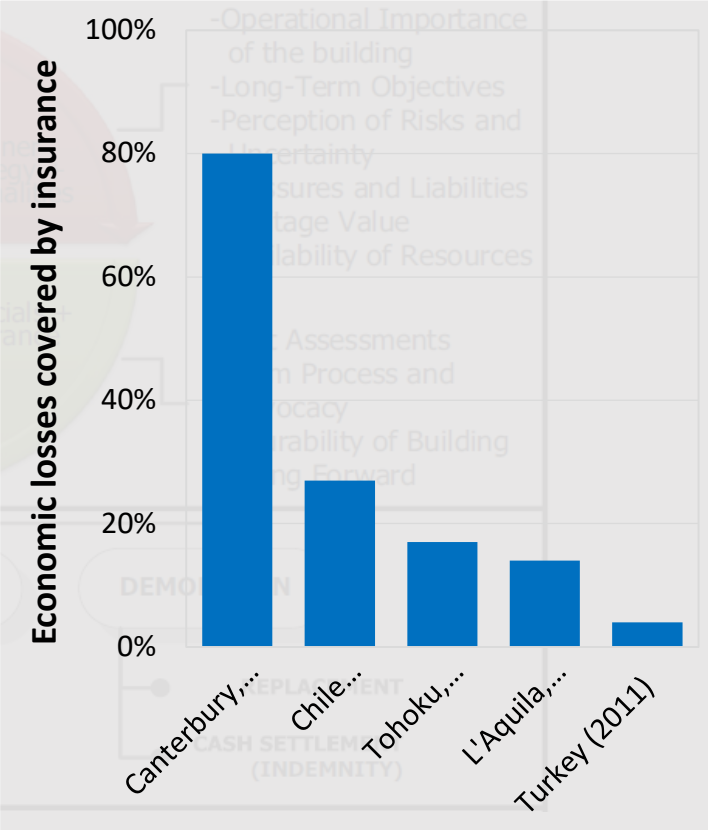
Collapsed precast floor units


Will this be repeated in Wellington?
Is this acceptable?
Demand for better performance!

# Demolition Decision Framework

*- Marquis et al. 2015*



# Concerns post-Christchurch

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1. Reduced strain capacity of reinforcing bar
   - Low-cycle fatigue
   - Strain ageing

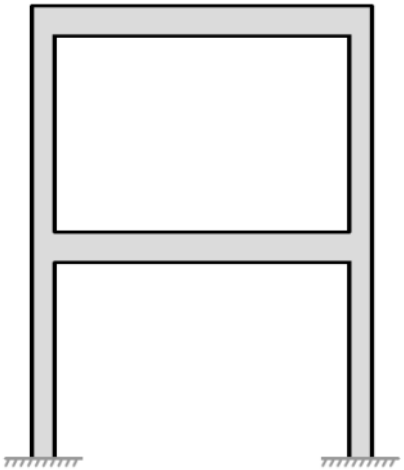
2. Poorly distributed cracking
   - Importance of dynamic loading rates?

3. Reparability
   - How to quantify?

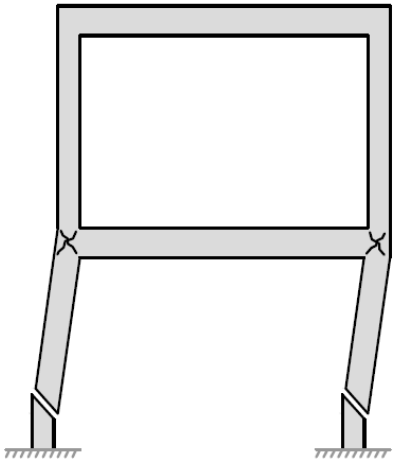
Residual Capacity

# When is residual capacity important?

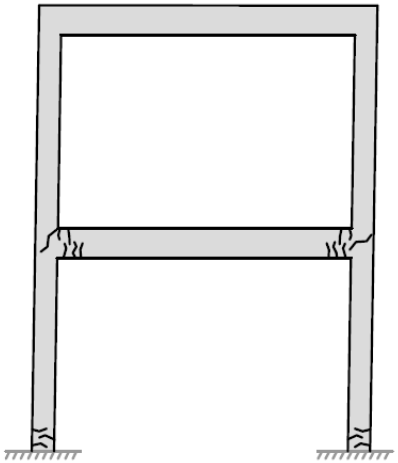
In post-earthquake situations, RC buildings can be broadly categorized into three categories:



1. Minimal damage: no further action required



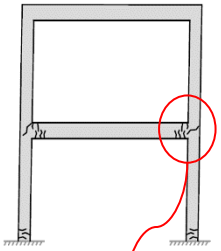
2. Heavy damage: demolition is necessary

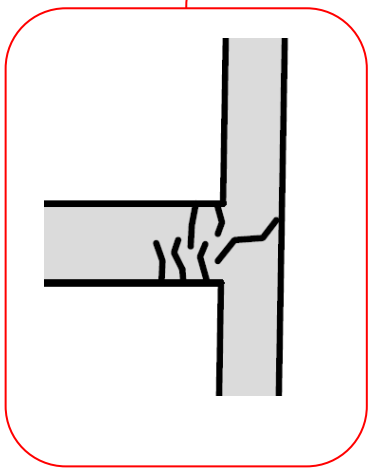


3. Moderate damage: **residual capacity?**

   ***Flexural damage (plastic hinging)***

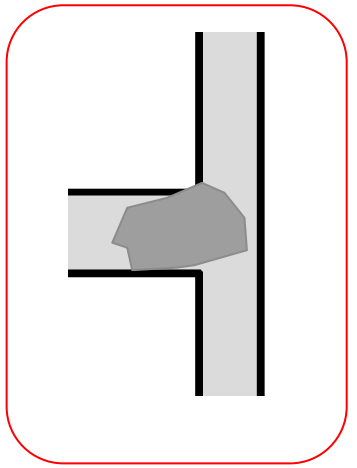
# Component residual capacity





Component flexural damage

- Residual stiffness
- Residual strength
- Residual energy dissipation
- Residual deformation capacity
- Residual fatigue life



Repaired (epoxy injection)