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

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$M_w$ 7.8
13 separate faults
extending over $\sim 150$ km
Kaikoura EQ Response Spectra Wellington

NZS1170.5 Site Class Unknown, compare with Class D
Z=0.4 R=1 Sp=1

NZS1170.5 Site Class B
Z=0.4 R=1 Sp=1

NZS1170.5 Site Class D
Z=0.4 R=1 Sp=1

5% damped elastic acceleration response spectra, Solid line = ULS, dotted=0.25*ULS

Sensor 1-X dir
Sensor 1-Y dir
Initial Reports in Wellington

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

Site classes: Semmens et al 2010
Double tee units collapsed from L1 and L2
Statistics House
Statistics House

~150mm frame dilation
Statistics House

Unit spalling

Ledge spalling

Stats House Investigation, MBIE
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**

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

**Observed damage:**
- None identified: 43%
- Local: 28%
- Isolated: 7%
- Distributed: 11%
- Significant: 11%

**Site classes:** Semmens et al 2010

(a) Lateral system damage
- No SFRS Damage: 48 (75%)
- SFRS Damage: 16 (25%)
- Critical Floor Damage: 5 (24%)
- Moderate Floor Damage: 9 (43%)
- Minor Floor Damage: 4 (19%)
- No floor damage: 3 (14%)

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

- Pre-2000s bare concrete or mortar
- Pre-2000s unreinforced ledge
- Starter bar lapped with mesh
- Precast hollowcore unit
- Precast half-beam
- CIP topping + beam top

**Pre-2000s: typ 50mm seating specified 0-50mm achieved?**
Hollowcore floor damage
1994 Northridge Earthquake
Matthews and Bull (2004)
2-bay x 1-bay specimen

Plan

Selected portion to be tested

300 series hollowcore units

250x750 tie beam

.750x750 columns

450x750 beams

450x750 beams

400x750 beams
2.5% drift

Kaikoura EQ damage
Incompatible displacements

Matthews et al. (2004)
Assessment of Precast Floors

– Demands
Elongation
- Fenwick and Megget (1993)

Unidirectional Plastic hinge

Unidirectional plastic hinge:
\[ e = \theta \frac{(d - d')}{2} \]

Reversing Plastic hinge

Reversing plastic hinge:
\[ e = C\theta \frac{(d - d')}{2} \]
(NZS 3101: C=2.6)
Elongation

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

- Movement at support ledge due to rotation added to elongation

![Diagram showing rotation and elongation](image1.png)

Rotation and Elongation

![Diagram showing rotation only](image2.png)

Rotation only

\[ \frac{h_b}{2} \]
Wall elongation

Elongation due to rotation

Wall centroid elongation

\[ = \theta_m (0.5L_w - c) \]

Kaikoura EQ damage
Drift Capacity of Hollowcore Floors – Failure modes

**Objective:**

- Determine inter-storey drift at which floor units no longer have **reliable** gravity load path.
Hollowcore Floors
– test data (Des Bull + students)

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<tr>
<th>Name</th>
<th>Researcher</th>
<th>Date</th>
<th>Type</th>
<th>Seating (mm)</th>
<th>Loading</th>
<th>Failure mode</th>
<th>Drift capacity (%)</th>
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</table>

Loss of reliable load path

Pre-2006 details

Seating Beam 75mm Topping
Additional Full-Span Self Weight
Vertical Displacement (Seating Beam Rotation)
Horizontal Displacement (Beam Elongation)

Jensen 2007
Loss of Seating (LOS) - Spalling
  • Kaikoura evidence
Loss of Seating (LOS)

Hollowcore unit

Early cracking at end of unit

LoS data from tests

Ledge spalling increases with drift demand

Matthews 2004
Positive Moment Failure

Potential cracks

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)

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

![Graph showing Drift at Loss of Reliable Load Path with limited data points.](image-url)
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
Thank you!

Questions?
possible elongation
possible column rotation
possible compatibility damage
possible movement of column
possible damage at coupling beams
possible damage at collector junctions
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

6 2 - 16mm bottom bars at each end of unit

6 Paper clip or hairpin detail

1 Bearing on concrete or mortar

Bearing strip
Examples:
Beam Hinging
Plastic Hinge Damage

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; but expect degradation in stiffness leading to larger displacement demands in next event.
Critical Damage States – Primary structure

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

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<th>Transverse cracking - Visible from top</th>
<th>Transverse cracking - Visible from bottom</th>
<th>Transverse cracking - Full depth</th>
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</table>

- **Crack within ~400mm of support**
- **Crack beyond ~400mm of support**
Examples:
Support Damage
Mechanisms

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

Displacement incompatibility between the frame and h/c unit
Hollow-core unit sags, (applies to any precast floor)
Frame deforms in double curvature

Plastic hinge
Loss of strut in strut and tie analysis
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
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:

\[ \delta_{\text{el,unit}} = 1.3 \frac{\theta_p}{2} (h_L - d') \leq 0.018h_L \]

- Most units considered as restrained (i.e. use \( \delta_{\text{el}}/2 \))
Loss of Seating (LoS)

Construction tolerance = 0
IF inspected

Initial seating = 50mm

Construction tolerance + bearing = -25mm

Initial spalling = -15mm

Elastic elongation

Seating required to permit hinge elongation and support rotation

Additional spalling with drift

LOS = 1.15%

Interstorey Drift (%)

Available seating (mm)

Chris Poland
Negative Moment Failure (NMF)

Retrofit support:

- Effectively same as shorter starters!

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

Liew 2004