“Performance Assessment of Inadequately Detailed Reinforced Concrete Columns”

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Introduction

- Significant proportion of existing building stock with inadequate detailing, including:
  - Inadequate lateral restraint of longitudinal bars
  - Large separation between stirrup sets
  - Lap-Splices in PPHZ
  - Cranked Bars at the top of the Lap-Splice

- Can lead to:
  - Shear failure of columns due to insufficient transverse steel intersecting the failure plane
  - Subsequent Loss of axial load capacity
  - Structural Collapse if redistribution of load not possible

Drift Based Failure Model

- Elwood and Moehle (2005)
  - F-δ from M-Φ
  - Bi-Linear F-δ
  - Shear Limit
    \[ \delta_s = \frac{3}{100} + 4\rho \frac{d_t}{f_y} \cdot \frac{1}{f' \gamma} \cdot \frac{1}{P} \cdot \frac{1}{40A_s f_y} > 1 \]
  - Axial Limit
    \[ \delta_a = \frac{4}{100} \cdot \frac{1+\tan^2 65^\circ}{\tan 65^\circ + P} \frac{s}{A_s f_y} \frac{d_t}{\tan 65^\circ} \]
  - Backbone Model

Experimental Program

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Experimental Details

- 2 Cantilever Specimens
  - 1624mm high
  - 450mm square
  - 4 Grade 300 D25 bars
  - R10 Stirrups @ 300mm centres
  - 600mm Lap-Splices at Column Base
  - Cranked Reinforcement at Splice
  - 38mm (1.5") cover to main bars
  - Target $f'_c = 32$ MPa
- 2 Loading Protocols
  - 2D Quasi-Static
  - 3D Quasi-Static

Experimental Apparatus

- Axial Force:
  - Dartech
- Lateral Forces:
  - Self-reacting frames
  - Hydraulic actuators
- Ball Joints:
  - Bi-Directional Bending
- Counterweights:
  - Balance Frames

Specimen 1: 24L-300-2D
2D Test

- Material Strengths:
  - $f'_c = 33.6$ MPa
  - $f_y = 317$ MPa
  - $f_{yt} = 439$ MPa
- 2000kN Axial Load
  - $\sim 0.29f'_cA_0$

Specimen 1: 24L-300-2D
Loading Protocol

- 2D Loading Protocol
  - 3 Cycles @ Drift:
    - 0.1%
    - 0.25%
    - 0.5%
    - 1.0%
    - 1.5%
    - 2.0%
    - 3.0%
    - 5.0%
Specimen 1: 24L-300-2D

**Experimental Results**

- **Key Events:**
  - 0.5% Drift: Minor Flexural Cracks
  - 1.0% Drift: Minor Shear Cracks
  - 1.5% Drift: Minor Splitting Cracks
  - Shear Cracks Extend
  - 2.0% Drift: Splitting and Expulsion
  - Shear Cracks Extend
  - 3.0% Drift: Shear Failure prior to First Positive Peak
  - 3.0% Drift: Axial Failure Prior to First Negative Peak

**Modelling**

- F-δ from M-Φ
- Bi-Linear F-δ
- Shear Limit
- Axial Limit
- Corrected Axial Limit
- Backbone Model

**Experimental Comparison**

- Shear Failure occurs on 1\textsuperscript{st} positive cycle to 3.0% Drift
- Axial Failure occurs on 1\textsuperscript{st} negative cycle to 3.0% Drift
- Axial failure does not occur exactly on the limit but soon follows
- Backbone model fits well for 2D loading

Specimen 2: 24L-300-3D

- **3D Test**
  - Material Strengths:
    - f'_c = 28.4 MPa
    - f_y = 317 MPa
    - f'_{yt} = 439 MPa
  - 2000kN Axial Load
    - \( \sim 0.35f'_{c}A_g \)
Specimen 2: 24L-300-3D Loading Protocol

- 3D Loading Protocol
  - 3 Cycles @ Drift:
    - 0.1%
    - 0.25%
    - 0.5%
    - 1.0%
    - 1.5%
    - 2.0%
    - 3.0%
    - 5.0%
- In-Plane Drifts:
  - Maxima @ ~30°
  - Vector Drift:
    - maxima 1.3 times larger @ 45°

Specimen 2: 24L-300-3D Experimental Results

- Key Events:
  - 0.50% Drift: Flexural Cracks Form
  - 0.75% Drift: Shear Cracks Form
  - 1.00% Drift: Shear Cracks Extend
  - 1.50% Drift: Shear Failure during 1st ‘Leaf’
  - 1.50% Drift: Axial Failure during 2nd ‘Leaf’

Specimen 2: 24L-300-3D Modelling

- Modelling in 3D
  - Backbone is unidirectional assessment
- Assess 3D loading by:
  - Calculate Backbone for 45° loading
  - Resolve backbone into N-S and E-W components
  - Allows assessment in a 2D plane.

Specimen 2: 24L-300-3D Modelling

- Key features:
  - Shear and Axial limits calculated for 45° loading
  - Lateral capacity calculated for 30° loading (peak demand for each 'leaf')
  - Backbone model resolved to in-plane component
Specimen 2: 24L-300-3D
Experimental Comparisons

- Shear Failure occurs during the 1st ‘Leaf’ @ 1.5% Drift and is orientation specific
- Axial Failure occurs during the 2nd ‘Leaf’ @ 1.5% Drift soon after drift limit exceeded

Conclusions: Implications

- Implications for existing Structures:
  - 3D loading causes loss of lateral and axial capacity at very low levels of drift
    - 1.5% in-plane for 3D
    - 2.5% for 2D
  - Highlights the inherent potential for catastrophic Failure of existing structures

Conclusions: Observations

- Model captures drift limits for:
  - Shear and Axial failures
  - 2D and 3D Loading
- Reduced 3D drift capacity due to
  - Reduced effectiveness of stirrups
  - Resolving vectorial drift capacity to in-plane capacity
- Shear Failure Plane necessary for Axial Failure (direction specific)
- 3D loading causes multiple shear planes (hourglass)

Conclusions: Future Work

- Implementation of model limits into Time-History software necessary for complete assessment of structures
  - Post-failure redistribution of load?
  - Progressive Collapse?
- 3D Failure surfaces necessary as opposed to unidirectional backbones
  - Direction dependent limits
  - Asymmetric specimen capabilities
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