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Damage to Concrete Buildings with Precast Floors in the 2016 Kaikoura Earthquake

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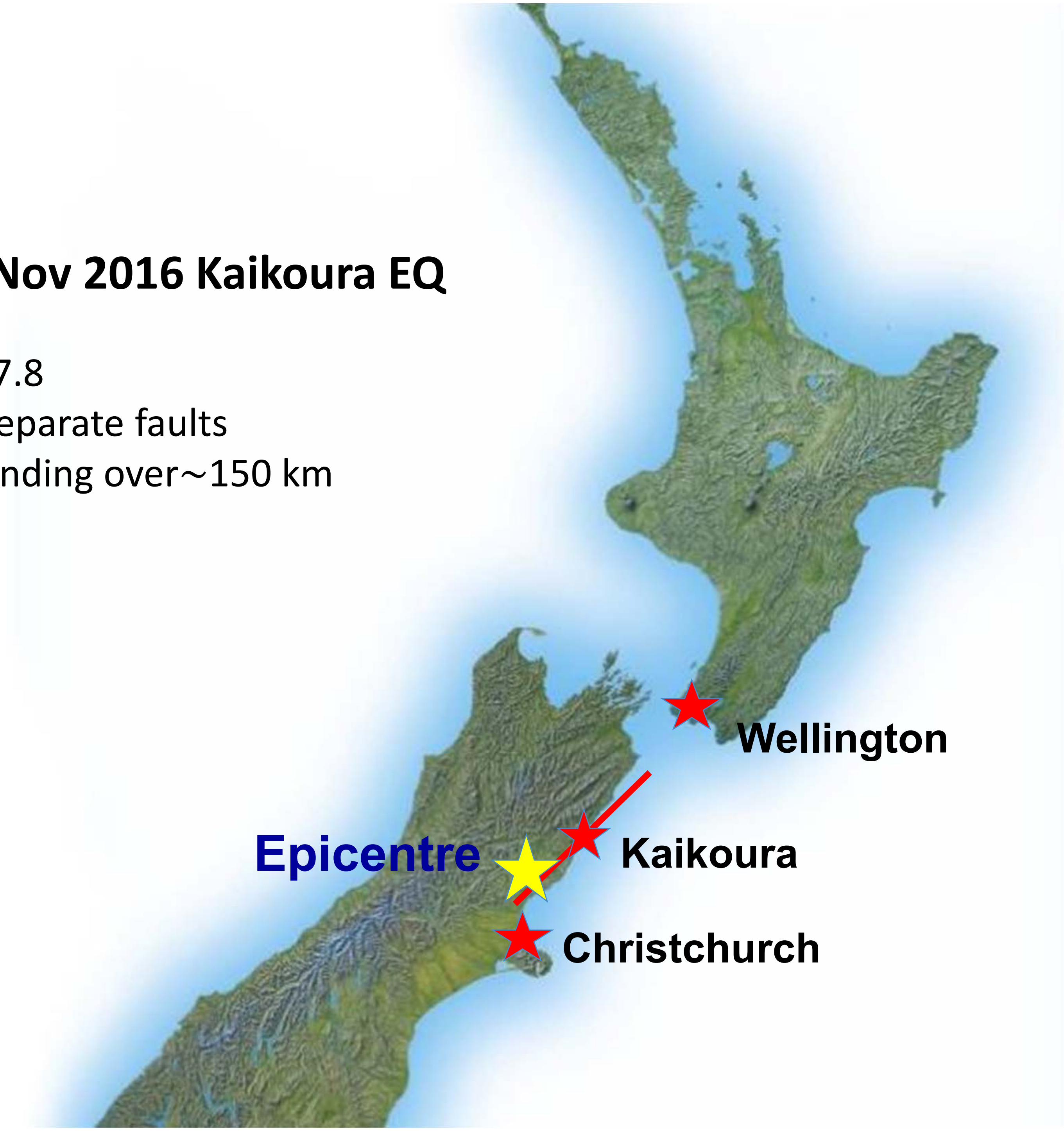
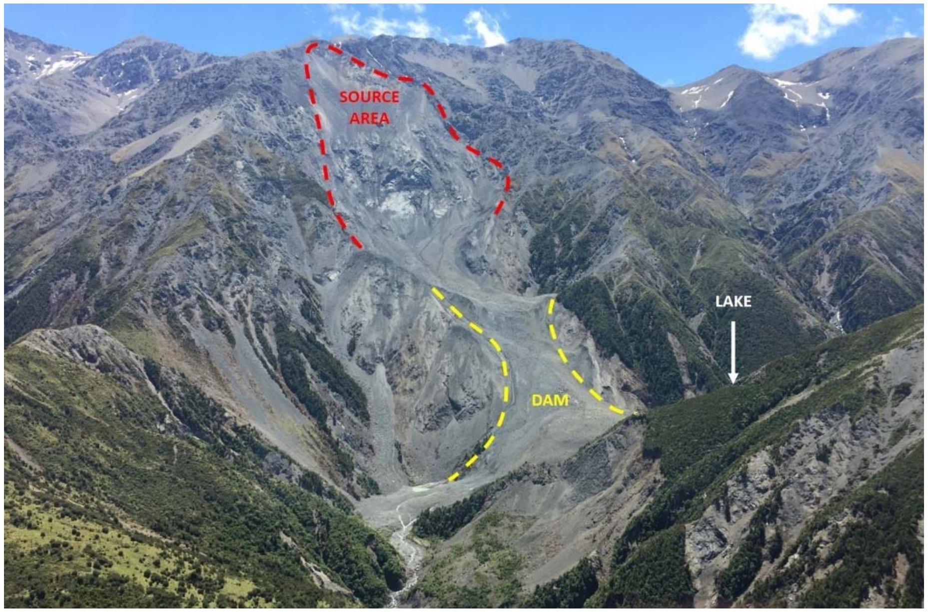
University of Auckland
New Zealand

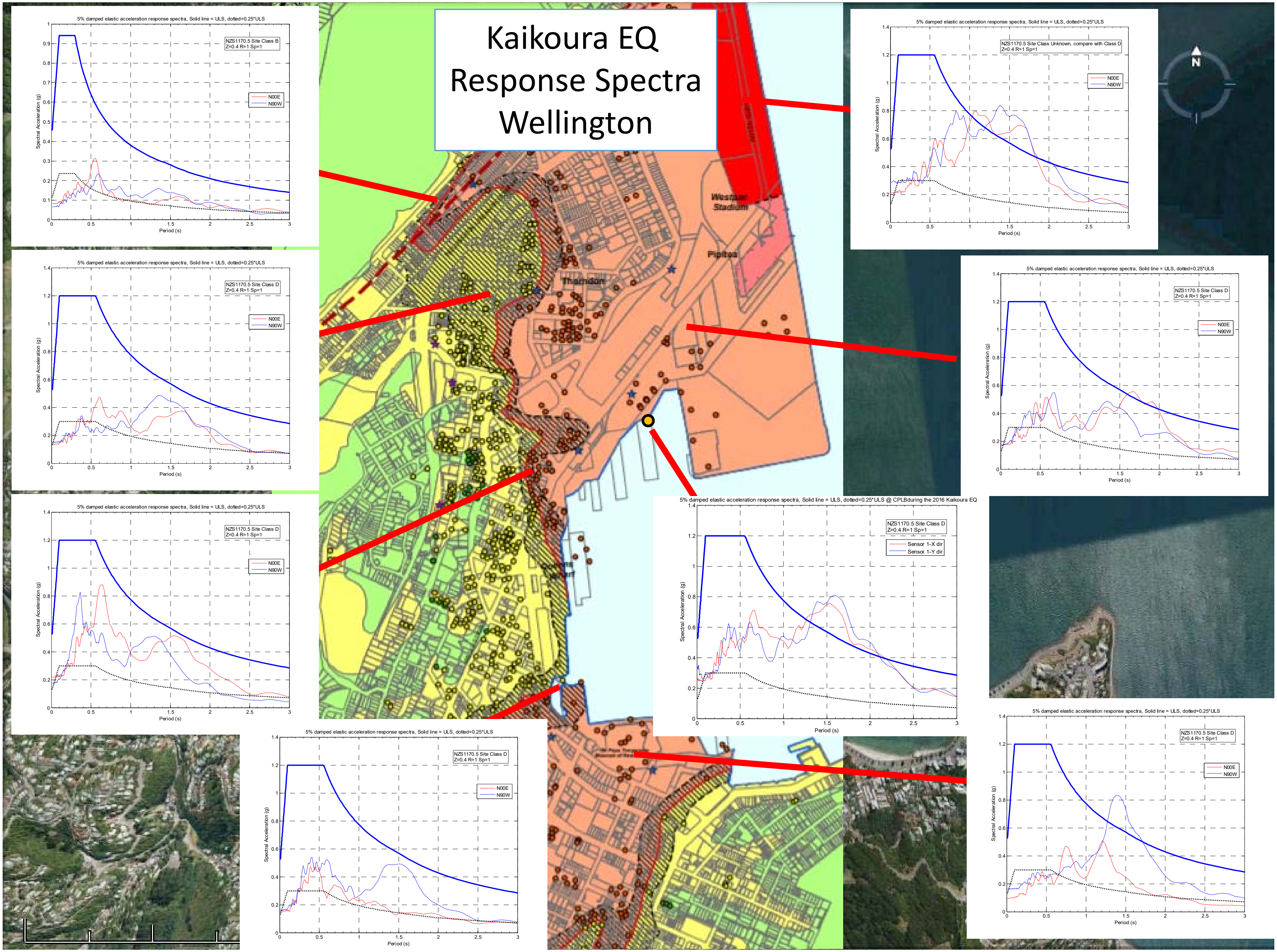
14 Nov 2016 Kaikoura EQ

M_w 7.8
13 separate faults
extending over~150 km




SOURCE AREA
LAKE
DAM

Kaikoura EQ Response Spectra Wellington



Initial Reports in Wellington

- Significant shaking
- Non-structural damage
- Some isolated structural damage
- Lack of URM damage

Statistics House

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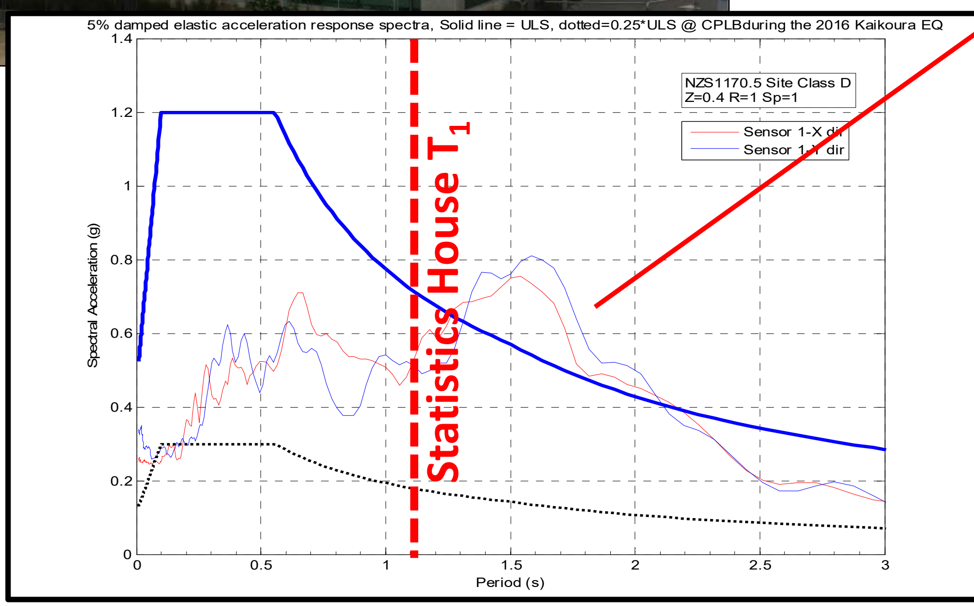

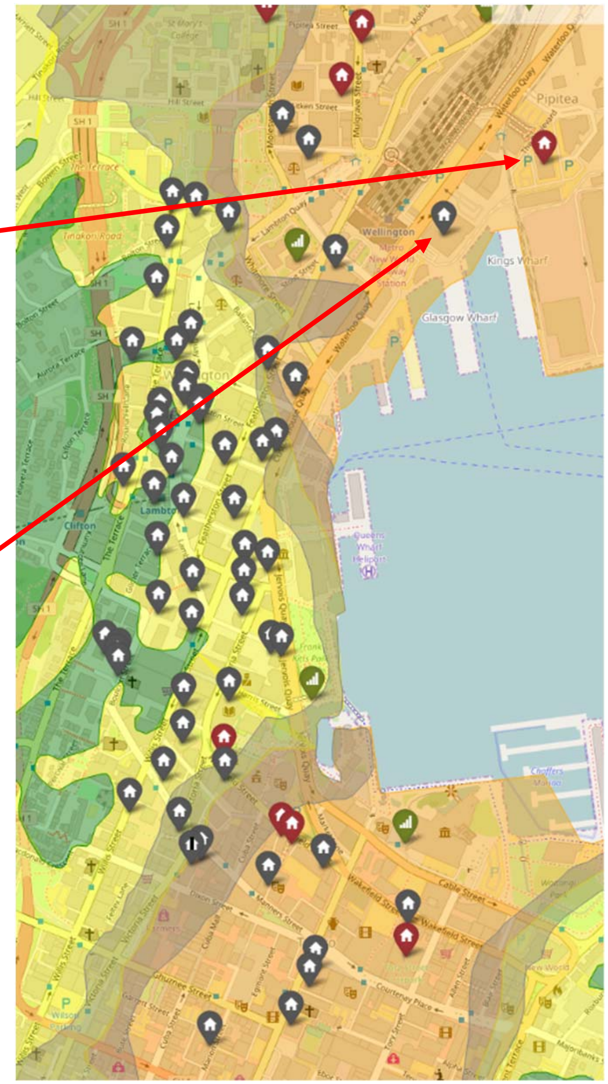

Site classes: Semmens et al 2010

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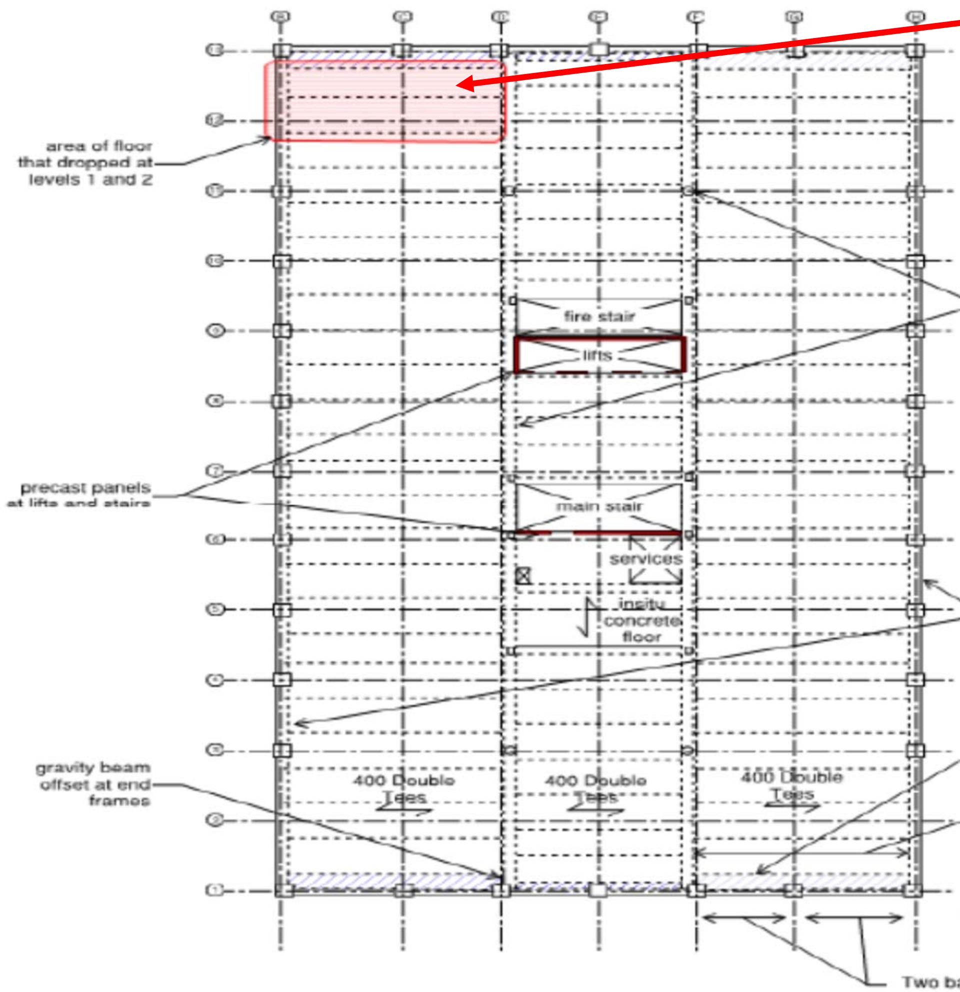
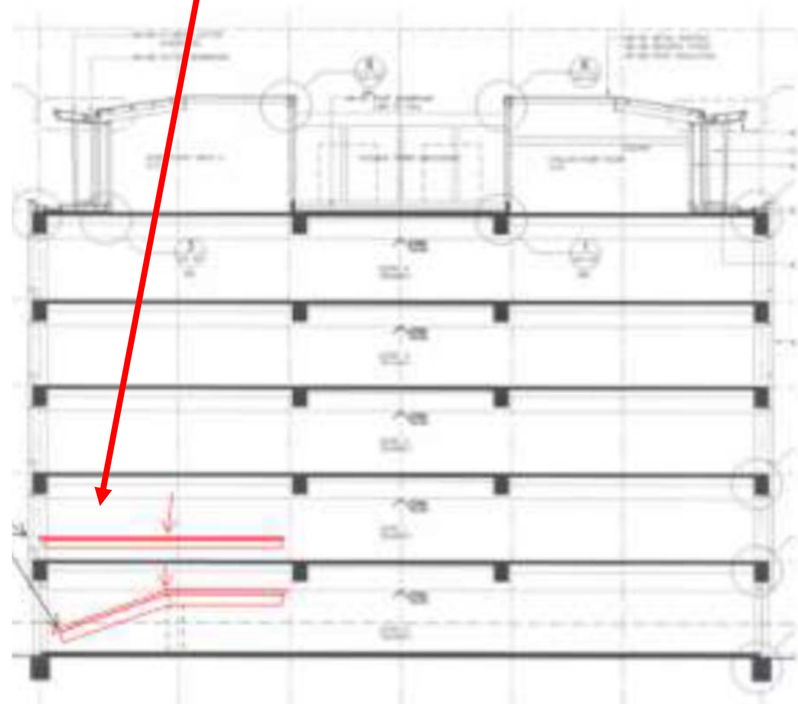
Statistics House

Double tee units collapsed from L1 and L2





Statistics House

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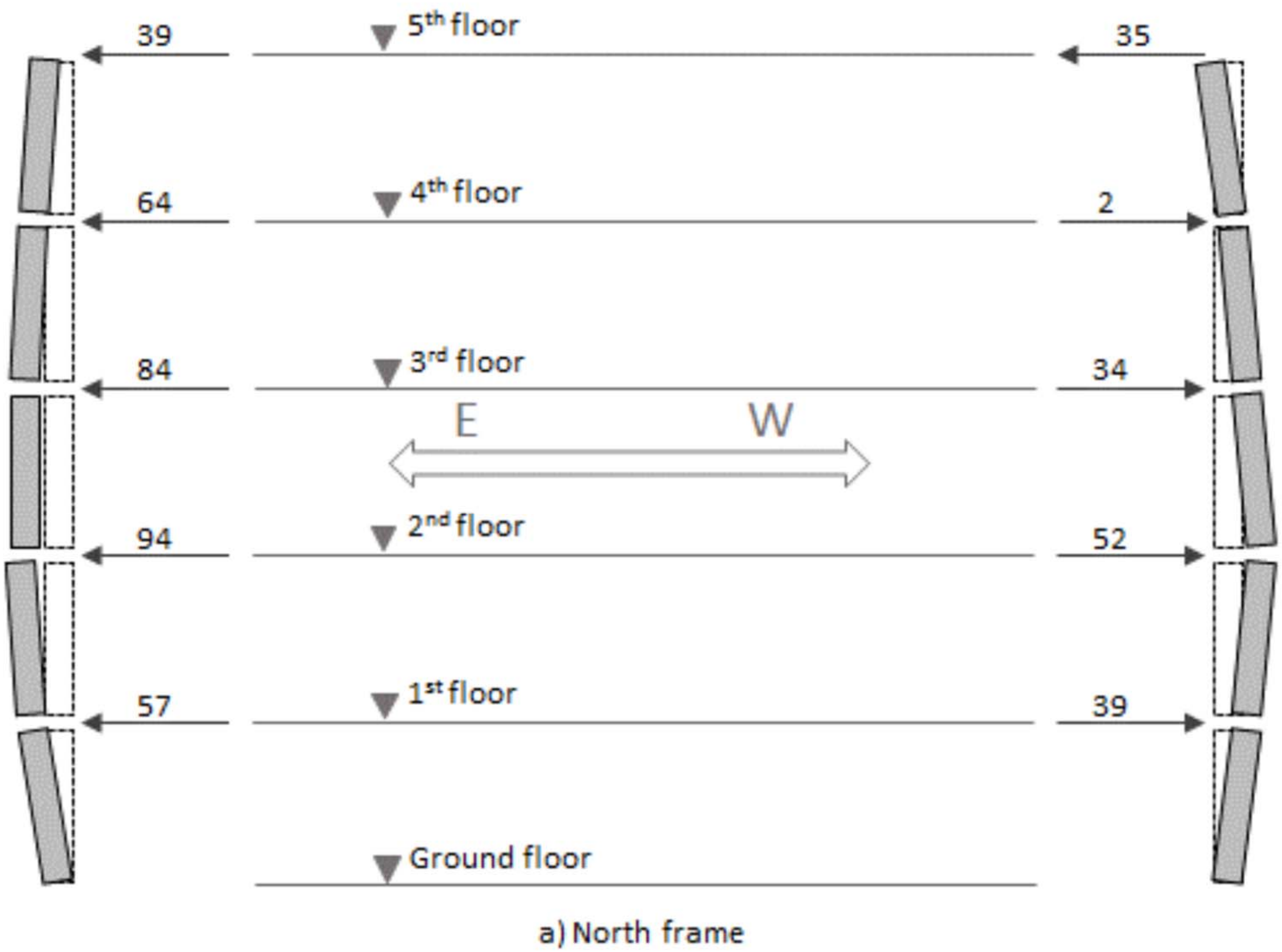
Stats House Investigation, MBIE

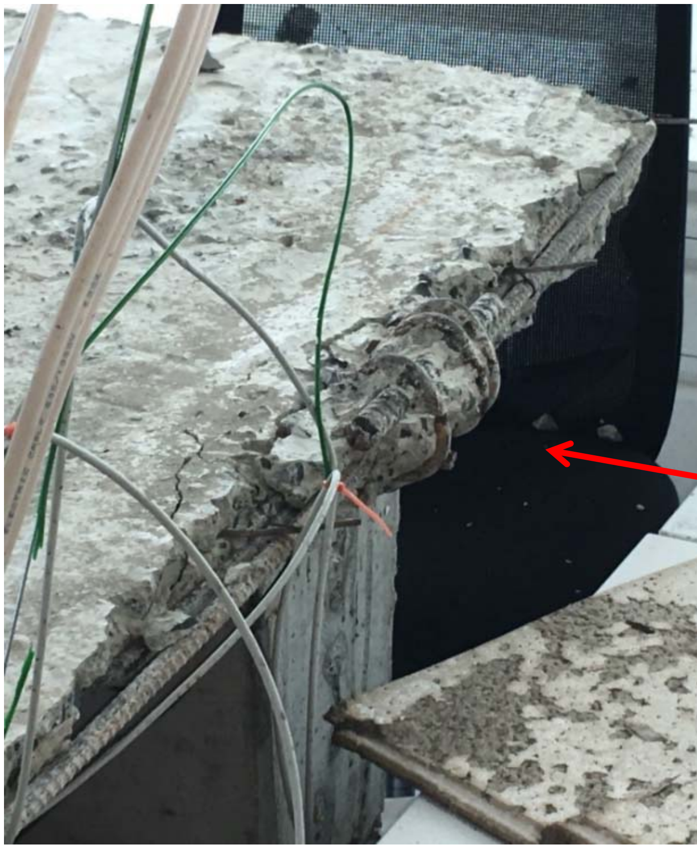
Statistics House

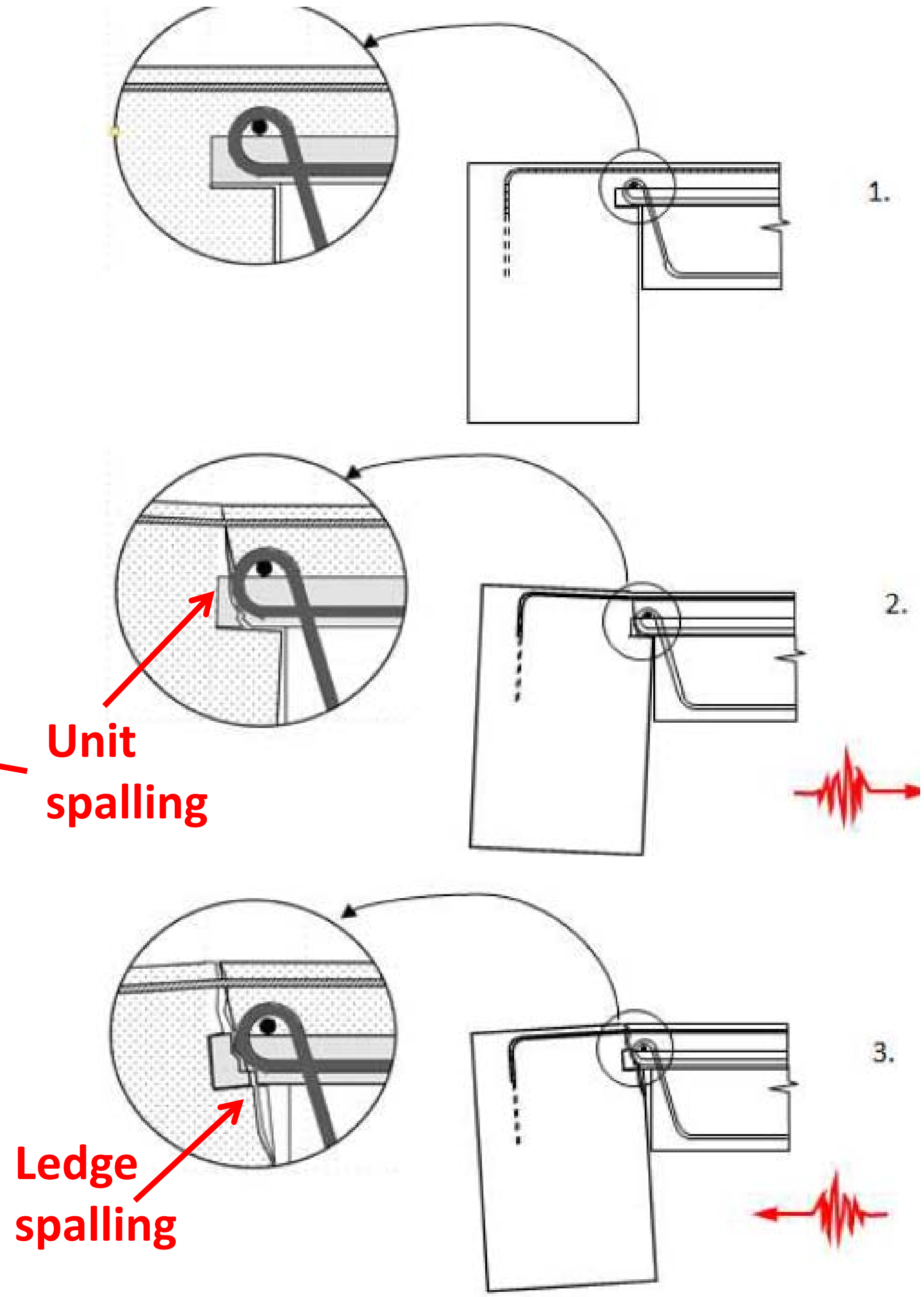
~150mm frame dilation



Stats House Investigation, MBIE

Statistics House





Stats House Investigation, MBIE

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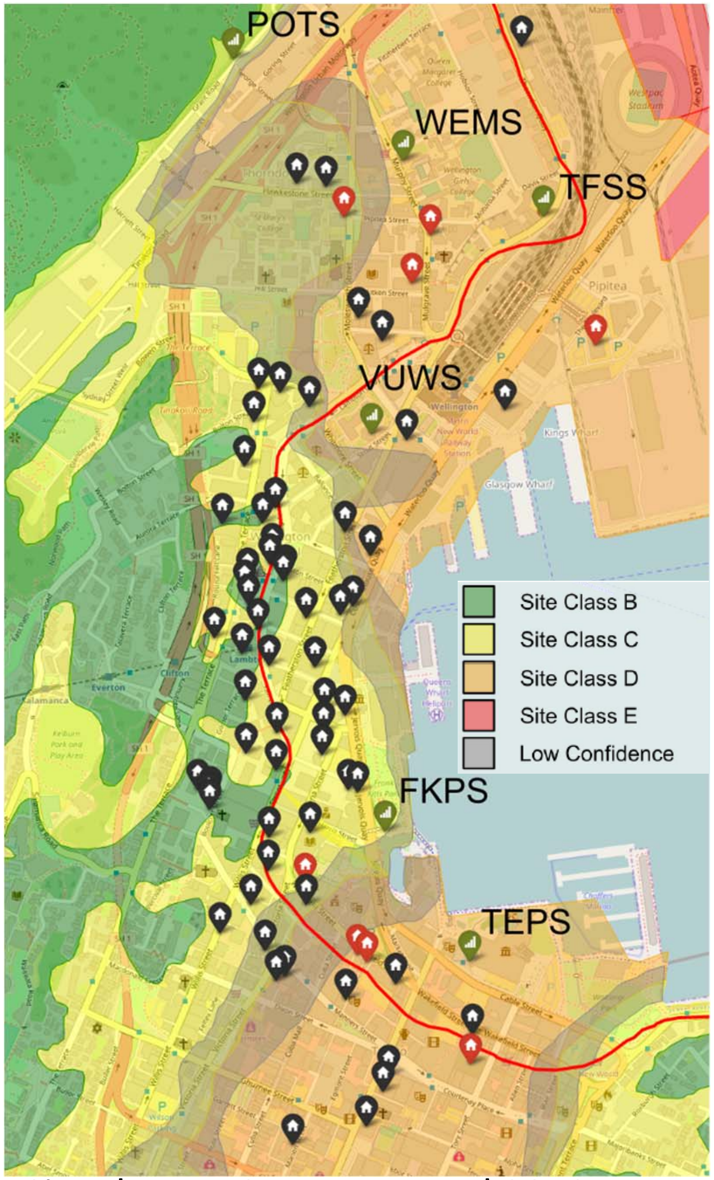
Further Damage

- Impacted buildings in Wellington
  - Deep soil sites (basin effects)
  - Flexible moment frame buildings 5-15 storeys
    (spike in spectra between 1-2s)
  - Precast floor damage
    (long duration → frame elongation)

- Damage discovered during detailed examinations

- Initiated Wellington City Council targeted damage evaluations

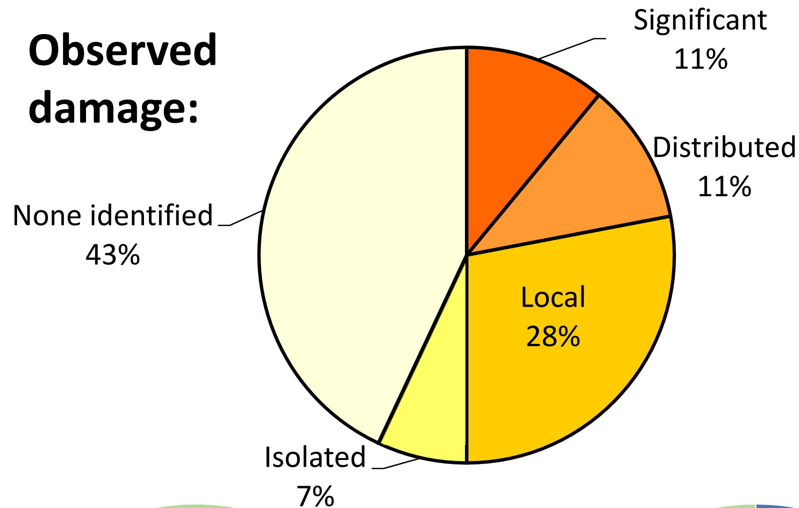
Targeted Damage Evaluations

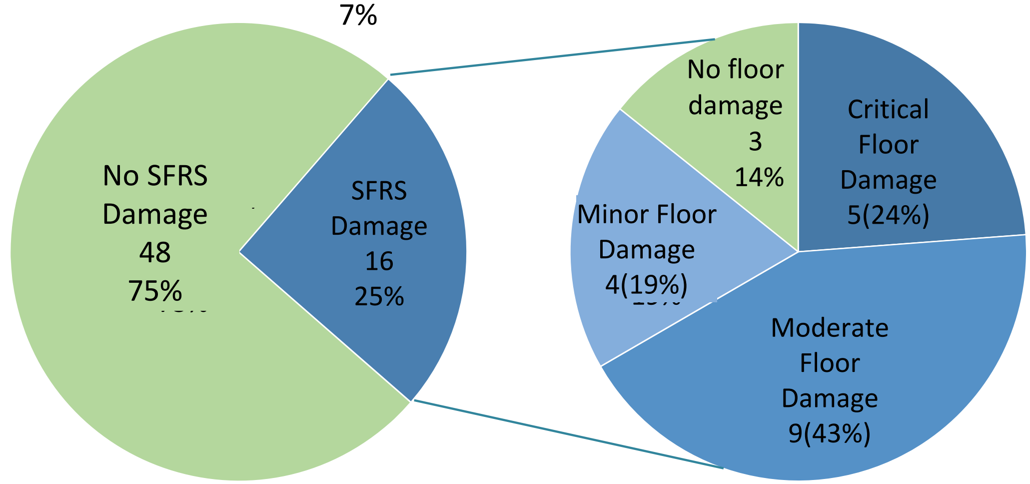


Site classes: Semmens et al 2010

- ✓ 64 inspected buildings with precast floors
- ✓ 8 others with significant damage

Observed damage:

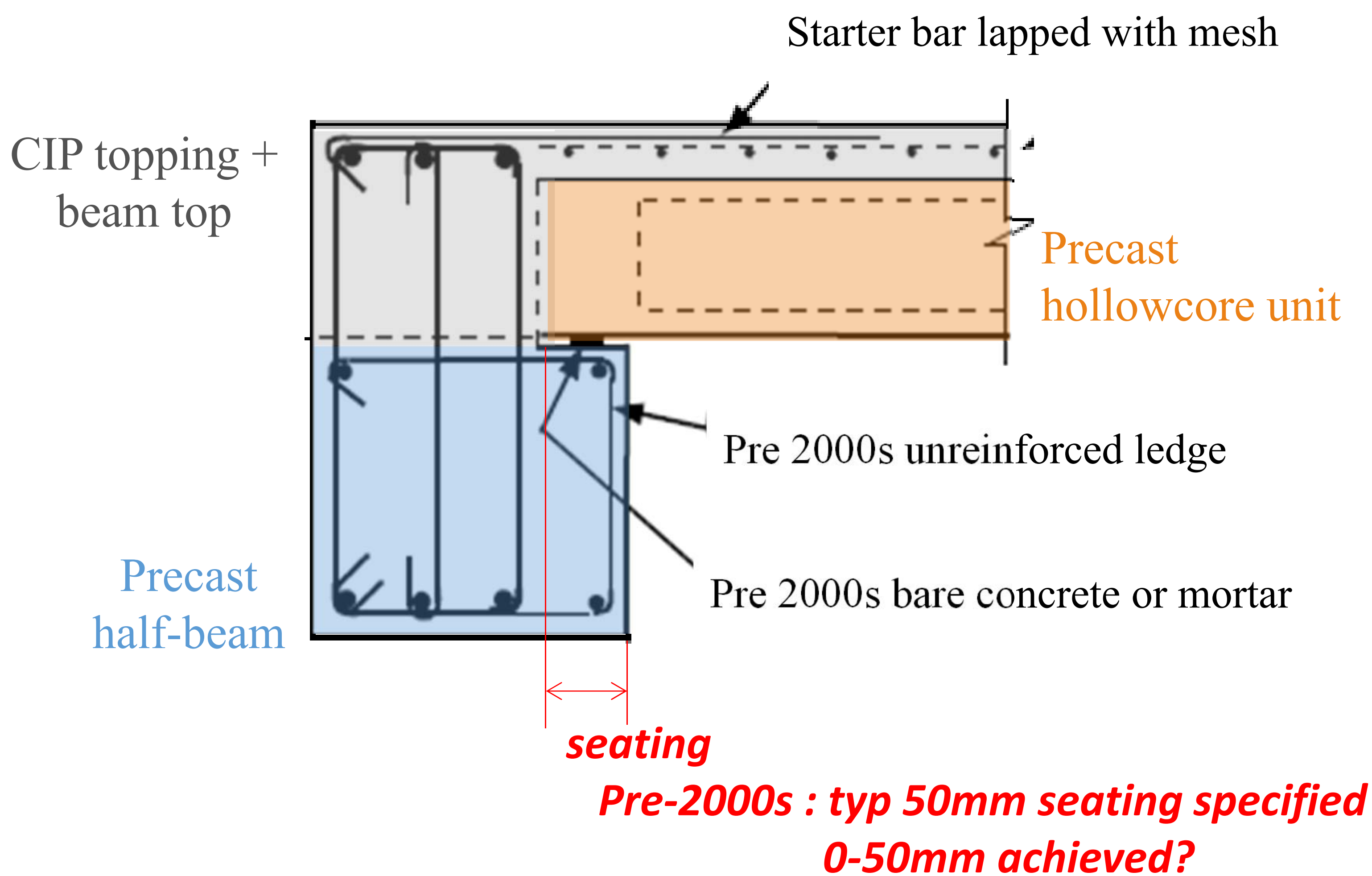




(a) Lateral system damage

(b) Type of floor damage in those building presenting lateral system damage

Hollowcore seating details



Hollowcore floor damage

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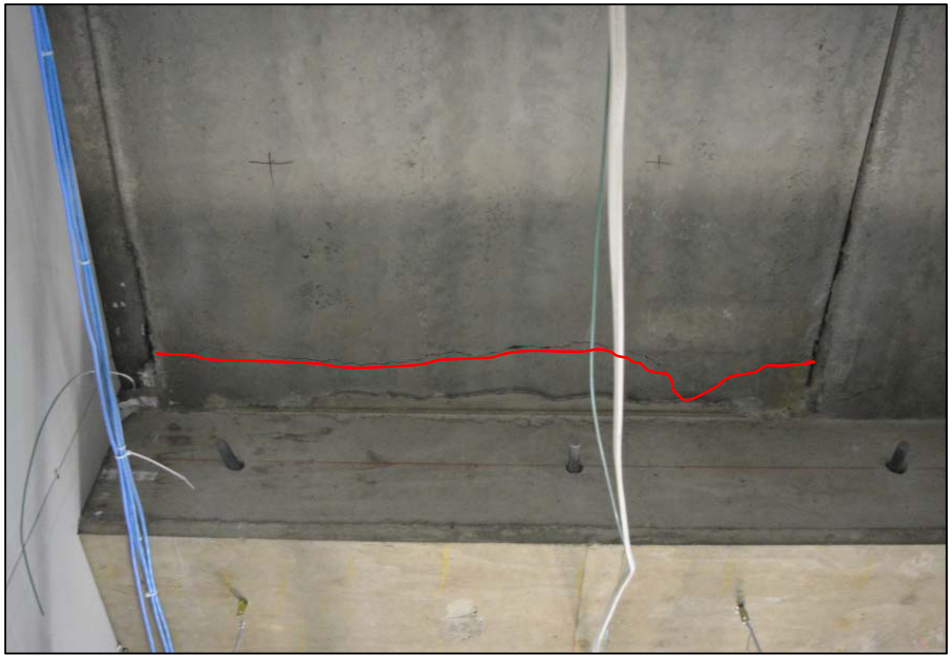
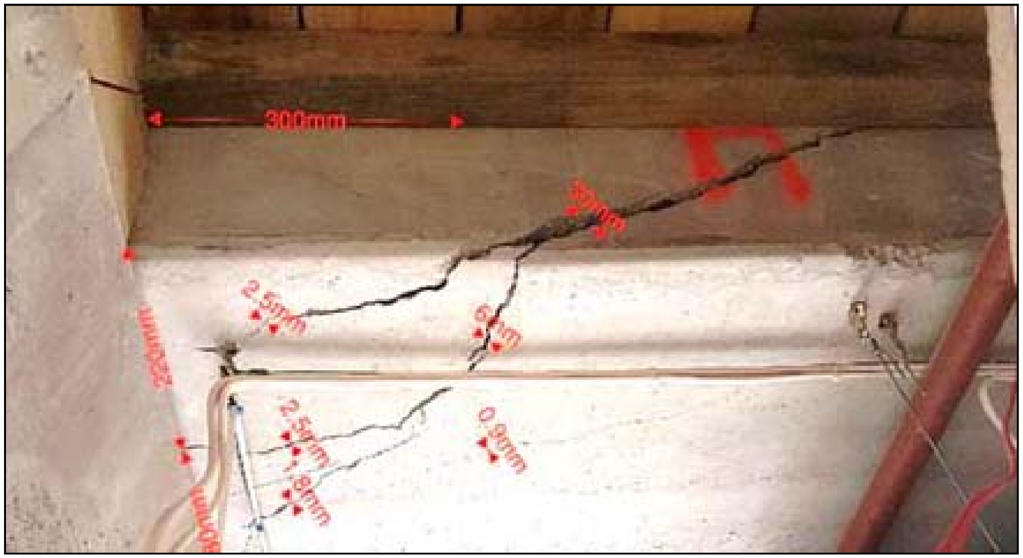
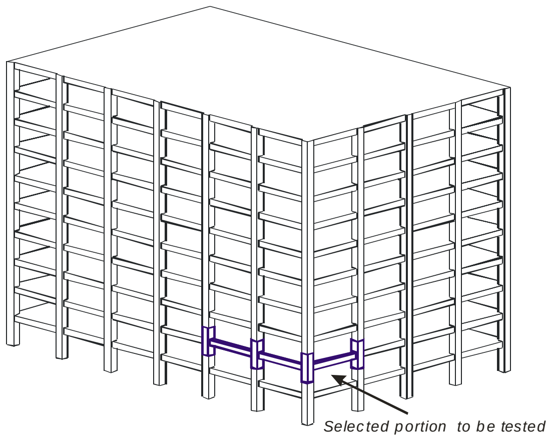
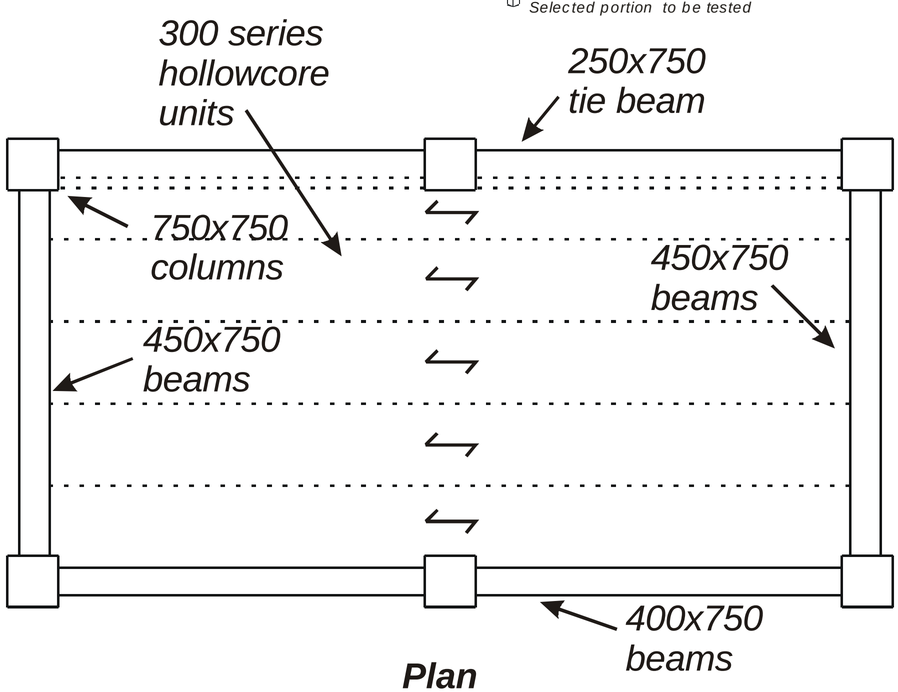




1994 Northridge Earthquake

Matthews and Bull (2004)
2-bay x 1-bay specimen



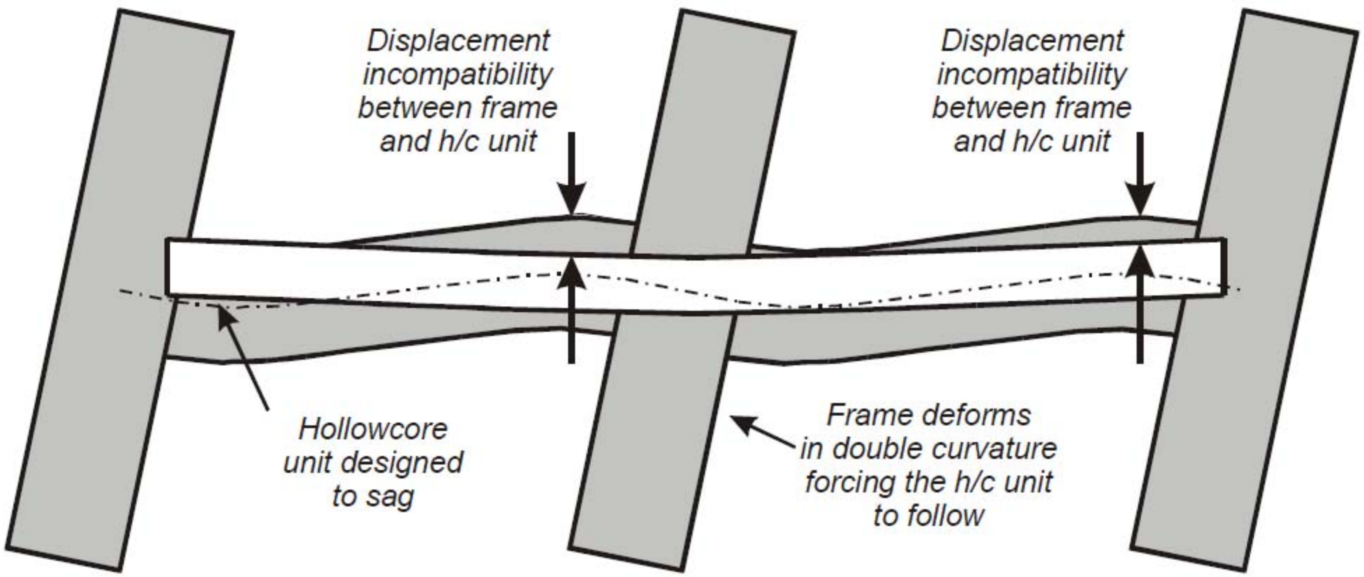


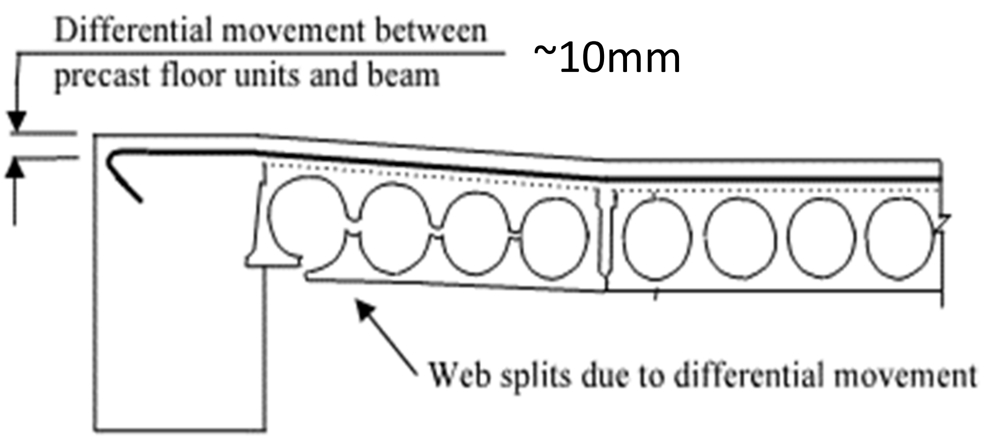
Matthews(2004)

UoC test – *Matthews (2004)*

2.5% drift

Incompatible displacements



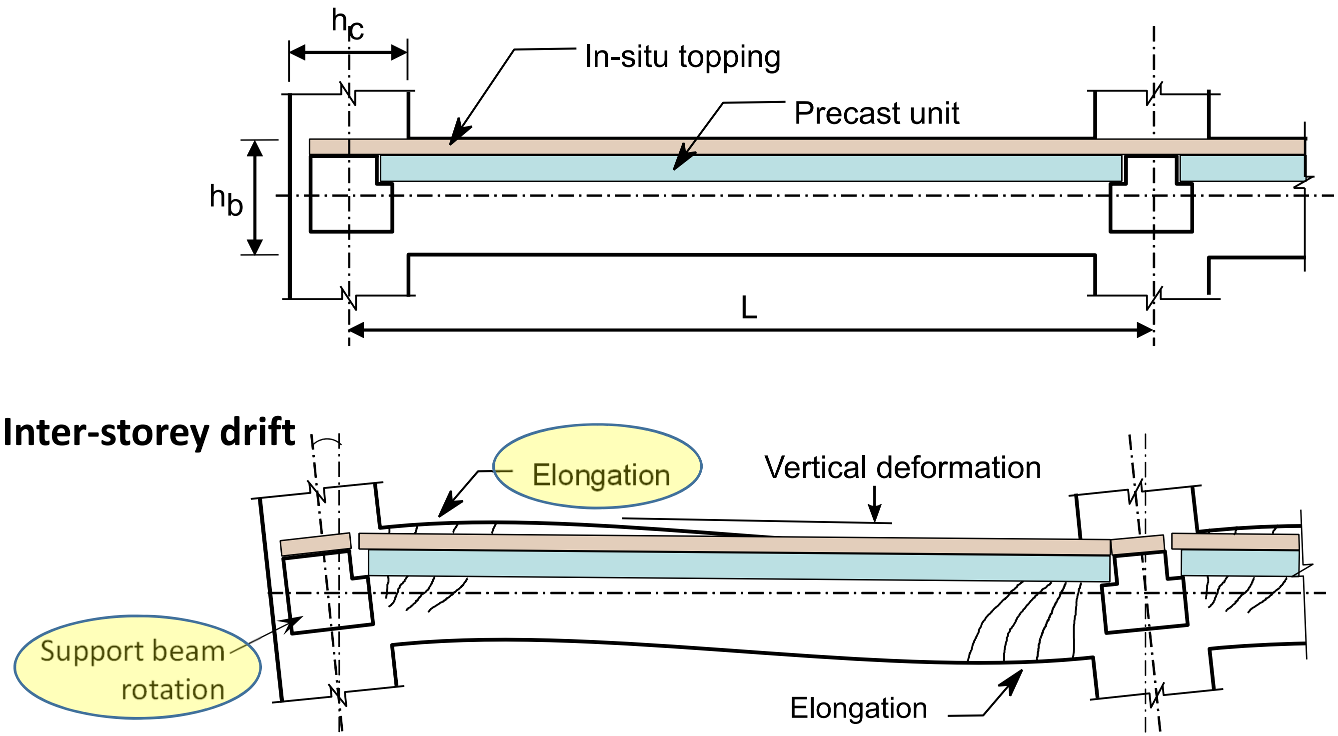


~10mm

Matthews et al (2004)

UoC test – *Matthews (2004)*

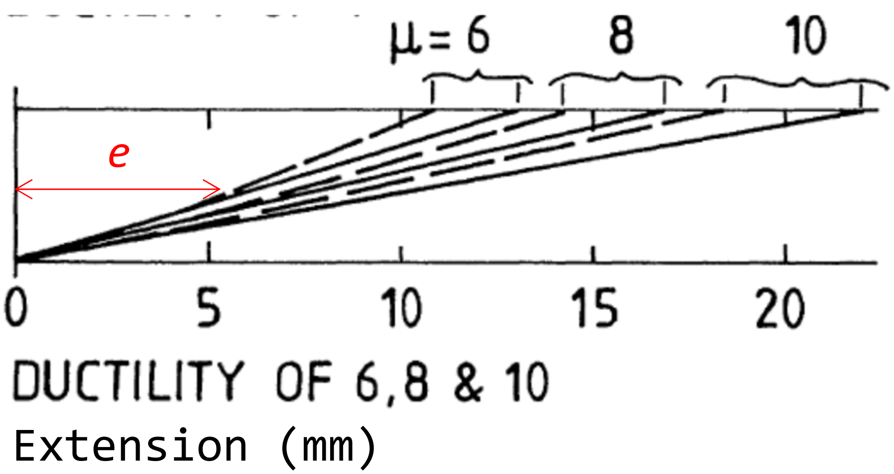
Assessment of Precast Floors
– *Demands*



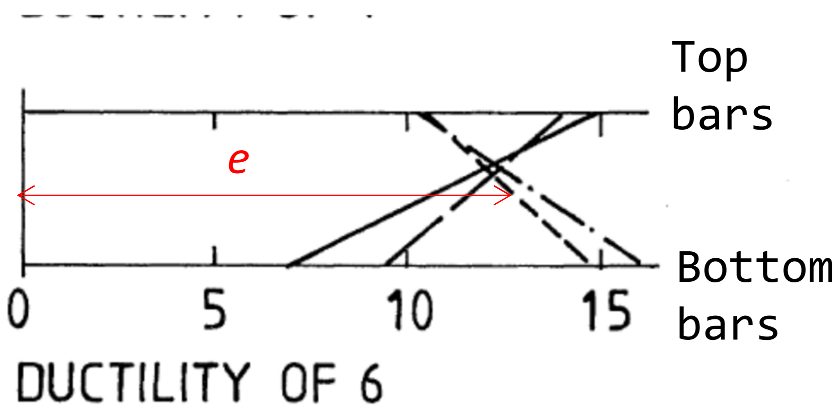
Elongation

- Fenwick and Megget (1993)

Unidirectional Plastic hinge



Reversing Plastic hinge



Unidirectional plastic hinge:

$$e = \theta \frac{(d - d')}{2}$$

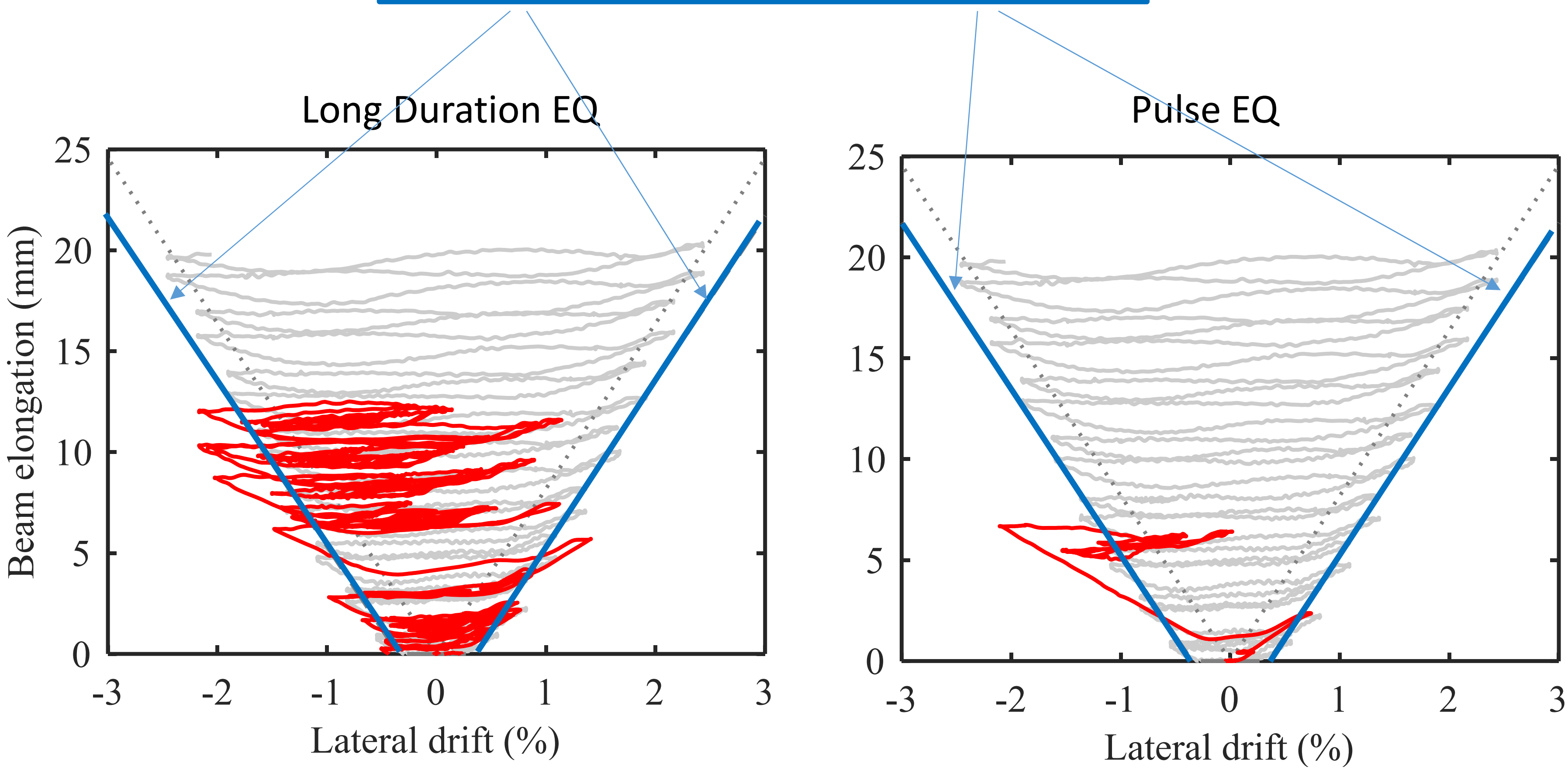
Reversing plastic hinge:

$$e = C\theta \frac{(d - d')}{2}$$

(NZS 3101: C=2.6)

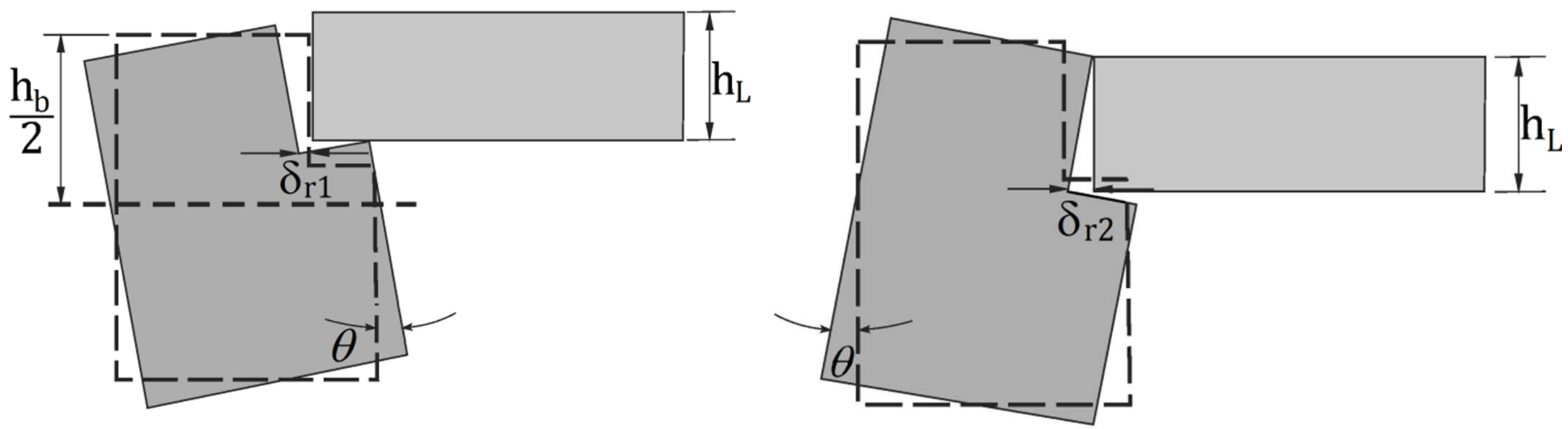
Elongation

$$e = 2.6\frac{\theta_p}{2}(d - d') \leq 0.036h_b$$



Rotation

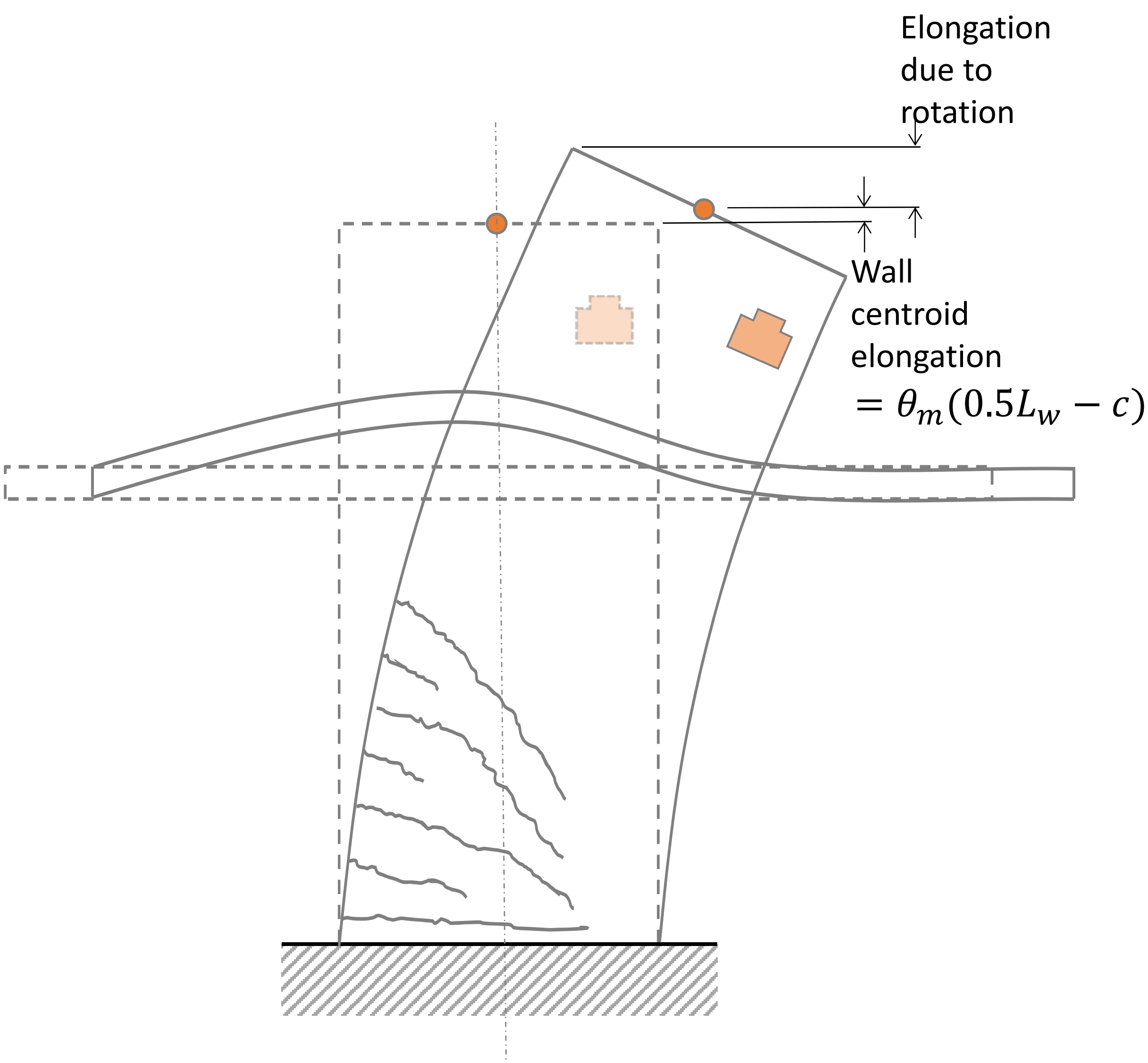
- Movement at support ledge due to rotation added to elongation



Rotation and Elongation

Rotation only

Wall elongation



Kaikoura EQ damage

Drift Capacity of Hollowcore Floors
– *Failure modes*

Loss of Seating (LOS)

Positive Moment Failure (PMF)

Negative Moment Failure (NMF)

Objective:

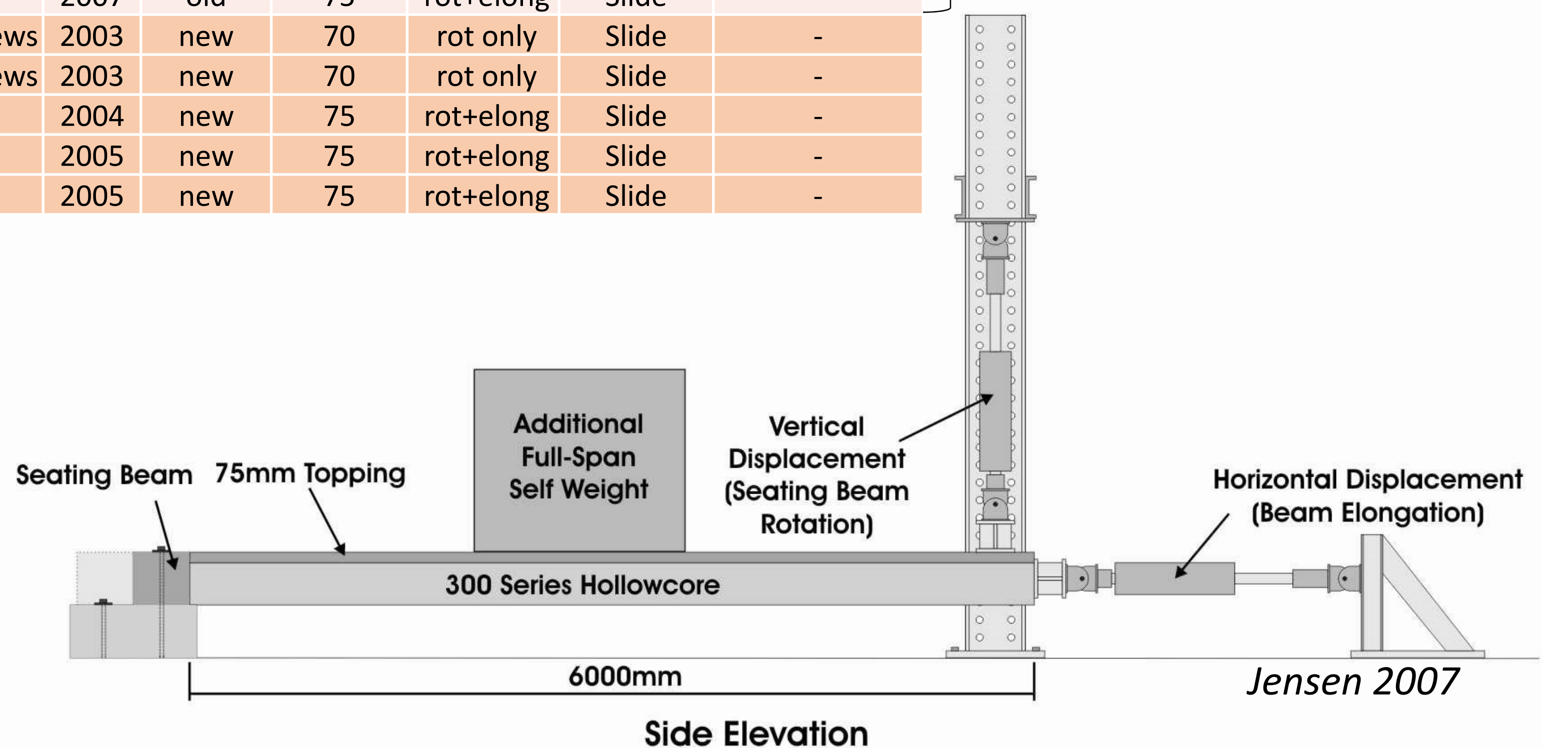
- Determine inter-storey drift at which floor units no longer have ***reliable*** gravity load path.

Hollowcore Floors
– *test data (Des Bull + students)*

Name	Researcher	Date	Type	Seating (mm)	Loading	Failure mode	Drift capacity (%)
HC1-B-03	Bull and Matthews	2003	old	50	rot only	PMF	3.0
HC4-B-03	Bull and Matthews	2003	old	50	rot only	PMF	1.8
S1-L-04	Liew	2004	old	0	rot only	NMF	1.1
S2-L-04	Liew	2004	old	70	rot only	NMF	1.9
S3-L-04	Liew	2004	old-retro	20	rot only	NMF	1.8
HC1-J-07	Jensen	2007	old	35	rot+elong	LOS	1.7
HC3-J-07	Jensen	2007	old	50	rot+elong	LOS	1.7
HC4-J-07	Jensen	2007	old-retro	50	rot+elong	LOS + slide	2.5
HC2-J-07	Jensen	2007	old	75	rot+elong	Slide	-
HC2-B-03	Bull and Matthews	2003	new	70	rot only	Slide	-
HC3-B-03	Bull and Matthews	2003	new	70	rot only	Slide	-
S1-T-04	Trowsdale	2004	new	75	rot+elong	Slide	-
S1-M-05	Macpherson	2005	new	75	rot+elong	Slide	-
S2-M-05	Macpherson	2005	new	75	rot+elong	Slide	-

Loss of reliable load path (Drift capacity)

Pre-2006 details (rows HC1-B-03 to HC2-J-07)



Jensen 2007

Loss of Seating (LOS) - Spalling

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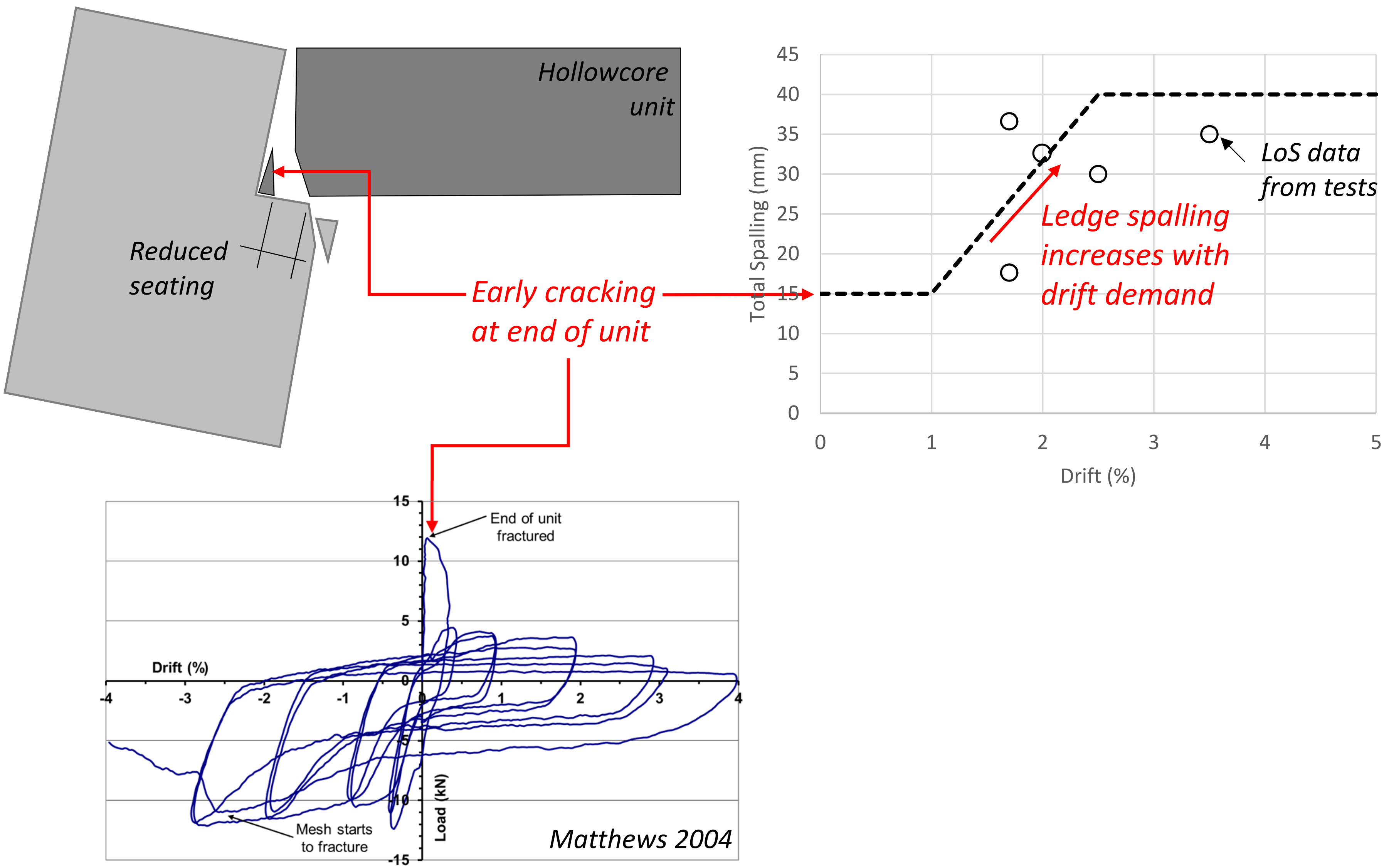
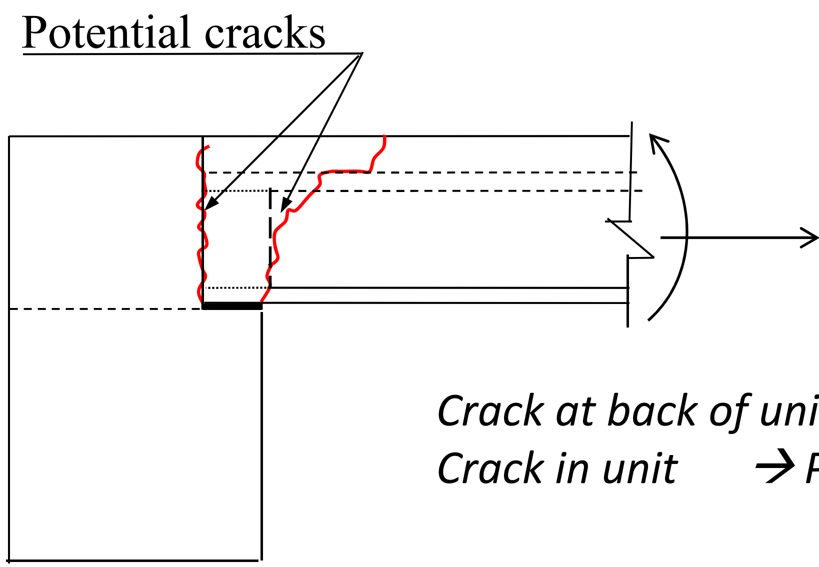
- Kaikoura evidence

Loss of Seating (LOS)

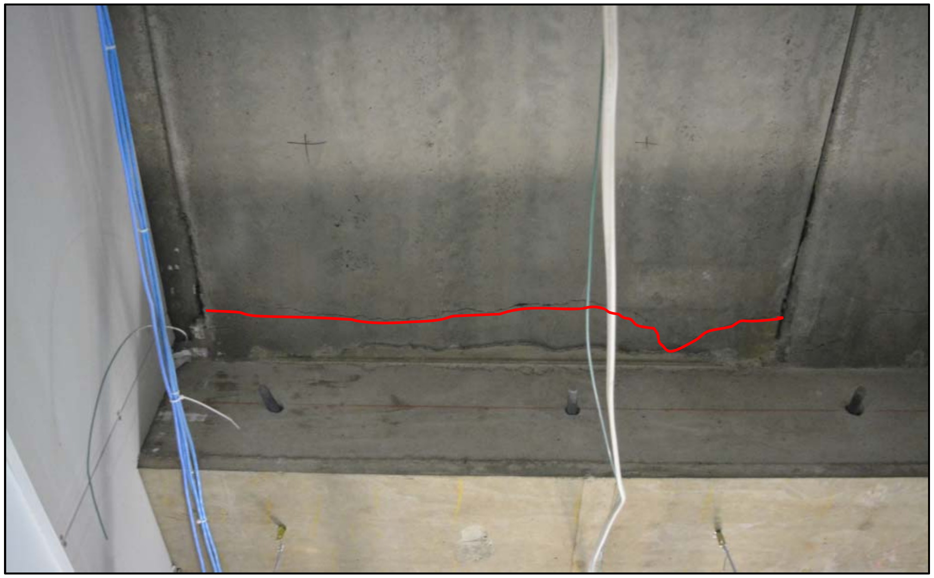


Positive Moment Failure



Crack at back of unit → Loss of Seating (LOS) critical
Crack in unit → Positive Moment Failure (PMF) critical

Matthews (2004)



Kaikoura EQ damage

Negative Moment Failure (NMF)

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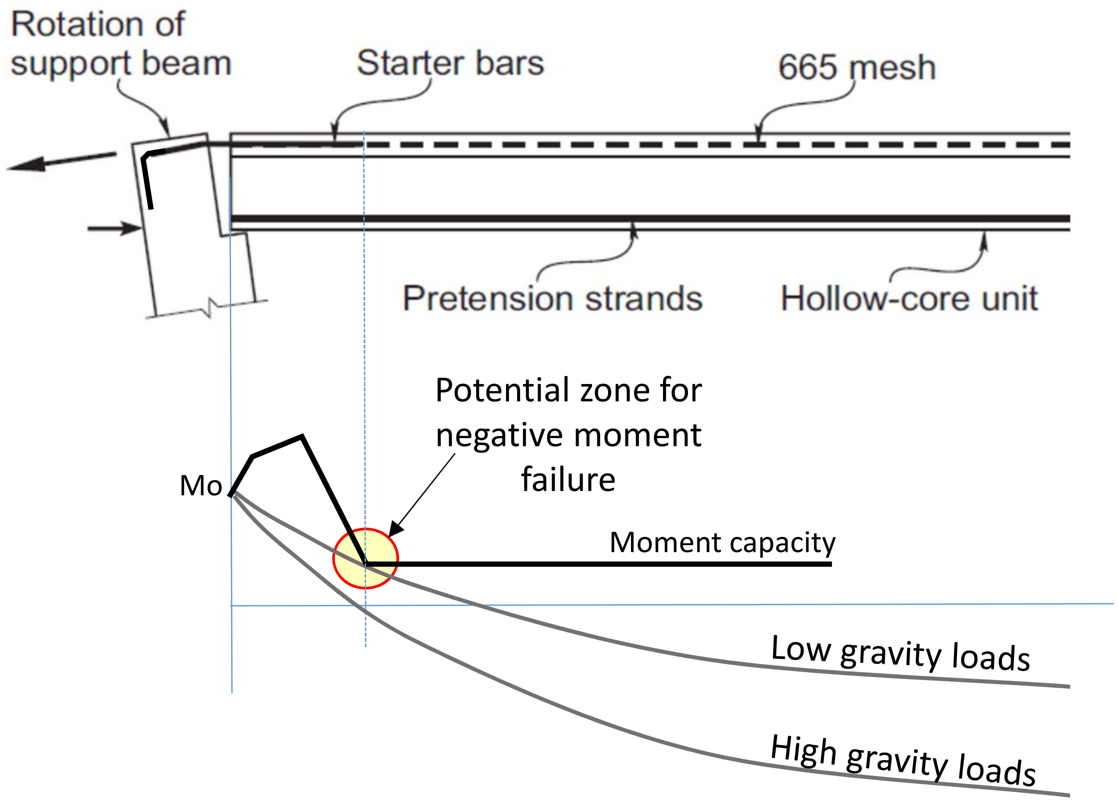
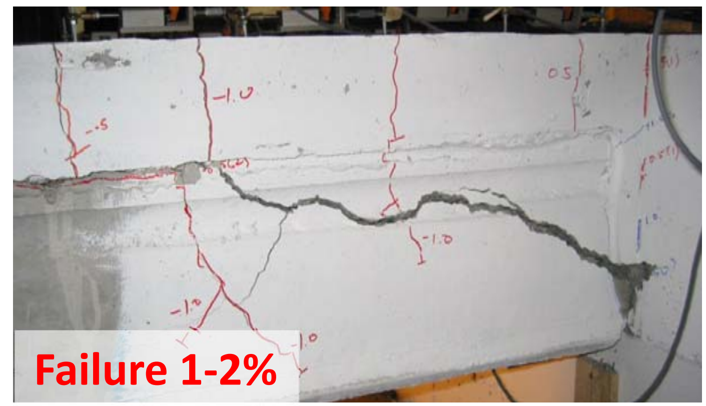


If NMF triggered
→ **Limiting drift = 1%**



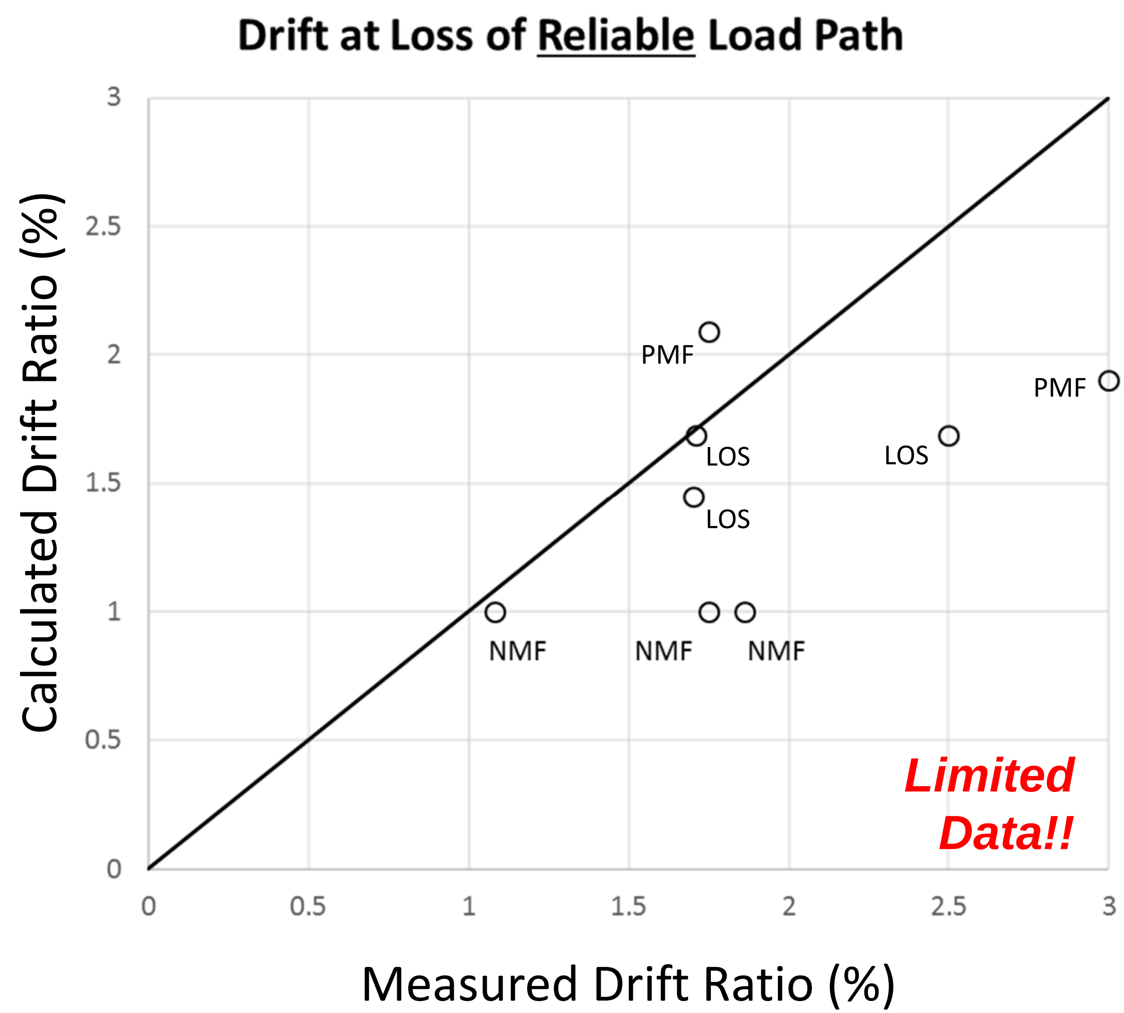
Liew 2004

Be aware of:

- *Low gravity loads*
- *Strong or short starters*

Hollowcore Floors – test data

- Validation of assessment



Summary

- Wellington vs. Christchurch
  - Long duration → frame elongation → floor damage
- Precast floor damage
  - Most issues with older detailing in existing (80s) buildings
  - Damage often hidden – ***How to inspect?***
  - Floors fragile – ***easily damaged, but how to repair?***
- Precast floor assessment provisions developed
  - www.eq-assess.org.nz

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Thank you!

Questions?

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

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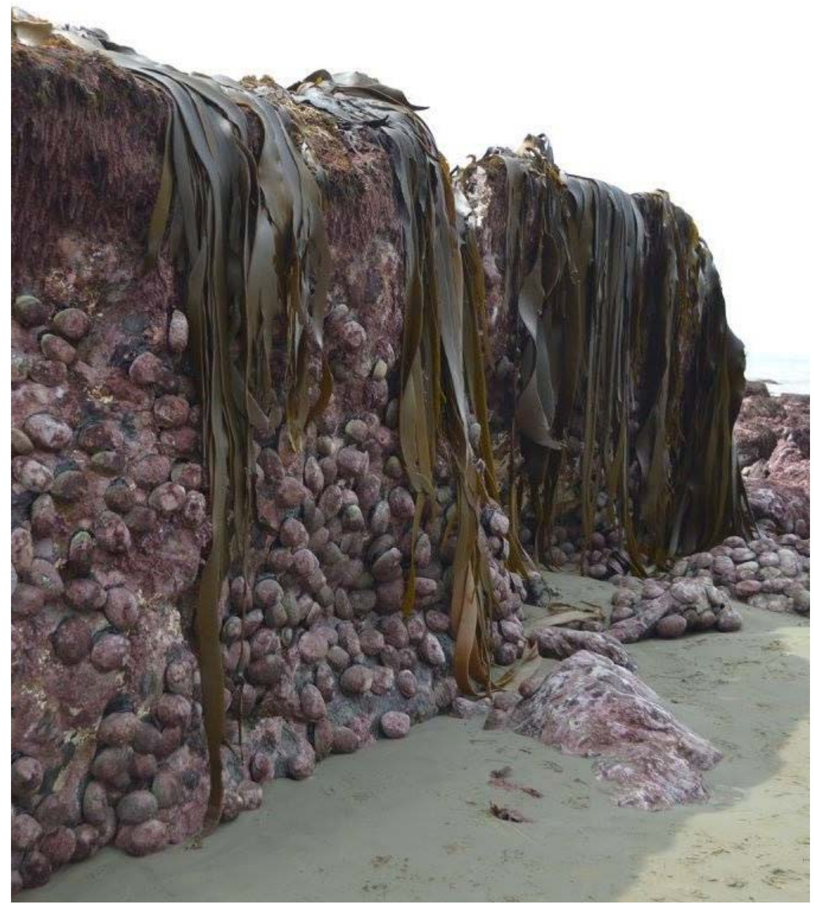

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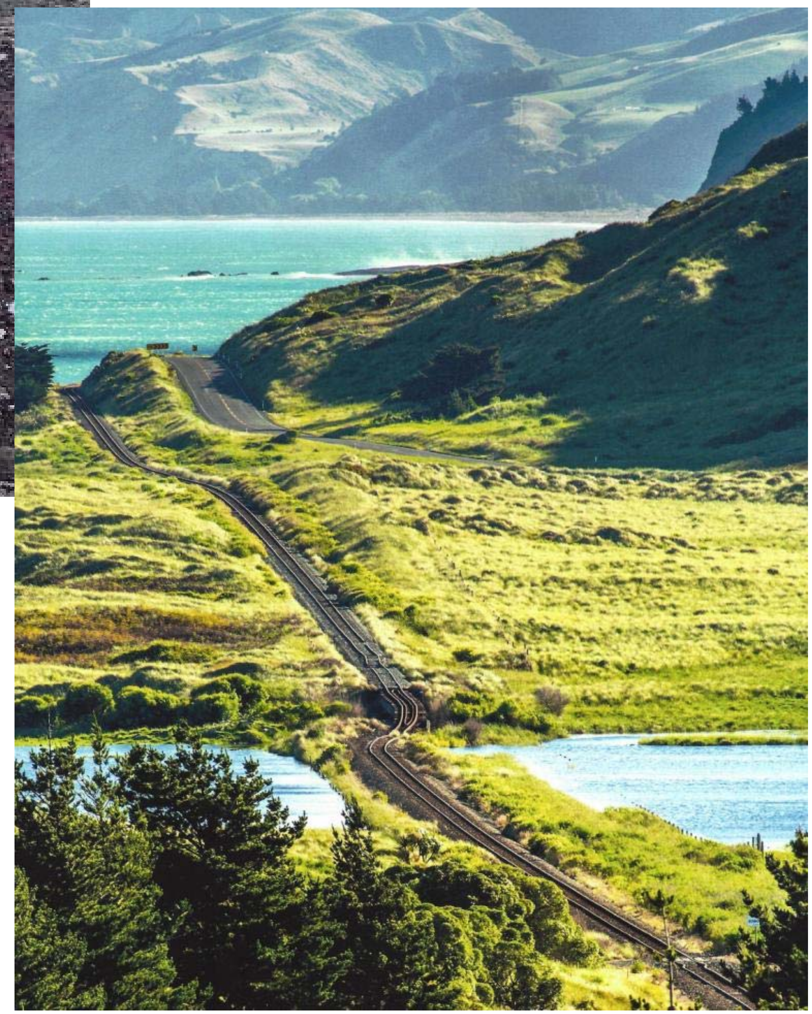

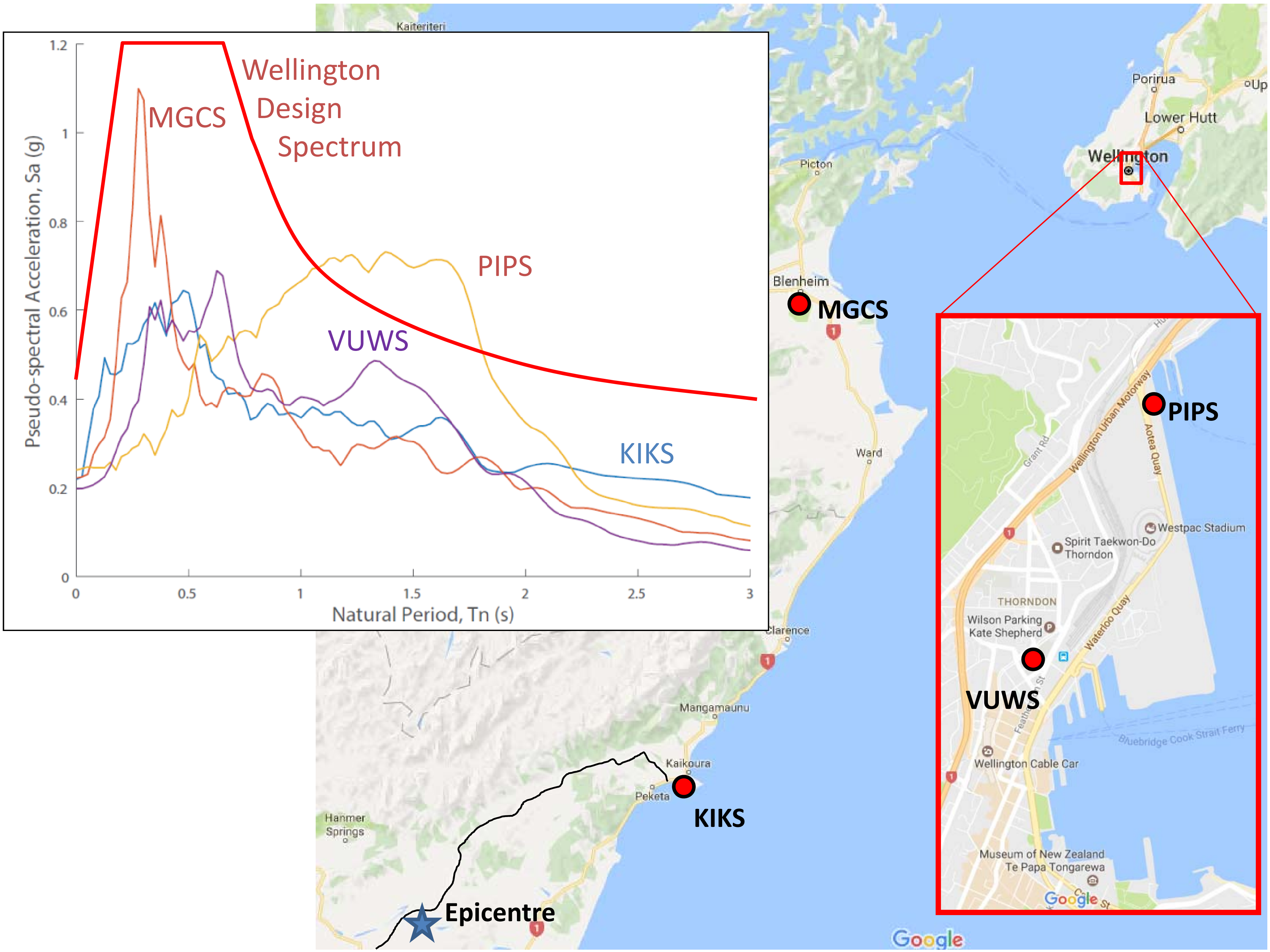

Pseudo-spectral Acceleration, Sa (g)
Natural Period, Tn (s)
1.2
1
0.8
0.6
0.4
0.2
0
0.5
1
1.5
2
2.5
3
Wellington Design Spectrum
MGCS
PIPS
VUWS
KIKS
Kaiteriteri
Porirua
Lower Hutt
Wellington
Picton
Blenheim
Ward
Clarence
Mangamaunu
Kaikoura
Peketa
Hanmer Springs
Epicentre
Wellington Urban Motorway
Grant Rd
Aotea Quay
Westpac Stadium
Spirit Taekwon-Do Thorndon
THORNDON
Wilson Parking Kate Shepherd
Waterloo Quay
Wellington Cable Car
Bluebridge Cook Strait Ferry
Museum of New Zealand Te Papa Tongarewa
Google

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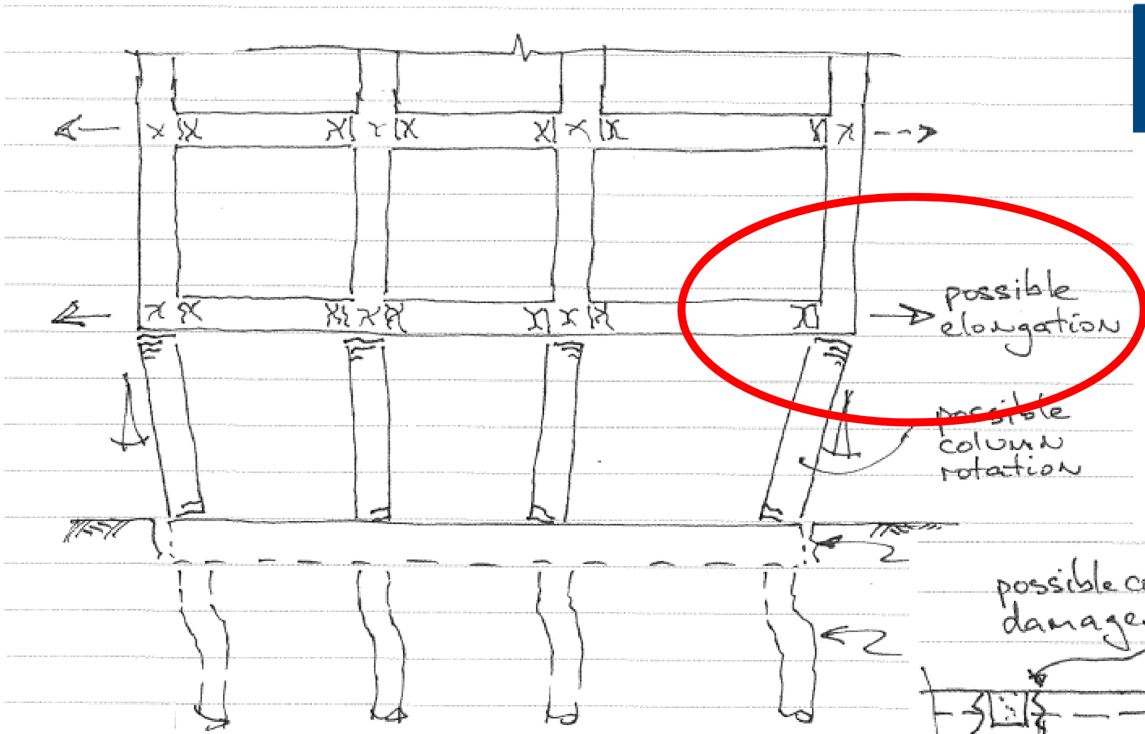
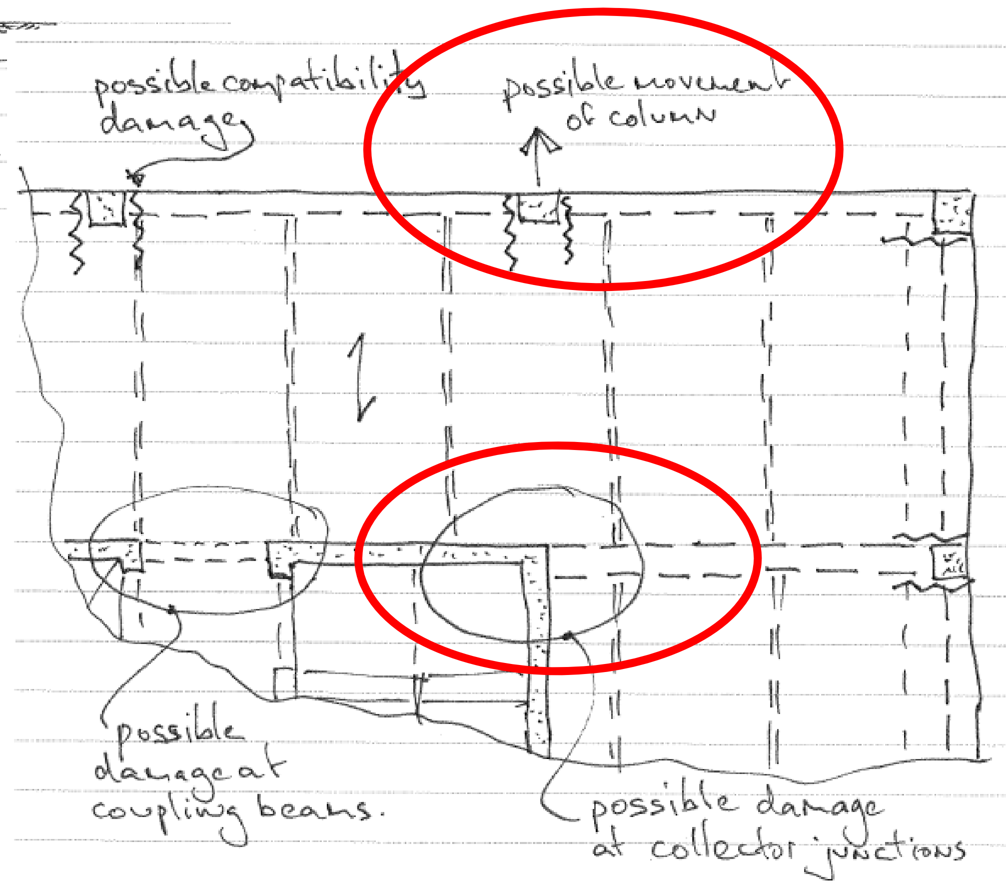
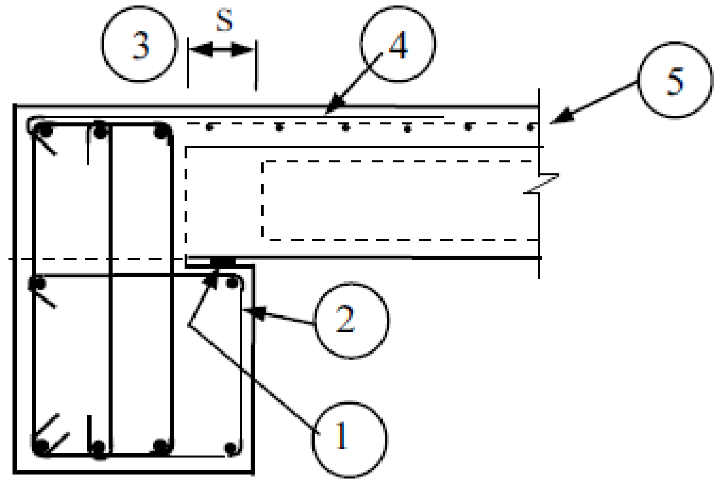




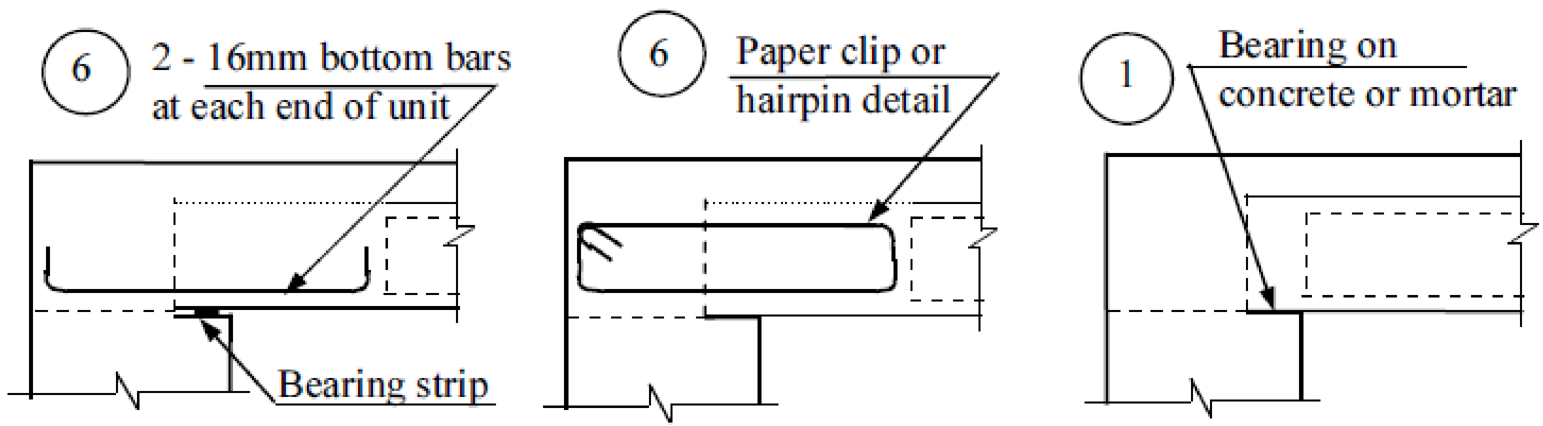
Hollowcore



Refer to Table 5 -1 for reference numbers

7 Negative moment zone due to continuity with the support reduces the shear strength of the floor.

(a) Current practice



Examples: Beam Hinging

Plastic Hinge Damage

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If ANY of the following apply, ***plastic hinge*** residual capacity may have been reduced by earthquake:

1. Total crack width in plastic hinge > 0.005d
2. Sliding has occurred on a crack
3. Wide (>0.5mm) diagonal cracks
4. Concrete degradation, indicated by significant spalling (concrete cover can be removed by hand)

If none apply:

Do not expect degradation in strength, deformation capacity, or energy dissipation; <u>but expect degradation in stiffness leading to larger displacement demands in next event</u>.

Critical Damage States – Primary structure

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Very critical

Less critical

A: Local collapse risk (without aftershock)

A1 Transverse cracking at ends of hollow core or ribs within 400mm of the support beam, plus either associated vertical dislocation or diagonal crack in web

A2 Significant damage to support for flange-hung double tee floor units

B: Local or global collapse risk in aftershock

B1 Transverse cracking at ends of hollow core floor units or ribs within 400mm of the supporting beam & not classified as A1

B2 Reduced precast floor unit support

B3 Loss of lateral support for columns over multiple stories

B4 Shear damage to corner columns

C: Damage to primary structure posing lower risk

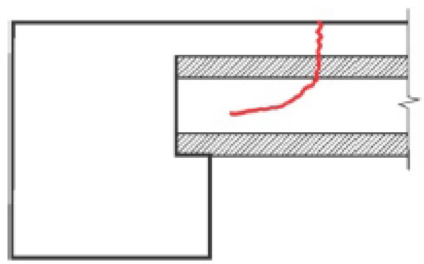
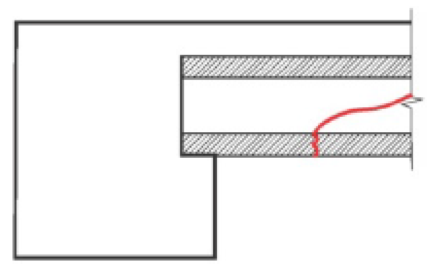
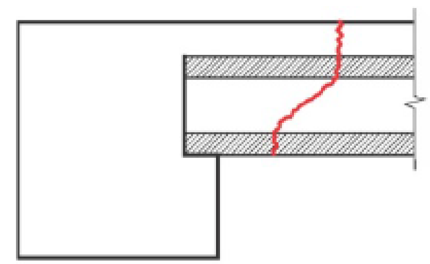
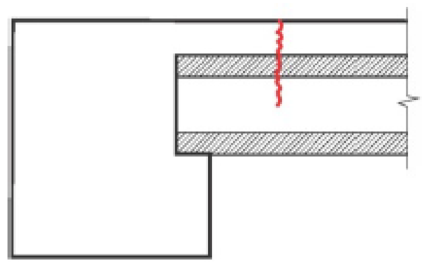
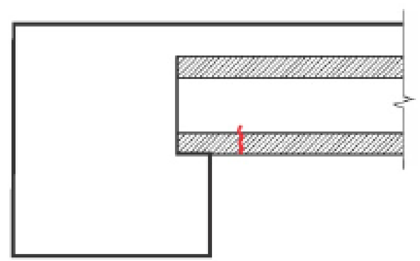
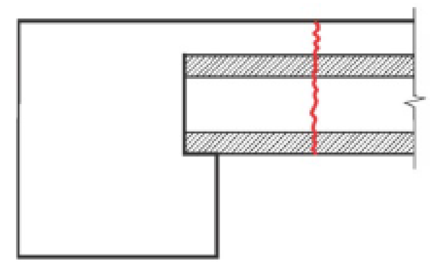
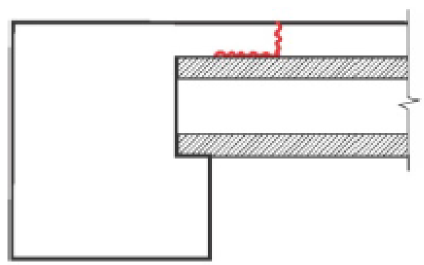
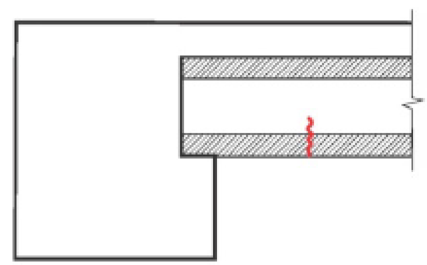
C1 Plastic hinge damage

C2 Web cracking in hollow core floor units

C3 Longitudinal cracking of hollow core floor units

C4 Mesh fracture in floor toppings

Types of Transverse Cracks

	Transverse cracking - Visible from top	Transverse cracking - Visible from bottom	Transverse cracking - Full depth
CDS A			
CDS B		 *Crack within ~400mm of support*	
Other		 *Crack beyond ~400mm of support*	

Examples: Support Damage

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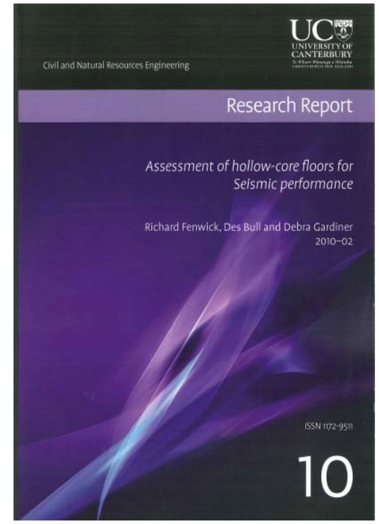
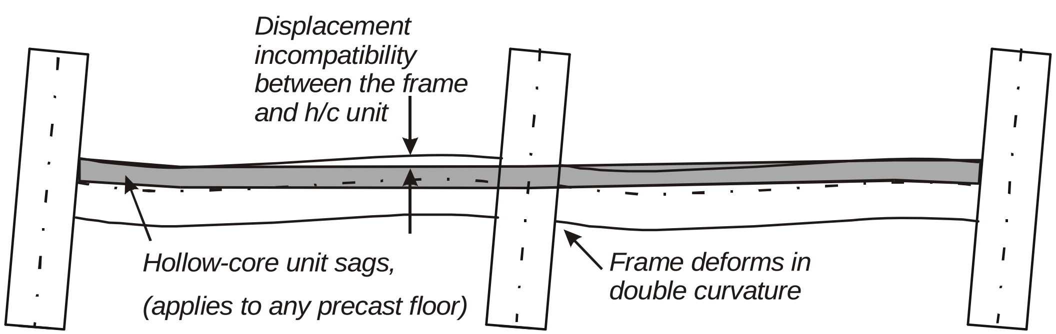
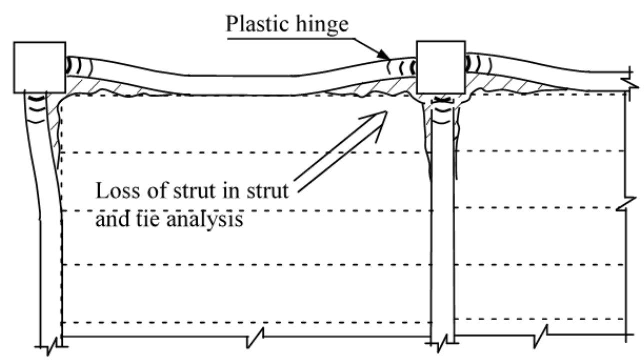
Mechanisms



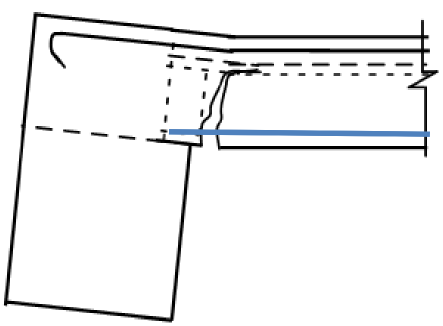
- Past research (Fenwick and Bull) highlighted effects of elongation and poor precast support detailing



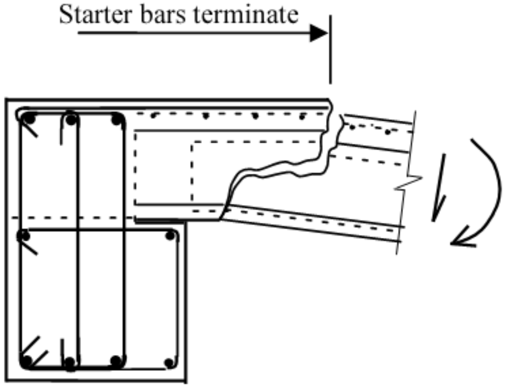


Transverse cracks at end of hollowcore

- Ends trapped or weak section at end of starters
- No reinforcement (long or trans)
- Prestressed stand not fully developed
- Positive or negative moment failure

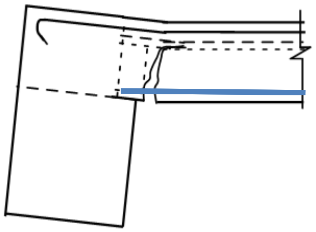


(b) Positive moment flexural failure with critical section near front face of support (see Section A4)

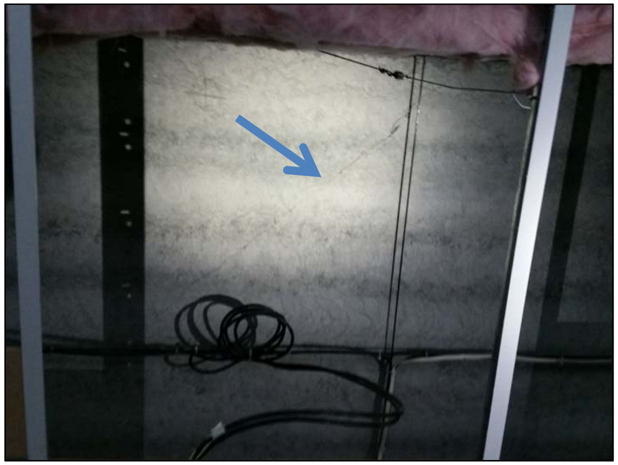


(a) Negative moment flexural failure

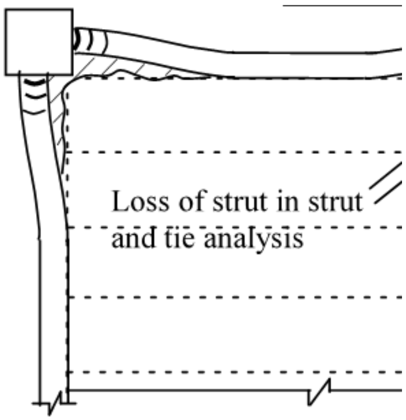
Examples: Transverse Cracks



Examples: Transverse Cracks



Examples: Transverse Cracks



Longitudinal Cracks in Hollowcore

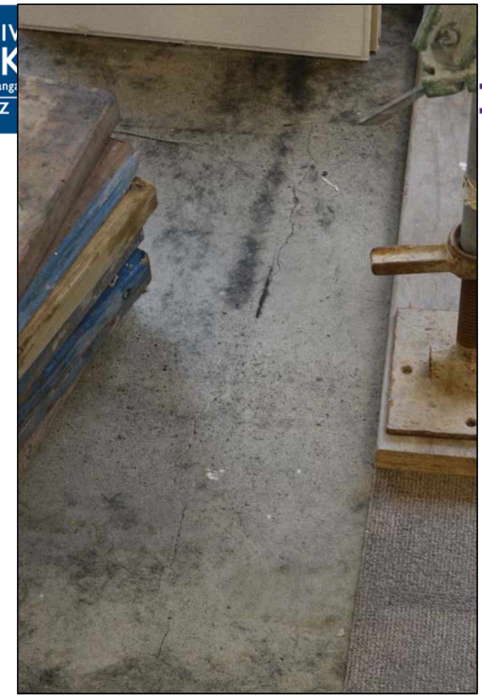
THE UNIVERSITY OF AUCKLAND
Te Whare Wānanga o Tāmaki Makaurau
NEW ZEALAND

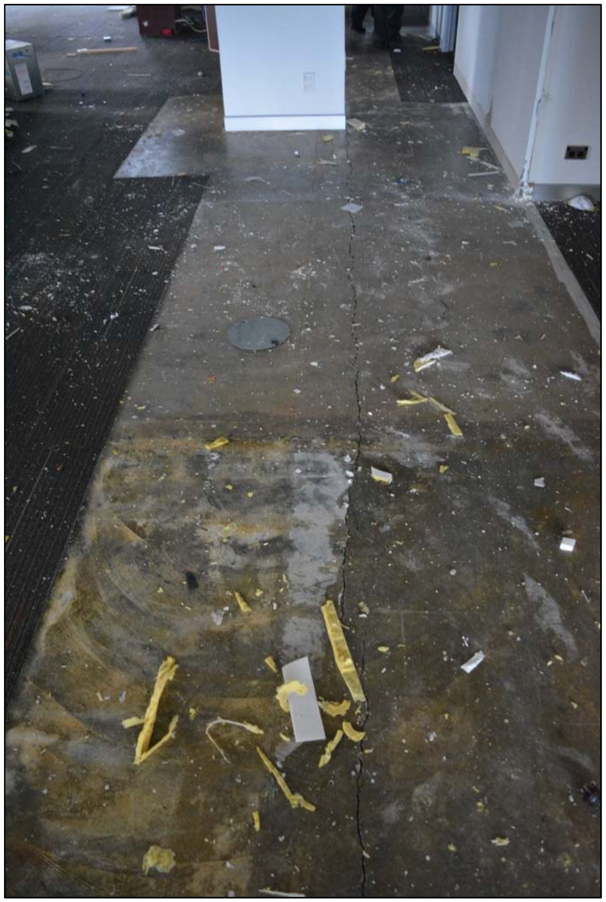
ENGINEERING

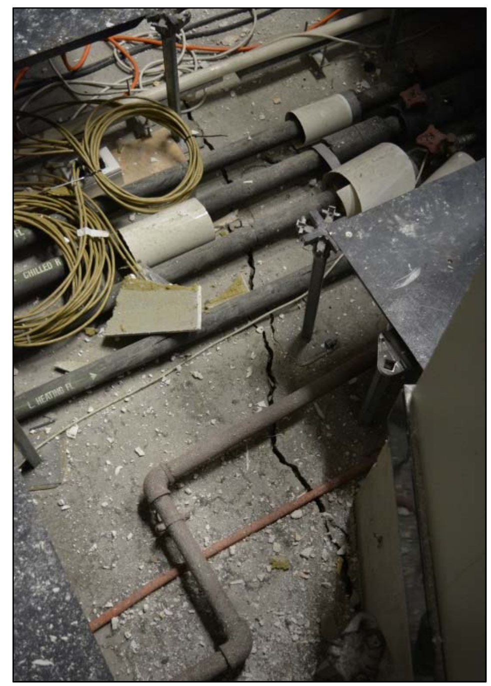




Topping Cracks



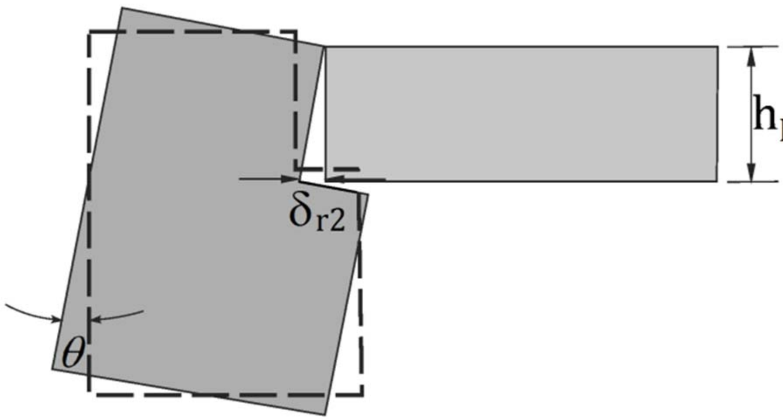




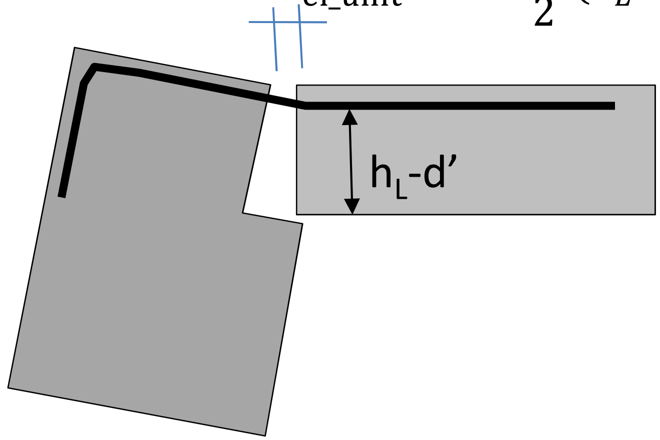
Repair and Retrofit

Unit movement (same for all unit types)

- For rotation only case, consider unit movement due to starter bar plastic strain:

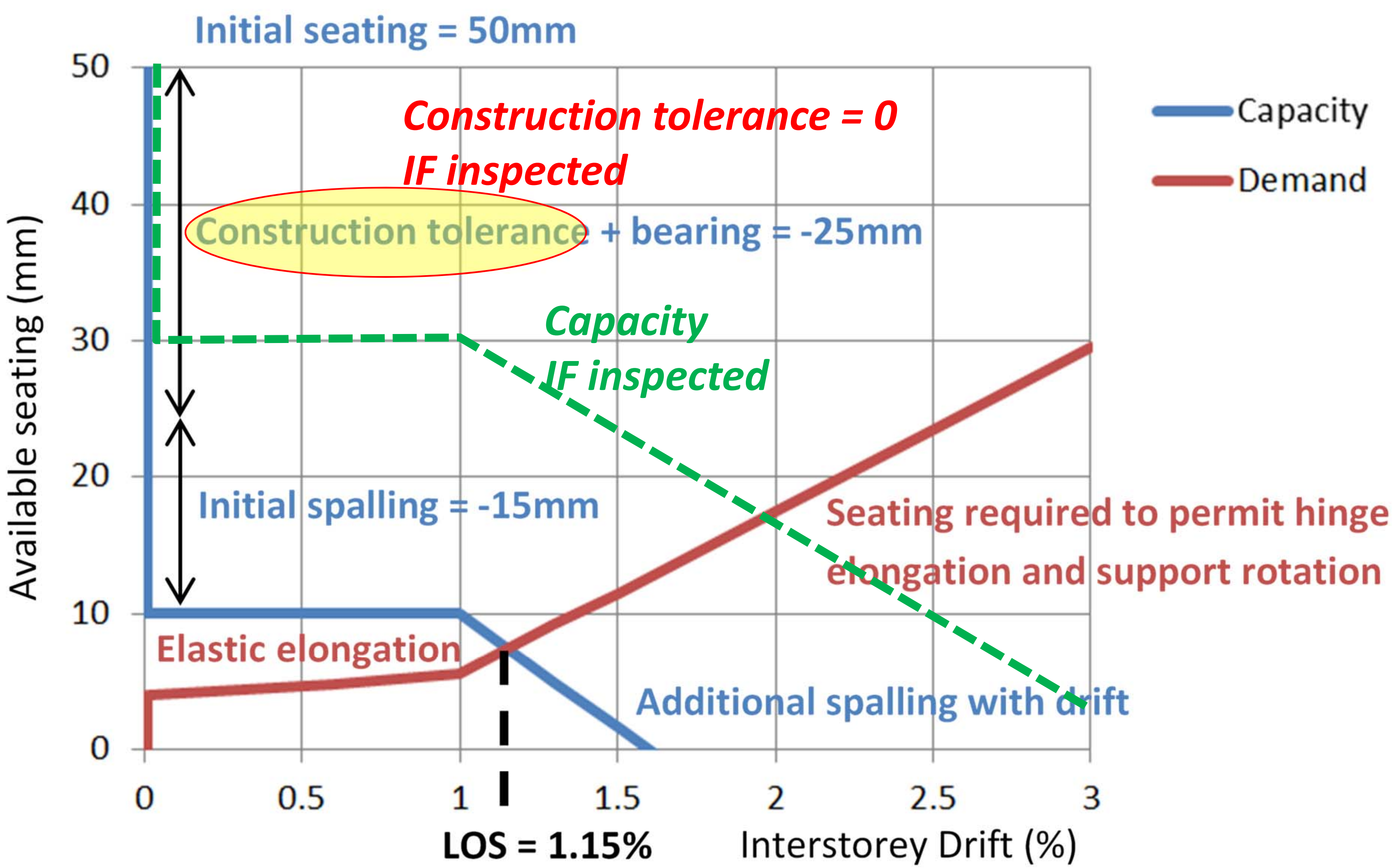


Unit movement: $\delta_{el\_unit} = 1.3\frac{\theta_p}{2}(h_L - d') \leq 0.018h_L$



- Most units considered as restrained (i.e. use $\delta_{el}/2$)

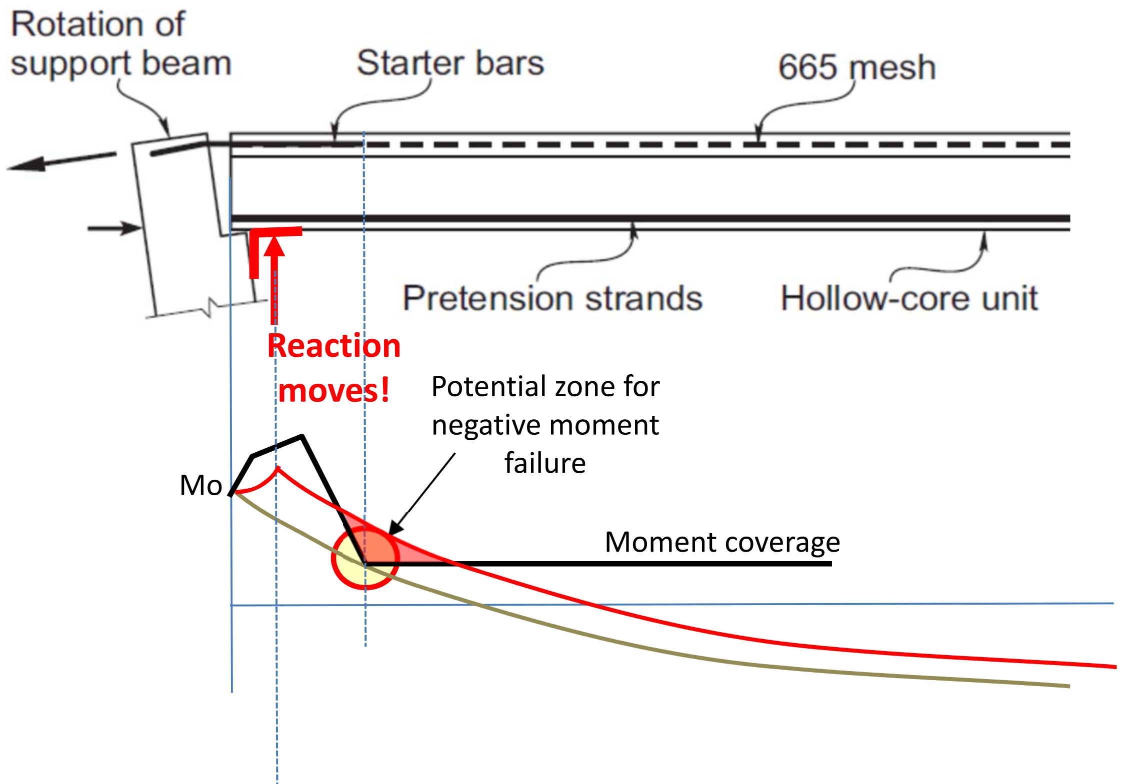
Loss of Seating (LoS)



Chris Poland

Negative Moment Failure (NMF)

Retrofit support:



Liew 2004

- *Effectively same as shorter starters!*

→ Keep retrofit supports below the unit to ensure no contact!
(Stay tuned for results from ongoing research.)