Experimental Evidence of the Damaging Effect of Vertical Earthquake Ground Motion

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Motivation

- Field Evidence

_Papazoglou and Elnashai (1996)_
Motivation

- Field Evidence
- Underestimation of the effect of vertical ground motion

(after Elnashai and Papazoglou, 1997)
Motivation and Objectives

- Field Evidence
- Underestimation of the effect of vertical ground motion
- Lack of experimental verification

Research Objectives

1. **Analytical assessment**
   - $V/H$ ratio and time interval between horizontal and vertical peaks

2. **Experimental assessment**
   - Pseudo-dynamic tests with and without vertical ground motion

Analytical Studies
- Saade
- Brode
- Papazoglou
- Elnashai
- Collier
- Button
- Mwafy and Elnashai (2006)
- Kunnath et al. (2008)
Effect of V/H ratio

- 16 V/H ratios per earthquake record
  - V/H ratio: 0.5 to 2.0 in an increment of 0.1
- Up to 600% increase in variation of axial load
- Shear demand and capacity
  - Shear strength model by Priestley et al. (1994)
  - Up to 25% reduction in shear capacity
Strain Comparison

- Longitudinal strain – No significant effect
- Spiral strain
  - Significant increase when vertical ground motion is included
Small Scale Tests

Overview

- Small-scale testing used to extend and complement the large-scale testing program
  - 3 hrs versus 6 weeks construction
  - 3 hrs versus 2 days to test
  - Less than $200 versus $20k cost
Small Scale Tests

Specimen Design

- 1/10 scale model of large-scale specimens ICC & ICT
  - Dia = 2.4 inch (61 mm)
  - H = 9.6 inch (244 mm)
- Tested in double curvature (h/d=2)
- Includes shallow end caps
- Steel end-connection plates
Small Scale Tests

Formwork and Assembly
## Small Scale Performance

### Prototype Specimen

- **Design and Loading**
  - $\rho_v = 0.5\%$ and $\rho_l = 2.7\%$
  - 30% Constant Compression
  - Designed for brittle shear failure
  - Failure mode predictable by available tools

### Force vs. Displacement Graph

The graph shows the comparison between experimental data and theoretical predictions.

<table>
<thead>
<tr>
<th></th>
<th>Force, kip</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experiment</td>
<td>1.33 kip</td>
<td>NA</td>
</tr>
<tr>
<td>UCSD Model</td>
<td>1.32 kip</td>
<td>-0.750%</td>
</tr>
<tr>
<td>R2K (MCFT)</td>
<td>1.37 kip</td>
<td>+3.01%</td>
</tr>
</tbody>
</table>
Small Scale Performance

Scale Comparison - Compression

Large Scale
Dia = 24 inch

Small Scale
Dia = 2.4 inch

15% $f'_c \times A_g$
Small Scale Performance

Repeatability and Consistency of Tests Results

3 Separate Tests at 2 Different Scales

Cyclic vs Monotonic Testing

Compression

Tension

Drift, %

Lateral Force, lbs

Drift, %

Lateral Force, lbs

Drift, %

Lateral Force, lbs

Large-Scale ICT
Small-Scale Specimen 1
Small-Scale Specimen 2
Small Scale Investigation

- 40 identical specimens
- Identical transverse loading
- Axial load treated as variable
  - Magnitude
  - Equivalent frequency
  - Phase relationship of vertical and lateral peaks

**Loading Definition**

\[
Axial = Dead Load + A_v \sin \left( \frac{2\pi t}{T_v} + \phi_v \right)
\]

\[
Lateral Disp. = A_h \sin(2\pi t)
\]
Axial Load Phase

Peak Compression Shifted Relative to Peak Lateral Drift

30% Compression

7.5% Tension

Dead Load

Test Data

**Coincident Compression**

**Coincident Tension**
Axial Load Frequency

Frequency Change with Compression in Phase

- Small Amplitude
- Large Amplitude

Drift, %

Force, lbs

T Lateral = 8 x T Vertical
T Lateral = 4 x T Vertical
T Lateral = 1 x T Vertical

Constant Comp. Envelope
Constant Tens. Envelope
Dead Load Envelope
Test Data

High Frequency  Low Frequency
Conclusion

Vertical Motion in Design and Assessment

- Analysis, small scale and full scale testing confirms that vertical component of earthquakes affect the response and failure
- Tools for including vertical motion are readily available
- There is no justification for not including vertical motion in design and assessment