"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

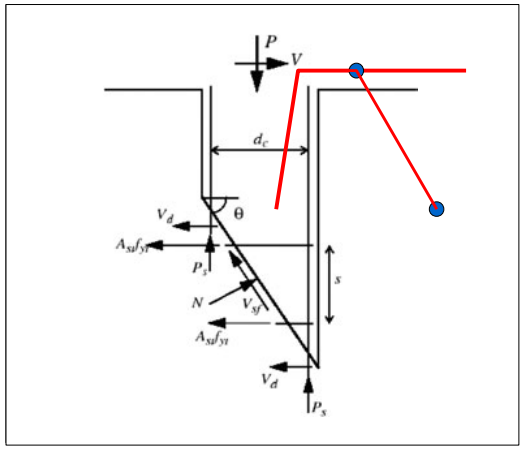
- Elwood and Moehle (2005)
  - F-δ from M-Φ
  - Bi-Linear F-δ
  - Shear Limit

$$\delta_s = \frac{3}{100} + 4\rho' - \frac{1}{40}\frac{\upsilon}{\sqrt{f'_c}} - \frac{1}{40}\frac{P}{A_g f'_c} \geq \frac{1}{100}$$

  - Axial Limit

$$\delta_a = \frac{4}{100}\frac{1+\tan^2 65°}{\tan 65° + P\left(\frac{s}{A_{st} f_{yt} d_c \tan 65°}\right)}$$

  - Backbone Model

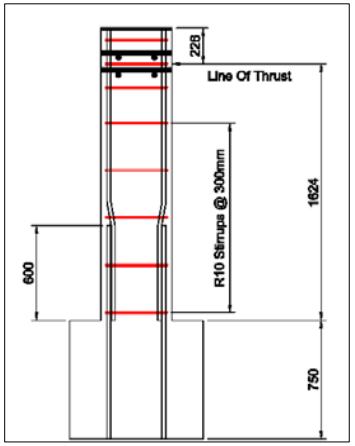


Experimental Program

Specimen Designation	Lap Length	Tie Details	Axial Load	Loading Protocol
24L-300-2D	600mm (24 d_b)	R10 @ 300mm	2000kN (0.3f'$_c$A$_g$)	2D Quasi-Static
24L-300-3D	600mm (24 d_b)	R10 @ 300mm	2000kN (0.3f'$_c$A$_g$)	3D Quasi-Static
30L-300-2D	750mm (30 d_b)	R10 @ 300mm	2000kN (0.3f'$_c$A$_g$)	2D Quasi-Static
30L-300-3D	750mm (30 d_b)	R10 @ 300mm	2000kN (0.3f'$_c$A$_g$)	3D Quasi-Static
24L-300-3D-R	600mm (24 d_b)	R10 @ 300mm	1000kN (0.15f'$_c$A$_g$)	3D Quasi-Static
24L-300-EQ	600mm (24 d_b)	R10 @ 300mm	2000kN (0.3f'$_c$A$_g$)	3D Quasi-EQ

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

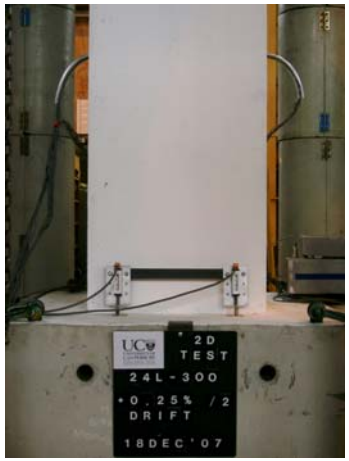


Experimental Apparatus

- 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
  - ~$0.29f'_cA_g$



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

- 2D Loading Protocol
  - 3 Cycles @ Drift:

    0.1%

    0.25%

    0.5%

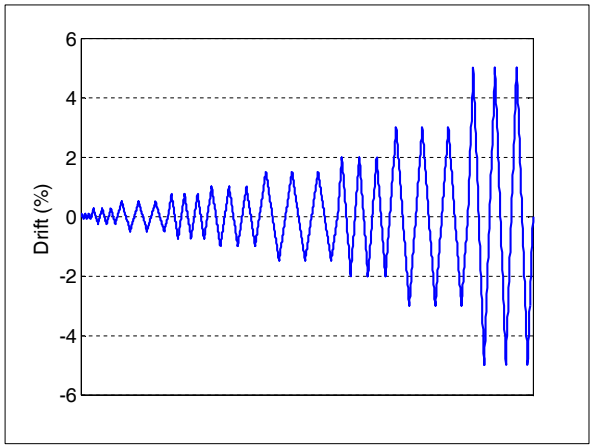
    1.0%

    1.5%

    2.0%

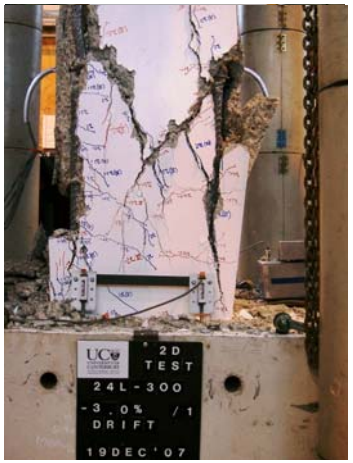
    3.0%

    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



Specimen 1: 24L-300-2D Modelling

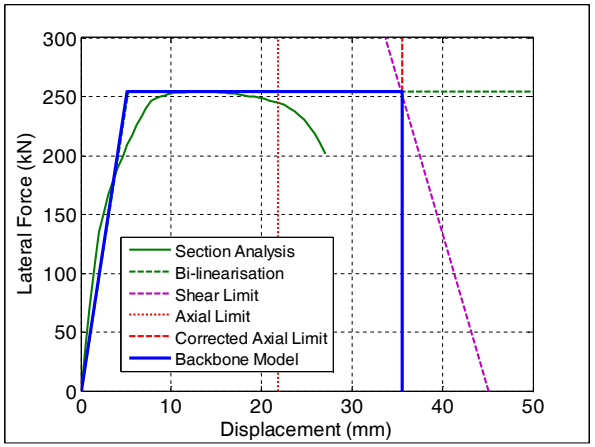
- Modelling
  - F-δ from M-Φ
  - Bi-Linear F-δ
  - Shear Limit

$$\delta_s = \frac{3}{100} + 4\rho' - \frac{1}{40\sqrt{f'_c}} - \frac{1}{40}\frac{P}{A_g f'_c} \geq \frac{1}{100}$$

  - Axial Limit

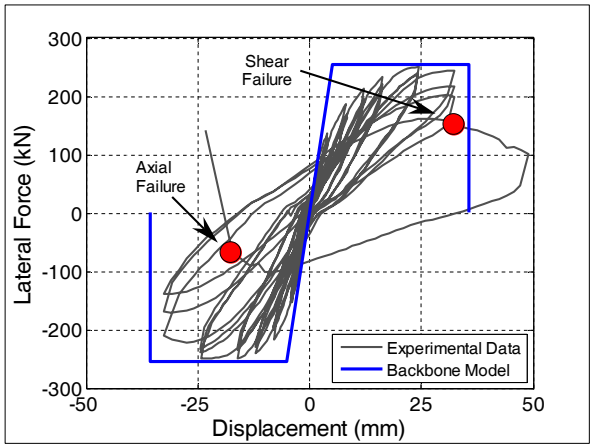
$$\delta_a = \frac{4}{100}\frac{1+\tan^2 65^\circ}{\tan 65^\circ + P\left(\frac{s}{A_{st} f_{yt} d_c \tan 65^\circ}\right)}$$

  - Backbone Model



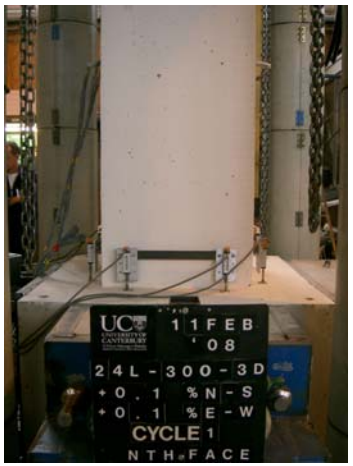
Specimen 1: 24L-300-2D Experimental Comparison

- Shear Failure occurs on 1st positive cycle to 3.0% Drift
- Axial Failure occurs on 1st 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



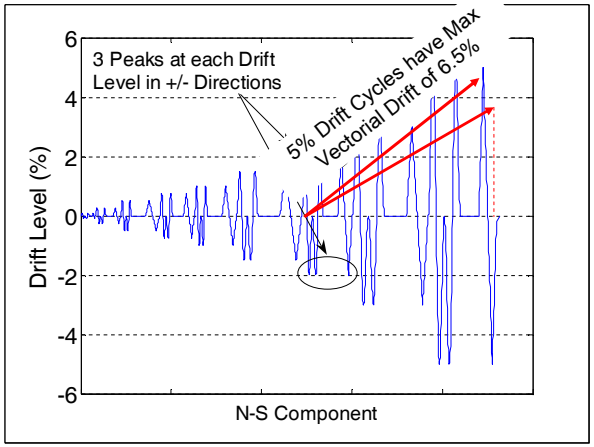
Specimen 2: 24L-300-3D 3D Test

- Material Strengths:
  - f'_c = 28.4 MPa
  - f_y = 317 MPa
  - f_{yt} = 439 MPa
- 2000kN Axial Load
  - ~$0.35 f'_c A_g$



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 °

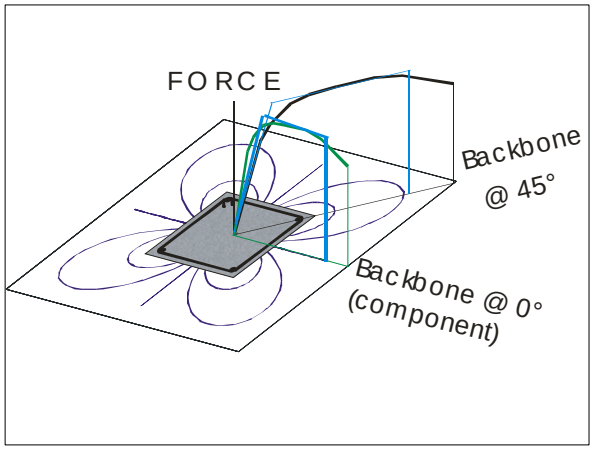


Specimen 2: 24L-300-3D Experimental Results

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

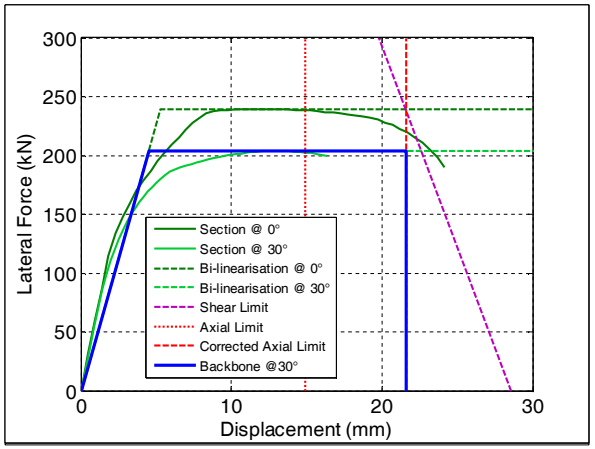
Specimen 2: 24L-300-3D Modelling

- 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.



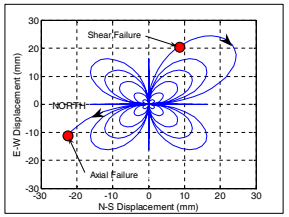
Specimen 2: 24L-300-3D Modelling

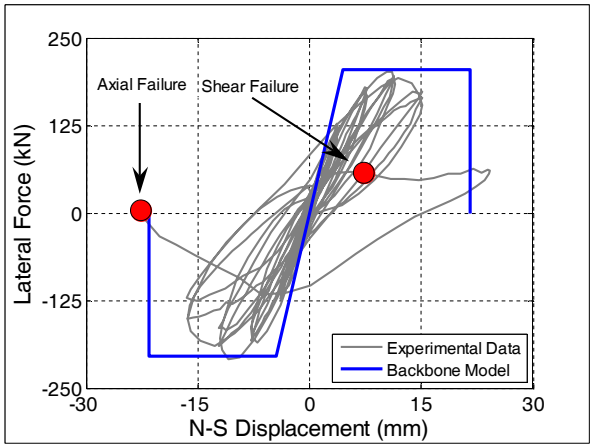
- Key features:
  - Shear and Axial limits calculated for 45° loading
  - Lateral capacity calculated for 30° loading (peak demand for each 'leaf')
- Backbone model resolved to in-plane component



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

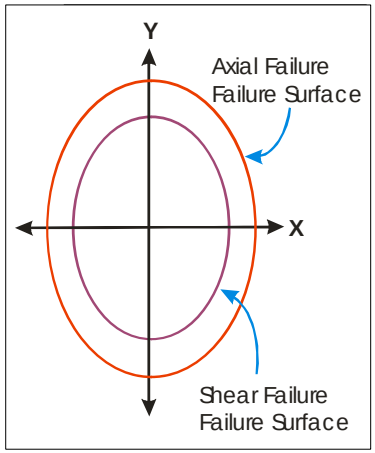
- Implications for existing Structures:
  - 3D loading causes loss of lateral and axial capacity at very low levels of drift
    - 1.5% in-plane for 3D
    - 2.5% for 2D
  - Highlights the inherent potential for catastrophic Failure of existing structures

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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