# Increasing the Seismic Moment Capacity of Concrete Columns Using EBR-FRP and FRP Anchors

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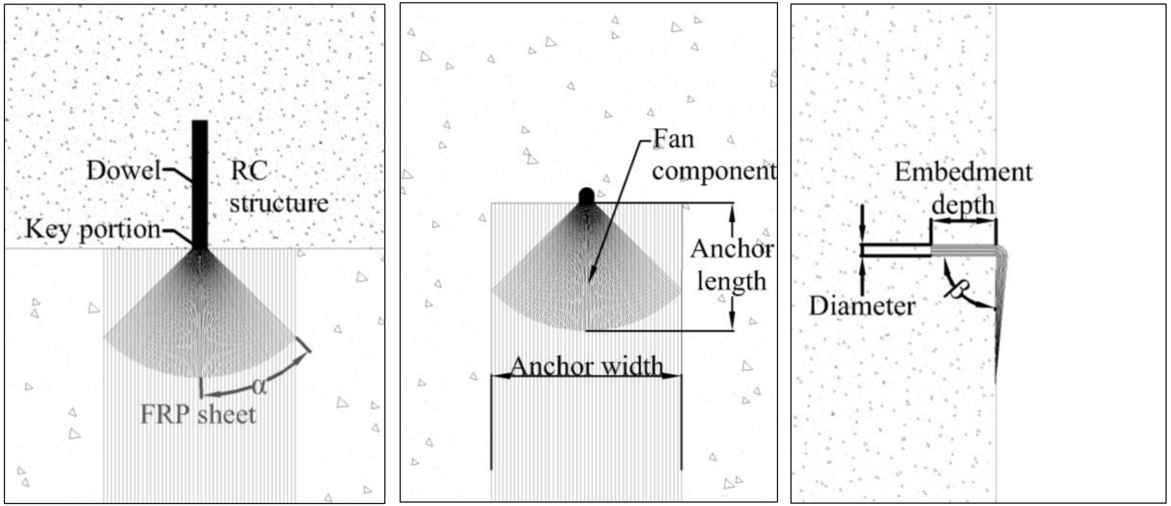
# Fibre anchors




del Rey Castillo, Enrique, Michael Griffith, and Jason Ingham. "Seismic behavior of RC columns flexurally strengthened with FRP sheets and FRP anchors." *Composite Structures* 203 (2018): 382-395.

# Case study

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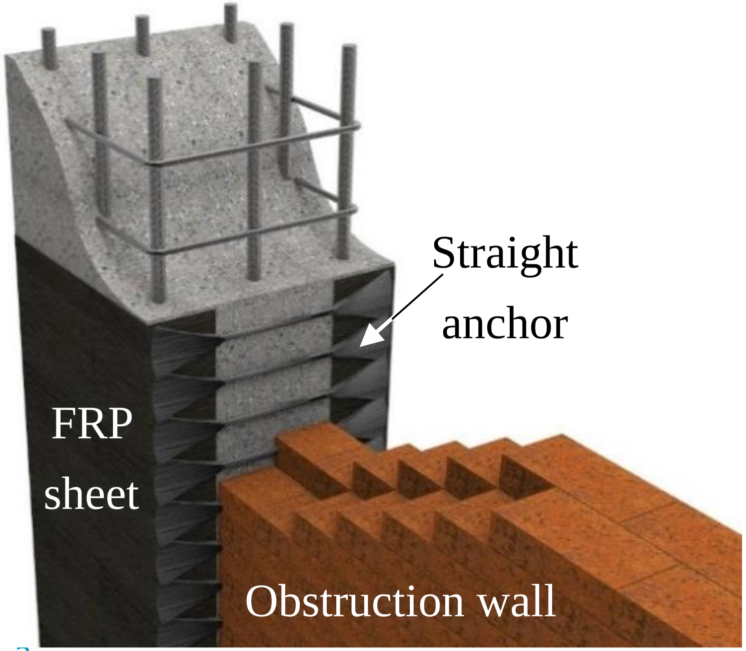
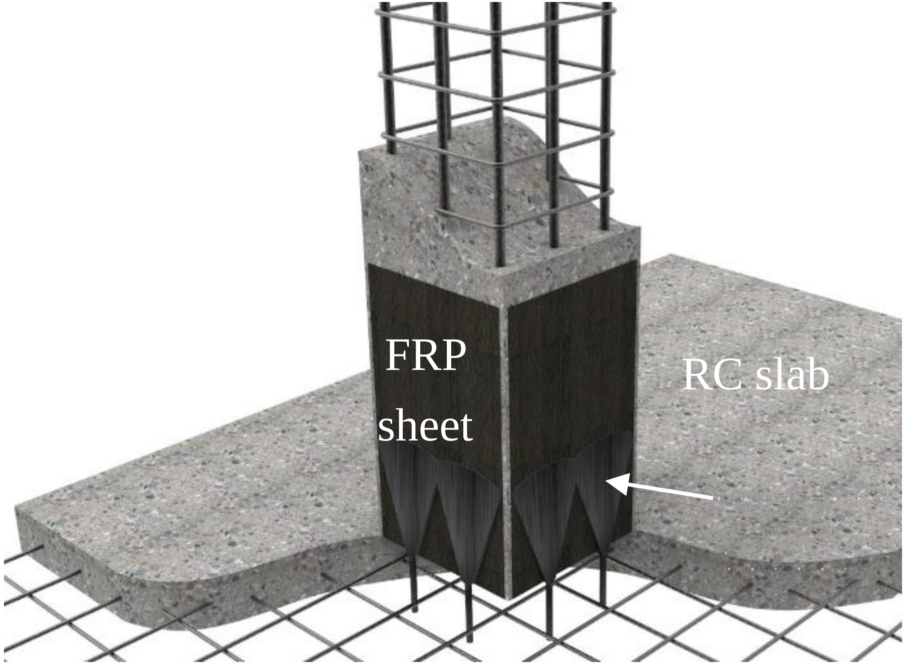
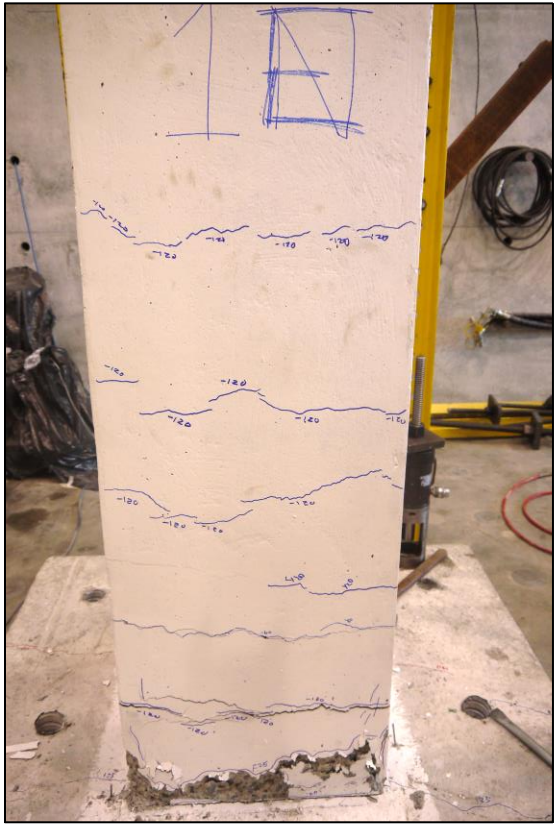
## Shear strengthening

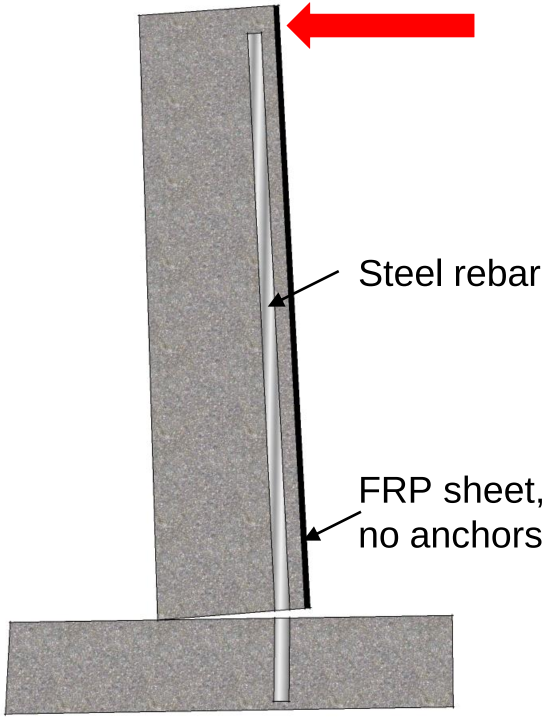



## Flexural strengthening

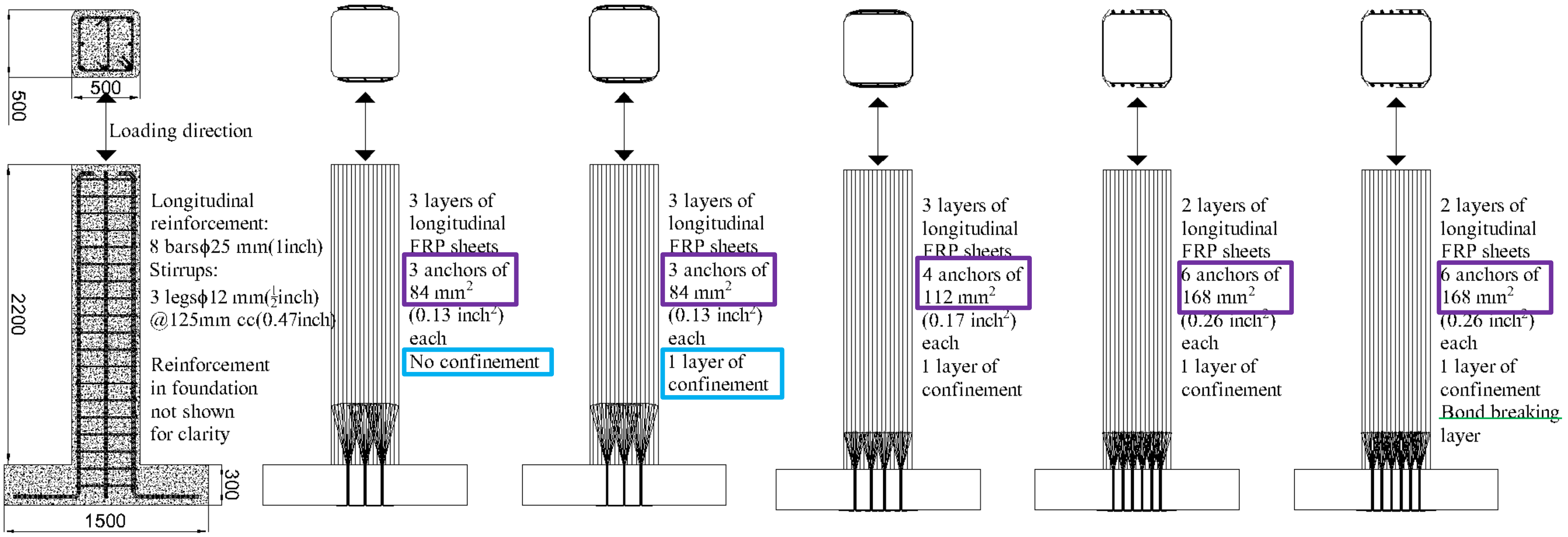


# FRP anchors are important!






# Columns design




(a) Column 1 (b) Column 2 (c) Column 3 (d) Column 4 (e) Column 5 (f) Column 6

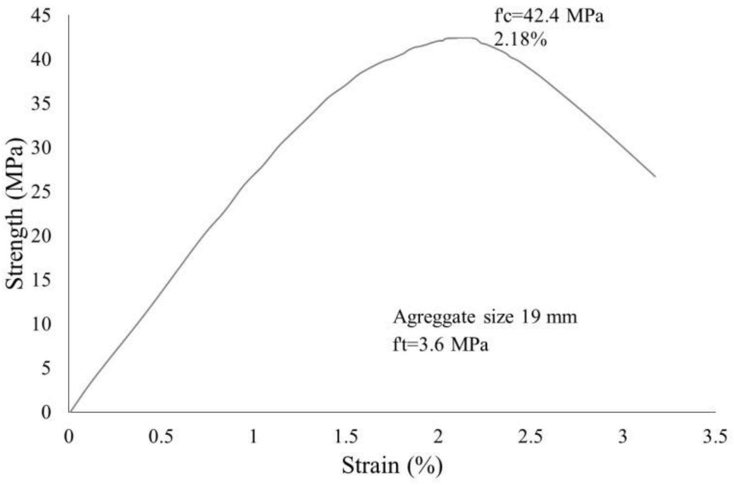
FRP anchor failure

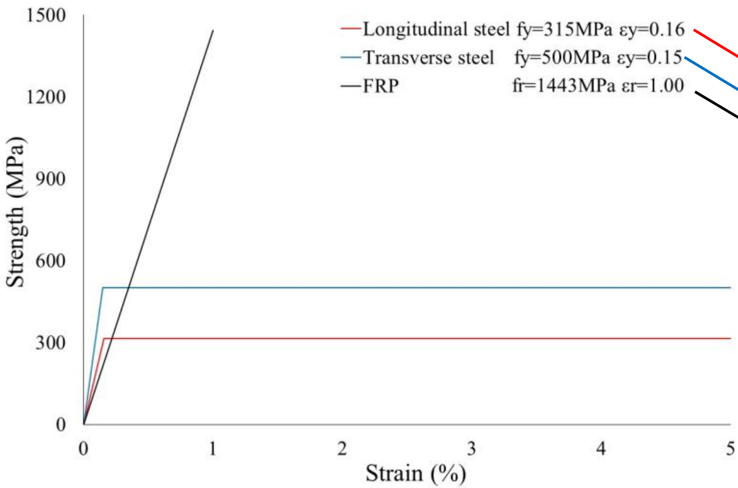
FRP sheet failure

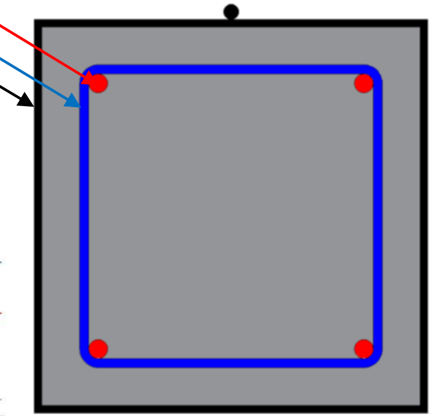
# Design methodology

Response 2000 was used, from University of Toronto

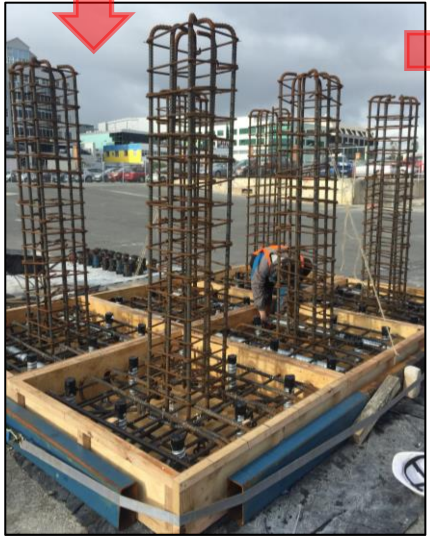
- Concrete sectional and moment curvature analyses
- Plane sections remain plane
- ACI 440 and FRP anchor research
- Material properties obtained from testing:



# Building of the columns



# Installing FRP

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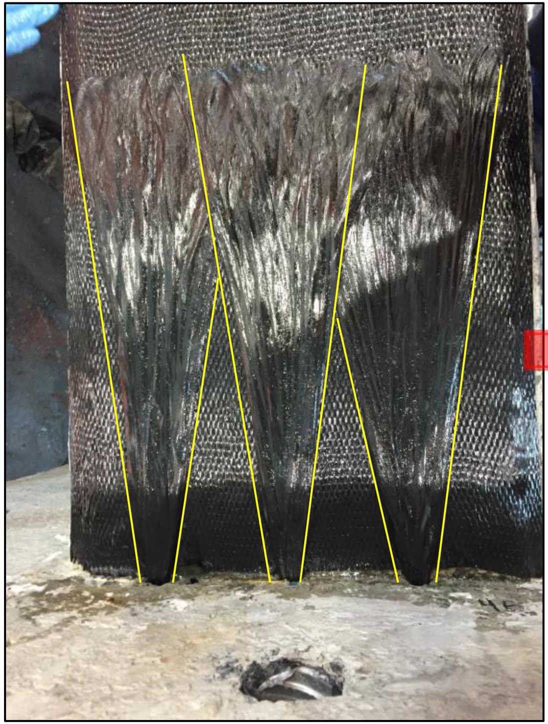
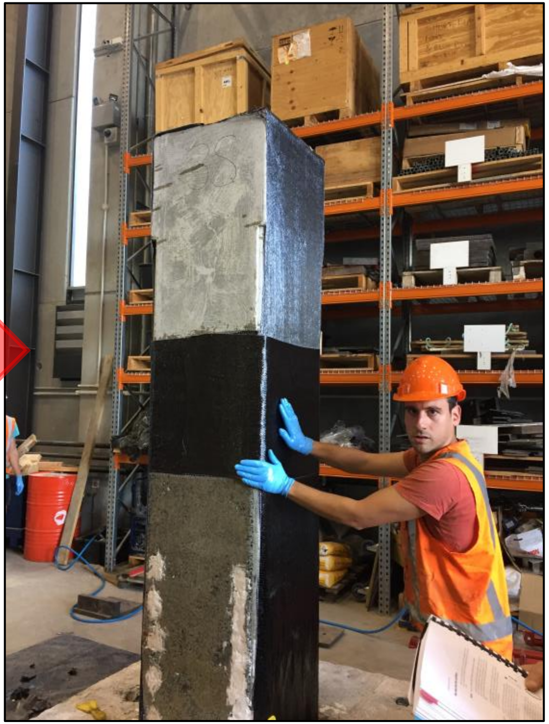
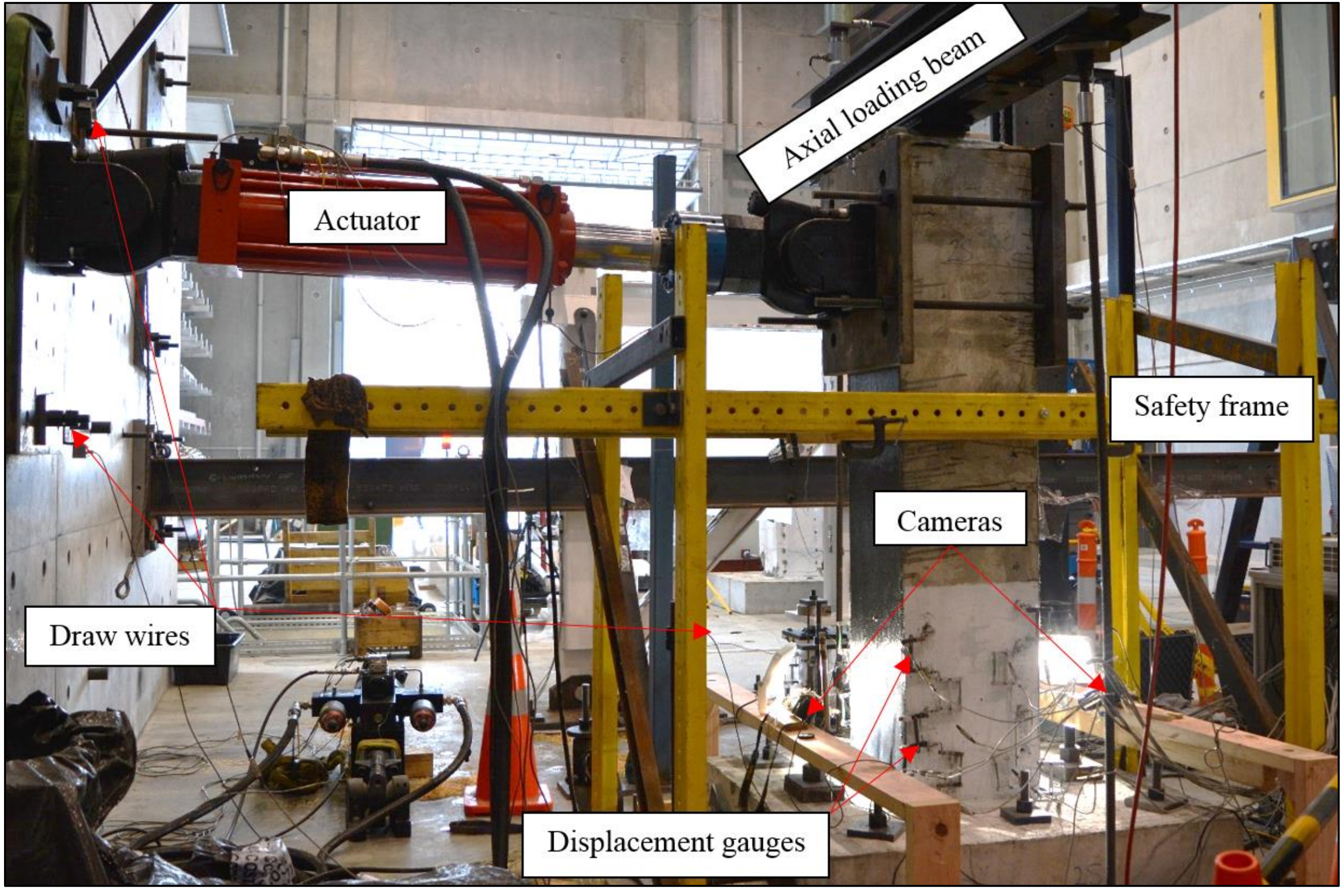
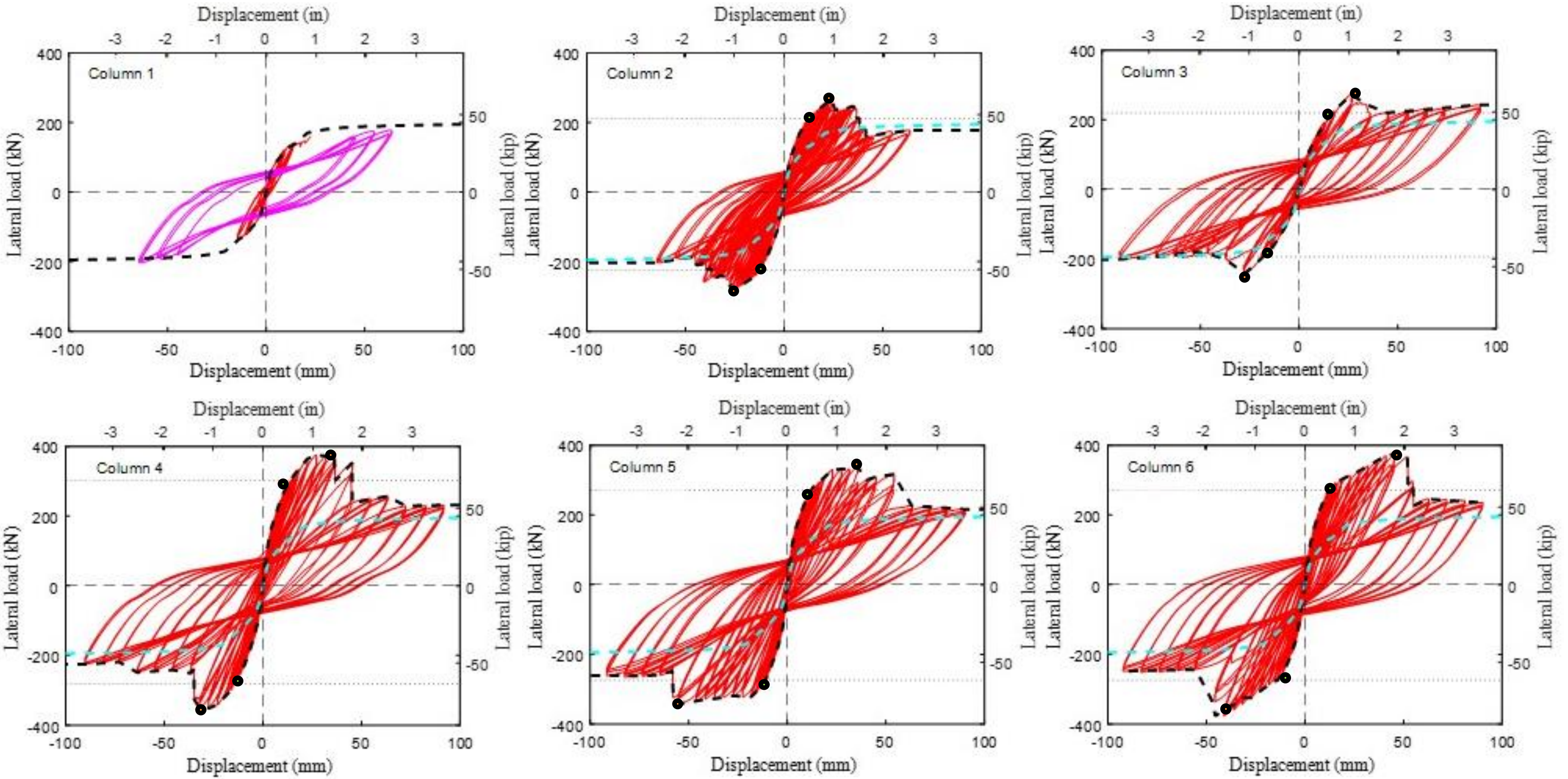




# Testing set-up

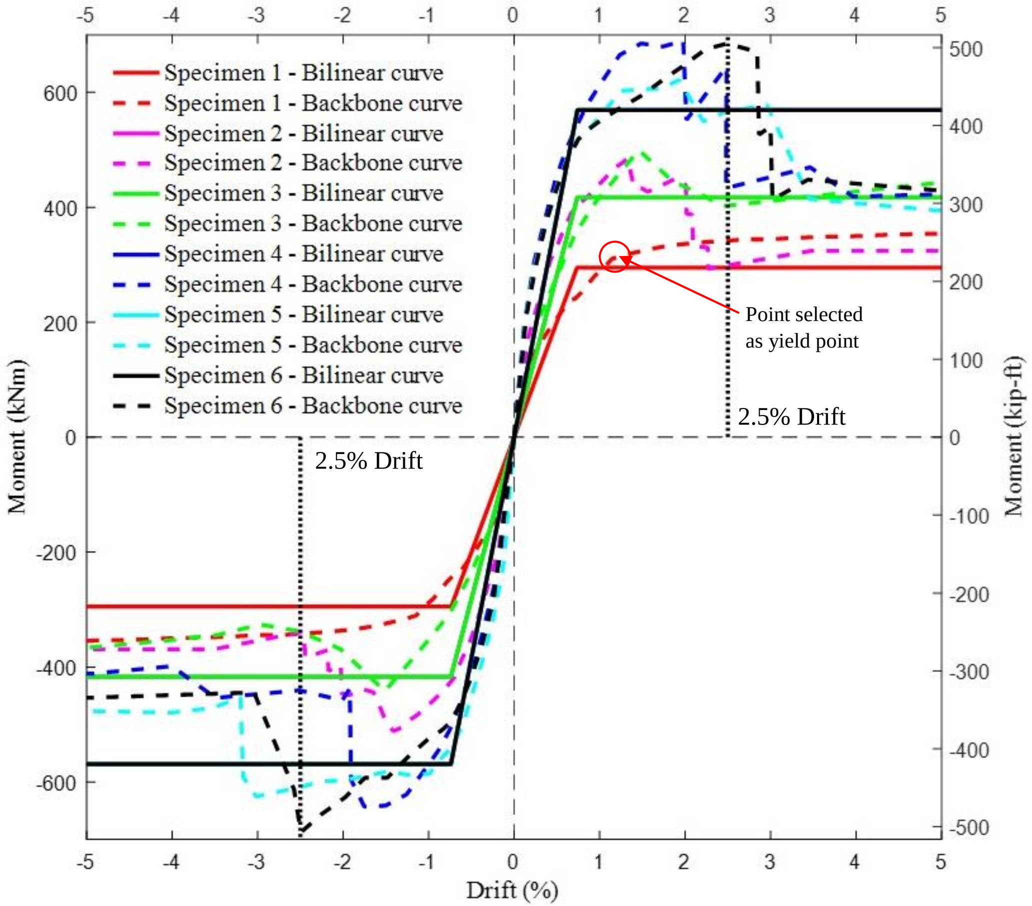


# Results


Column 1
Column 2
Column 3
Column 4
Column 5
Column 6
Displacement (in)
-3
-2
-1
0
1
2
3
Displacement (mm)
-100
-50
0
50
100
Lateral load (kN)
400
200
0
-200
-400
Lateral load (kip)
50
0
-50

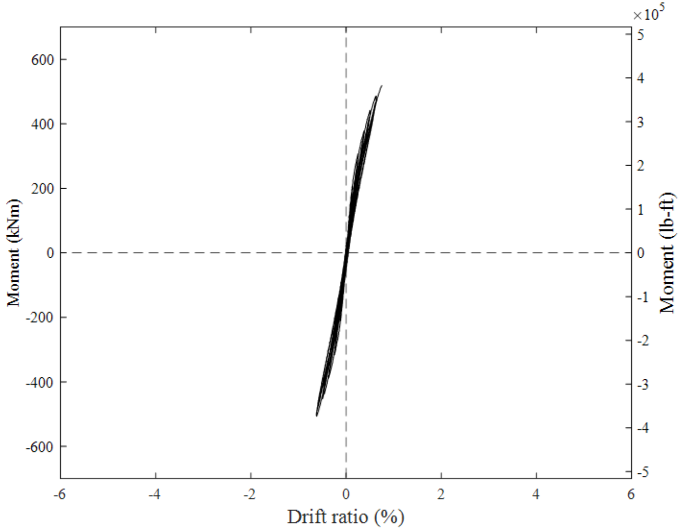
# Results

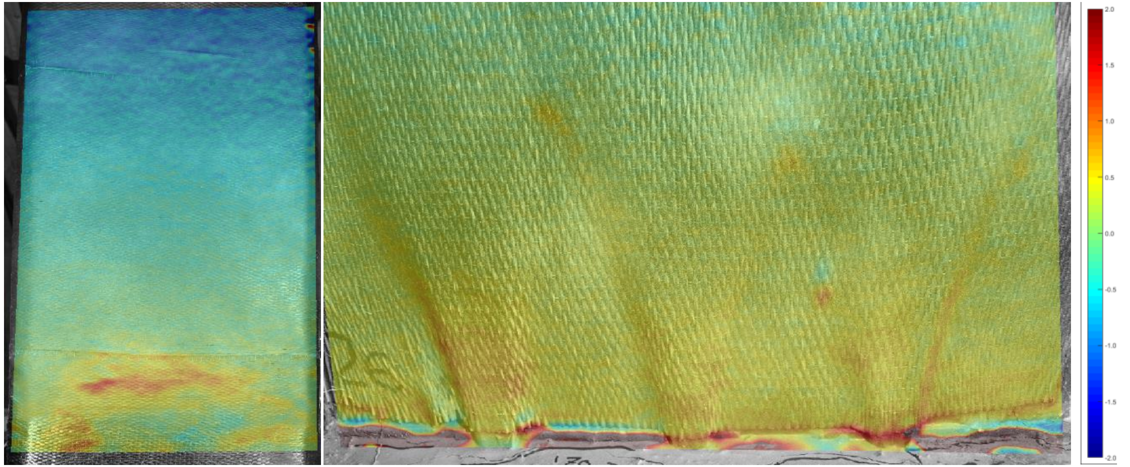
Idealised bilinear elastic-perfectly plastic behaviour does not capture the behaviour of FRP strengthened RC columns



# Behaviour

Stage 1: Elastic behaviour



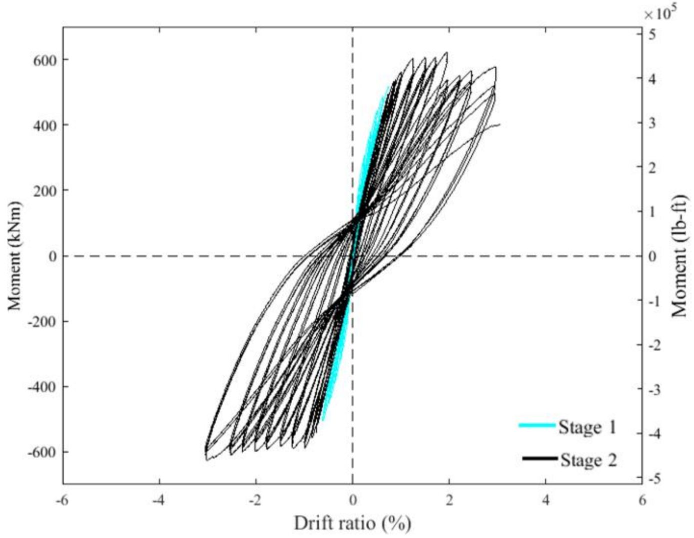



(a) Results on sheets – Column 5 cycle to ±1% drift

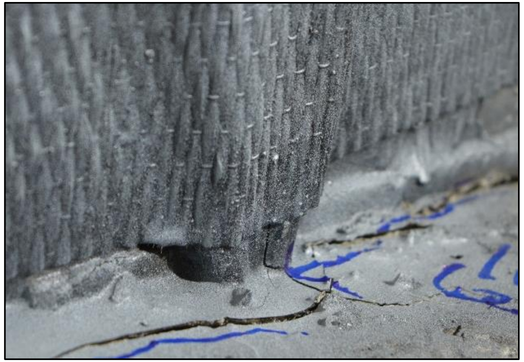
(b) Results on anchors – Column 2 cycle to ±1%drift

# Behaviour

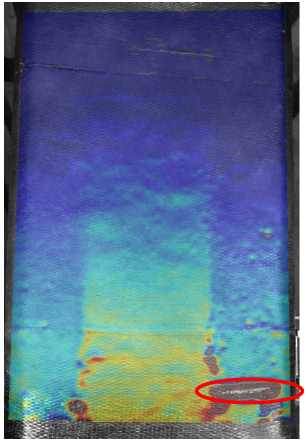
Stage 2: Inelastic plateau or hardening



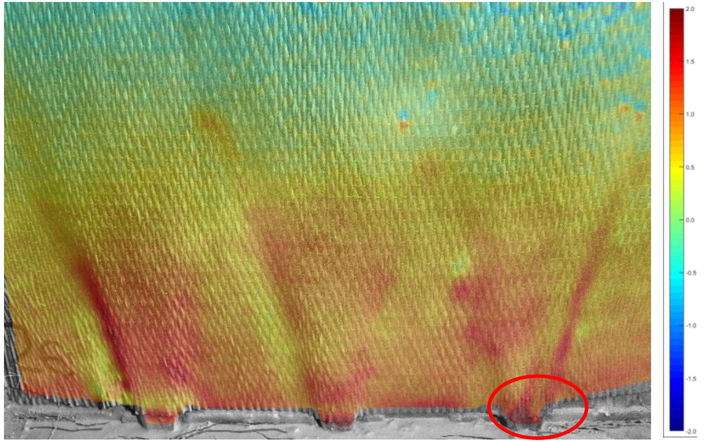

(a) First longitudinal FRP sheet damage - Column 6



(b) Concrete crack at the bottom of the column and first FRP crack in the anchor – Column 2



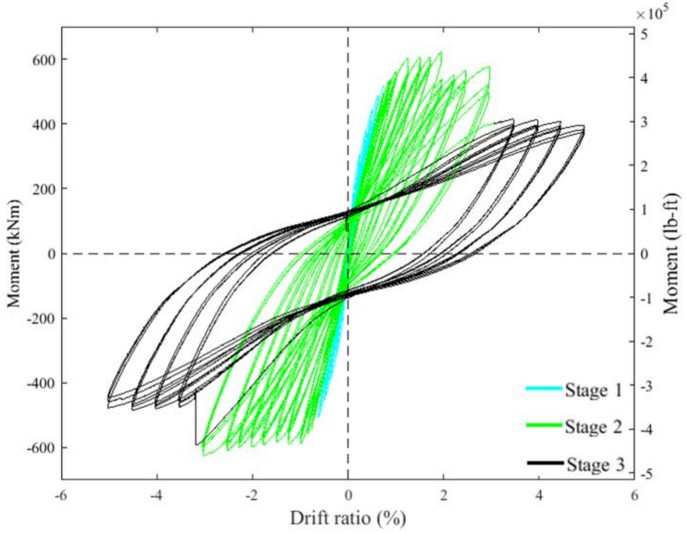
Results from sheets – Column 5 cycle to ±2.5% drift



(b) Results from anchors – Column 2 cycle to ±2.5% drift

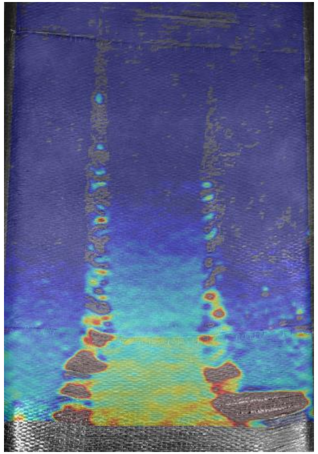
# Behaviour

Stage 3: Inelastic degradation

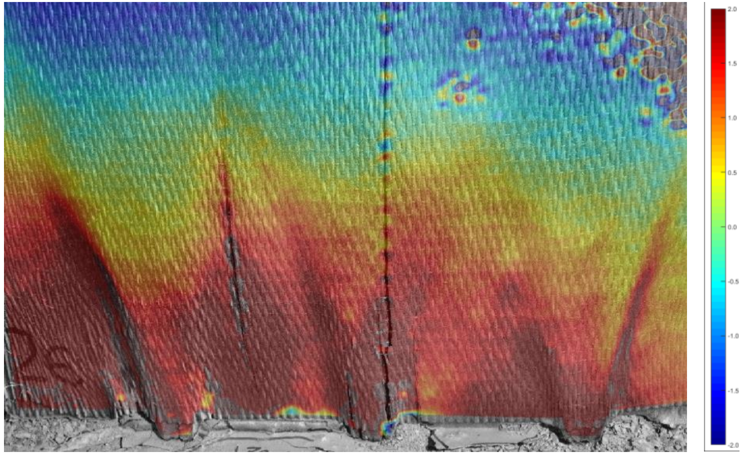



(a) General rupture of the longitudinal FRP sheets – Column 5

(b) Column 2 with all the anchors broken

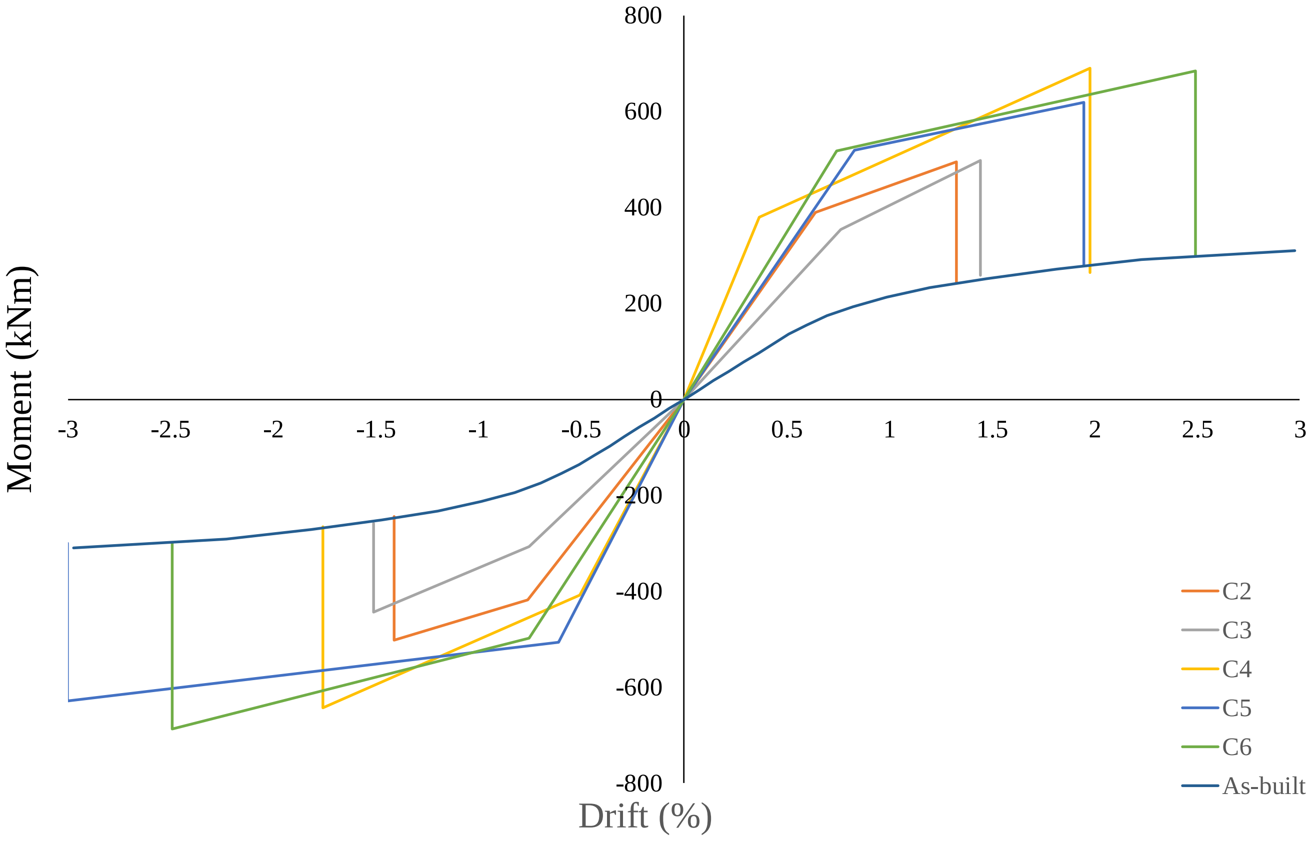


(a) Results from sheets – Column 5 cycle to ±5% drift



(b) Results from anchors – Column 2 cycle to ±5% drift

# Trilinear behavior



# Comparison

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| | Peak moment (kNm/x10$^5$ lb-ft) | | | Drift ratio at peak (%) | | |
|---|---|---|---|---|---|---|
| Column | R2k† | Push | Pull | R2k† | Push | Pull |
| 1 | 367/2.7 | 367/2.7† | 367/2.7† | 1.15 | 1.15‡ | 1.15‡ |
| 2 | 509.3/3.8 | 495.3/3.7 | 501.7/3.3 | 3.61 | 1.33 | 1.41 |
| 3 | 511.2/3.8 | 497.5/5.1 | 444.3/4.7 | 3.61 | 1.44 | 1.51 |
| 4 | 601.4/4.4 | 690.3/5.1 | 642.5/4.7 | 3.61 | 1.98 | 1.76 |
| 5 | 675.4/5.0 | 619.3/4.6 | 629.5/4.6 | 3.61 | 1.95 | 3.01 |
| 6 | 676.2/5.0 | 685.1/5.1 | 687.5/5.1 | 3.61 | 2.49 | 2.30 |

Average 6%

Wrong

†Obtained with moment curvature analysis using Response 2000 (R2K)

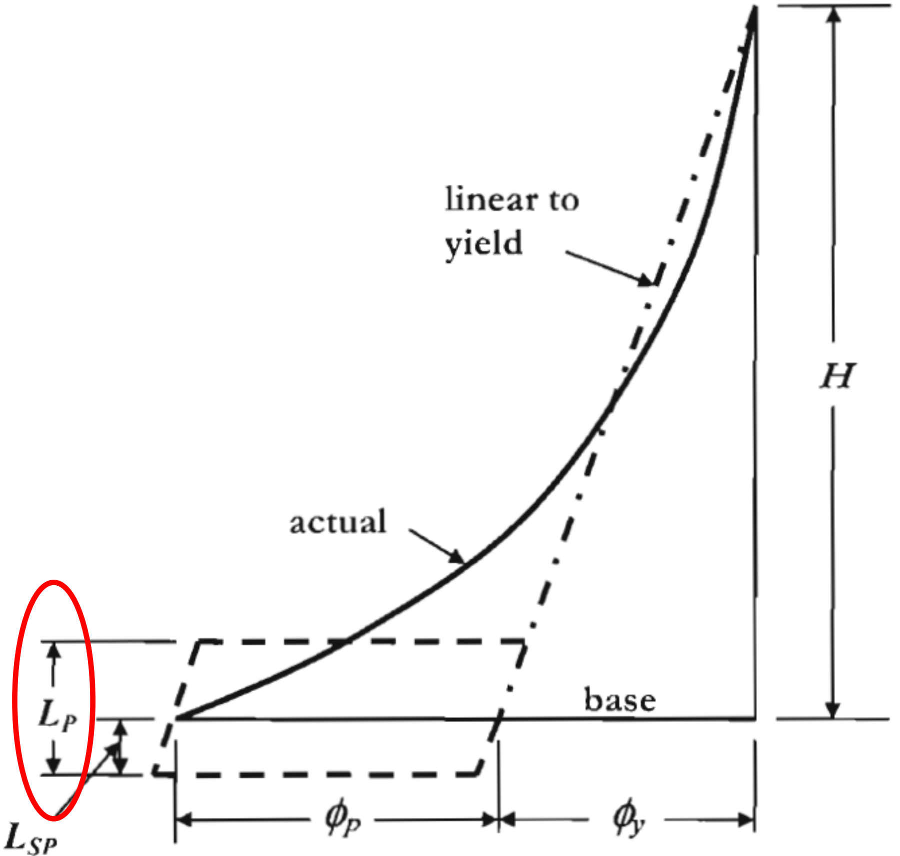
‡ Point where the ductility of the curve change to ductile

# Drift/displacement calculation

Plastic hinge model

$$\Delta = \underbrace{\Delta_y' \frac{M}{M_y}}_{\text{Elastic}} + \underbrace{\left(\phi - \phi_y' \frac{M}{M_y}\right) L_P H}_{\text{Plastic}}$$

| | | | |
|---|---|---|---|
| $\Delta$<br>$M$<br>$\phi$ | Displacement moment and curvature at peak | $\Delta_y'$<br>$M_y$<br>$\phi_y'$ | Displacement moment and curvature at yield |



# Proposed drift calculation
# Plastic hinge theory

Change to 0.05

$$\Delta = \Delta'_y \frac{M}{M_y} + \left(\phi - \phi'_y \frac{M}{M_y}\right) L_P H \Rightarrow L_P = \frac{\Delta - \Delta'_y \frac{M}{M_y}}{\left(\phi - \phi'_y \frac{M}{M_y}\right) H}$$

$$L_p = 2L_{SP}$$

$$L_{SP} = \psi f_y d_{bl}$$

$$L_{SP} = 0.0116 f_y d_{bl}$$

| Column | $L_P$ (mm/inches) | ψ |
|---|---|---|
| C2-Push | 182.52/7.2 | 0.011588 |
| C2-Pull | 182.52/7.2 | 0.011589 |
| C3-Push | 182.52/7.2 | 0.011589 |
| C3-Pull | 182.52/7.2 | 0.011589 |
| C4-Push | 182.54/7.2 | 0.011590 |
| C4-Pull | 182.54/7.2 | 0.011590 |
| C5-Push | 182.54/7.2 | 0.011590 |
| C5-Pull | 182.57/7.2 | 0.011592 |
| C6-Push | 182.55/7.2 | 0.011591 |
| C6-Pull | 182.55/7.2 | 0.011590 |
| Average | 182.54/7.2 | 0.0116 |
| CoV (%) | 0.01 | 0.01 |

# Conclusion

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- Negligible influence of tension-compression cycles and fatigue degradation on the anchor capacity
- Three behaviour stages as opposed to the bilinear idealised behaviour
- Bond breaking layer potentially controls drift
- Cross sectional analysis, FRP standards and FRP anchors research allows for moment capacity to be calculated accurately
- **New proposals for calculating drift/displacement – Further research needed**

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Questions

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