Stress-strain model of concrete confined by FRP laminate and spike anchors

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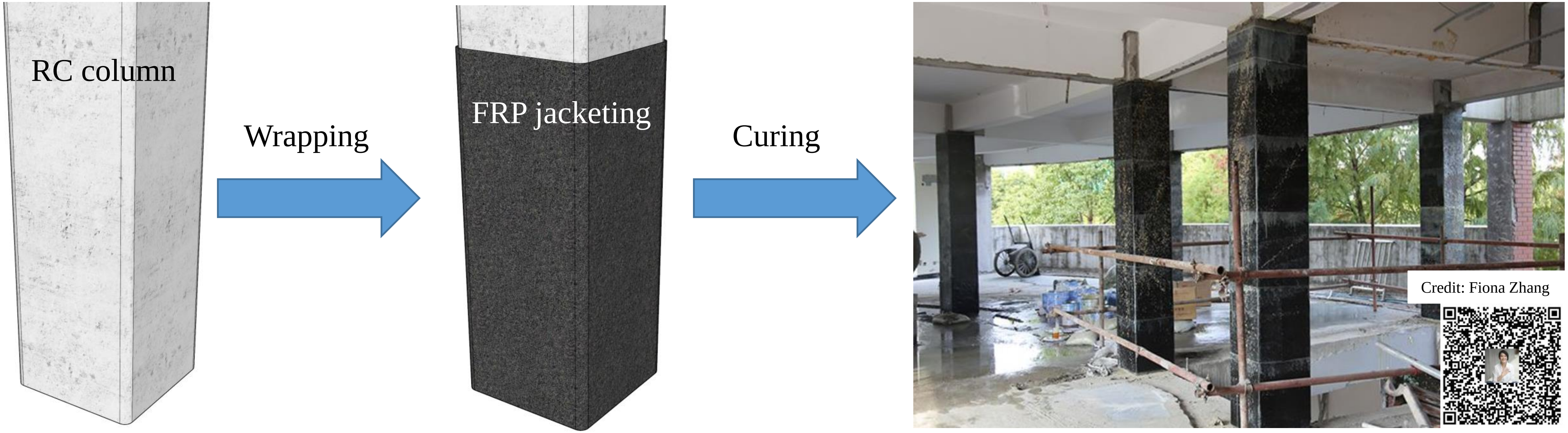
Research motivation

Traditional FRP-confinement: wrapping around free-standing columns

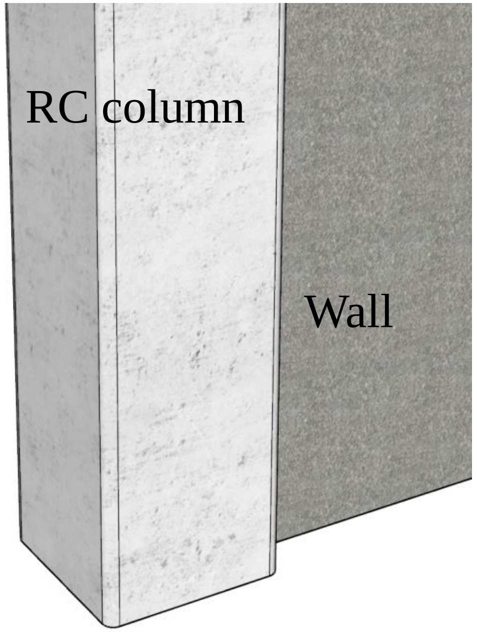


Conventional confinement using FRP jacketing for free-standing columns:

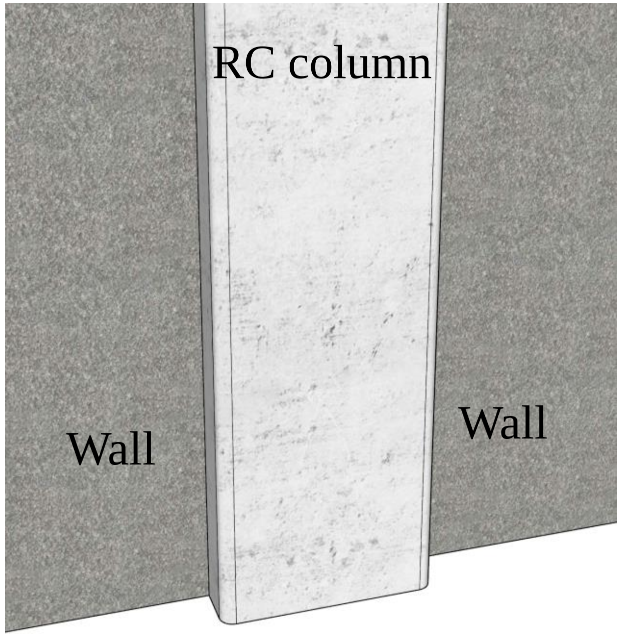
- √ Experimenmtal study;
- √ Stress-strain modeling;
- √ Design codes (Chapter 12 of ACI 440.2R);
- √ Practice.

Research motivation

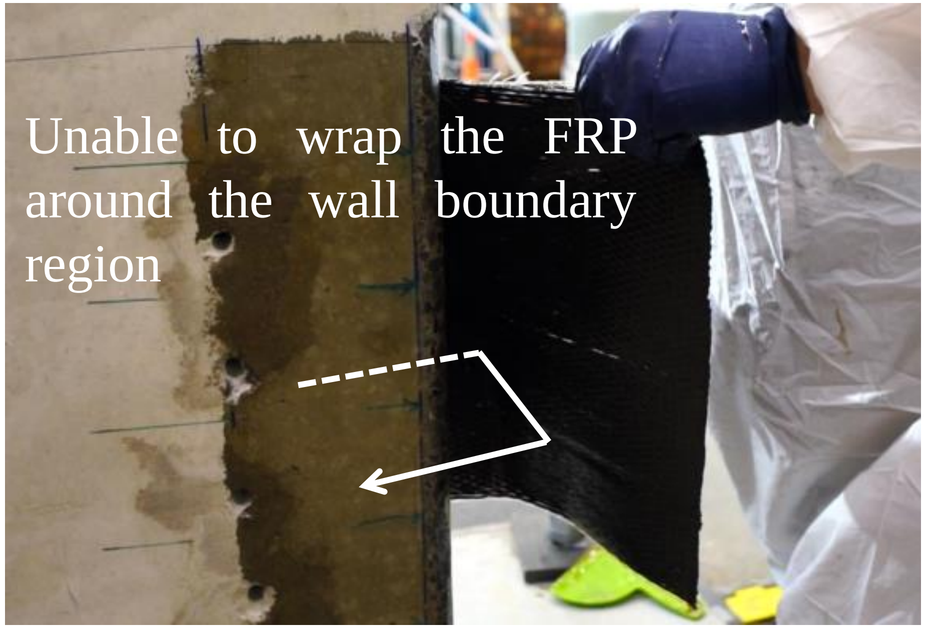
Difficulty in practical construction: blocked structures hampering the wrapping



One-side-blocked column



Opposite-side-blocked column



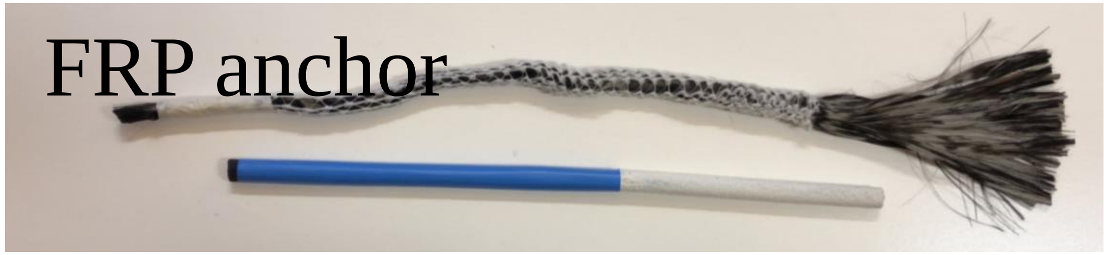
Wall boundary region

FRP confinement for obstructed structures:

- ❌ Research;
- ❌ Design code.

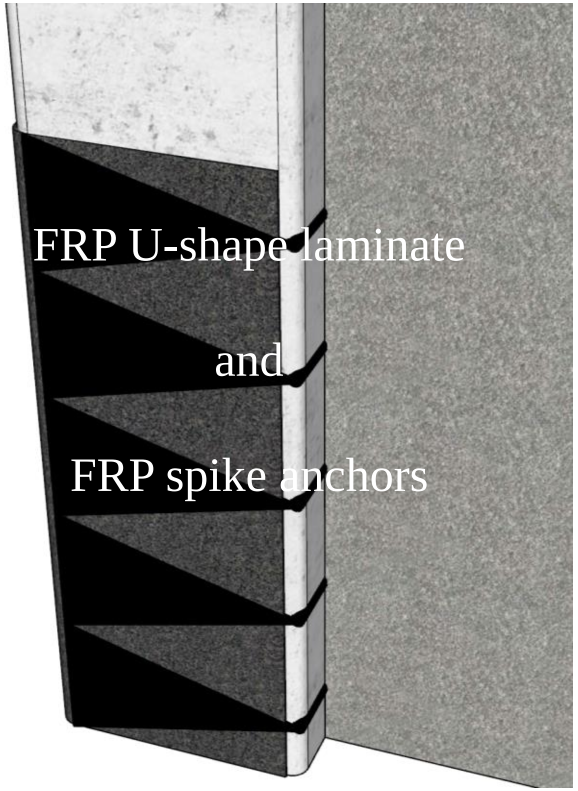
Research motivation

Solutions: integrating FRP laminate and spike anchors

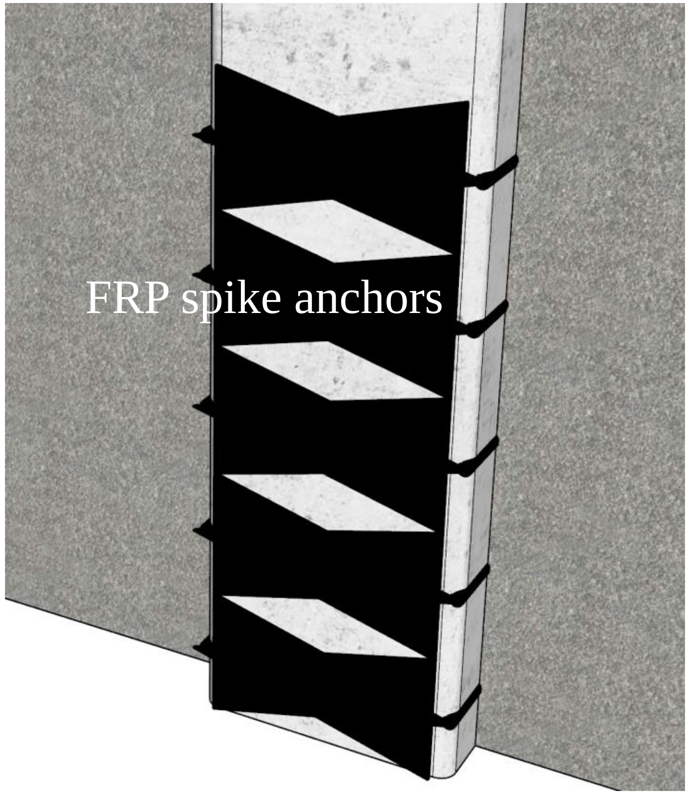


Research motivation

Solutions: integrating FRP laminate and spike anchors



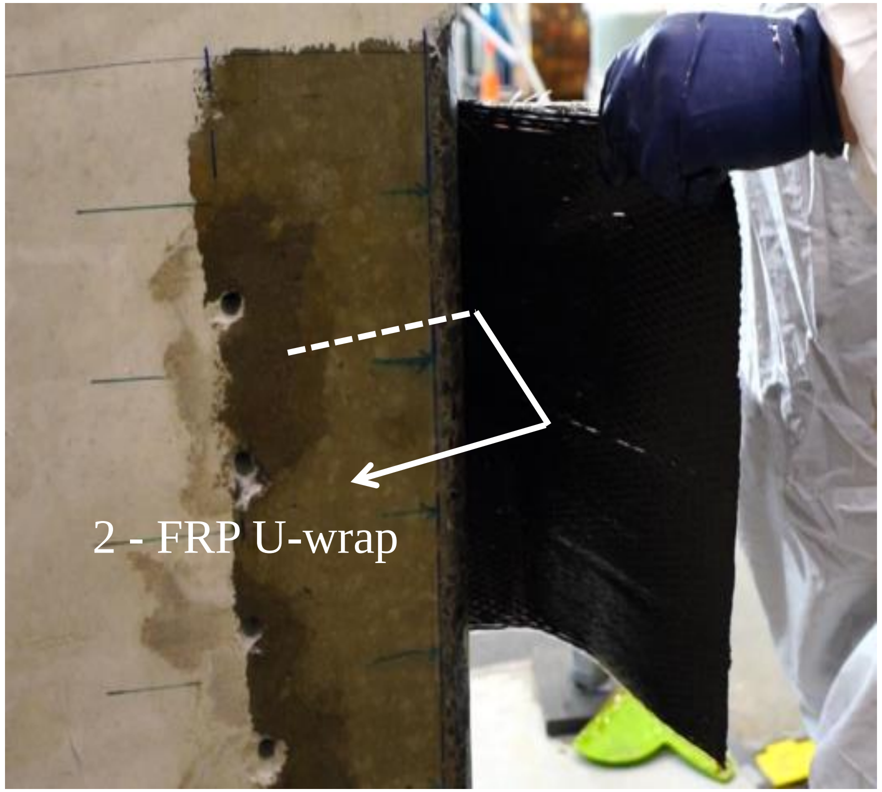
Confinement type A
for one-side-blocked column

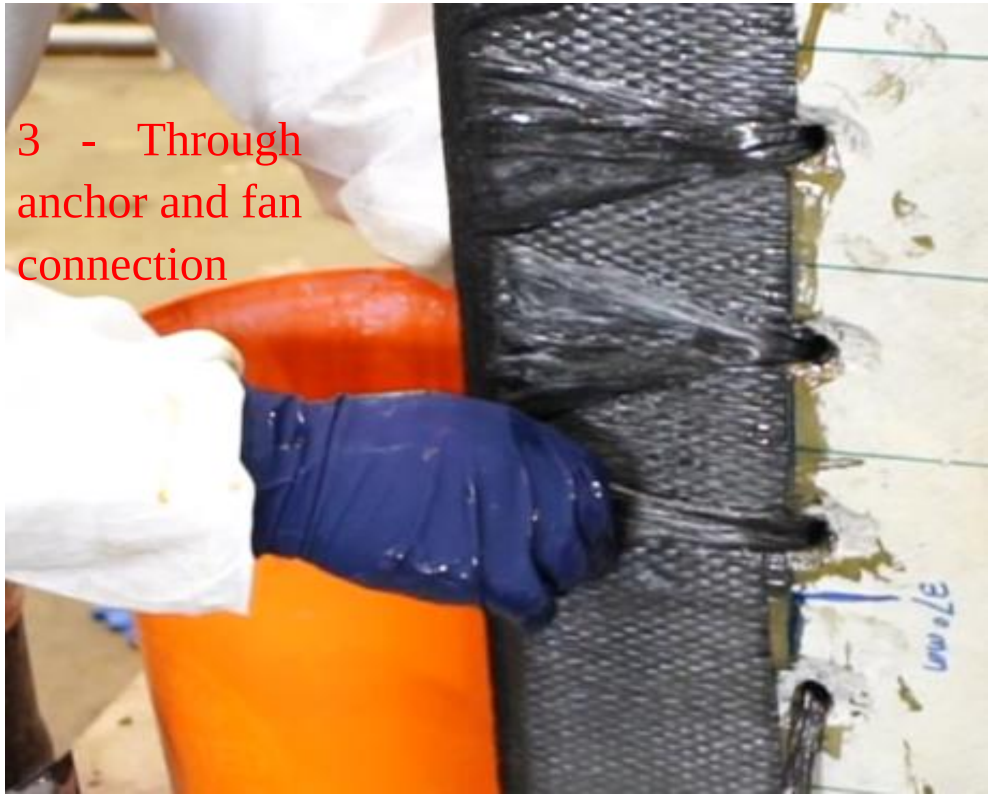


Confinement type B
for opposite-side-blocked column

Research motivation

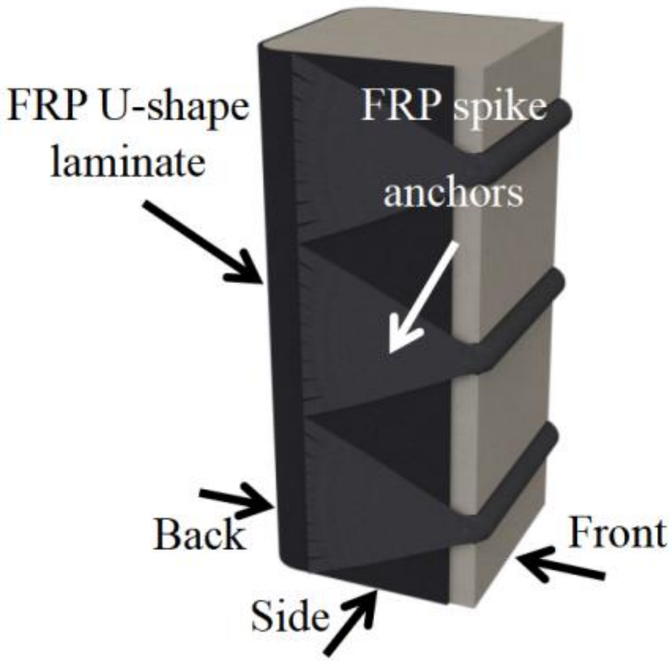
Solutions: integrating FRP laminate and spike anchors

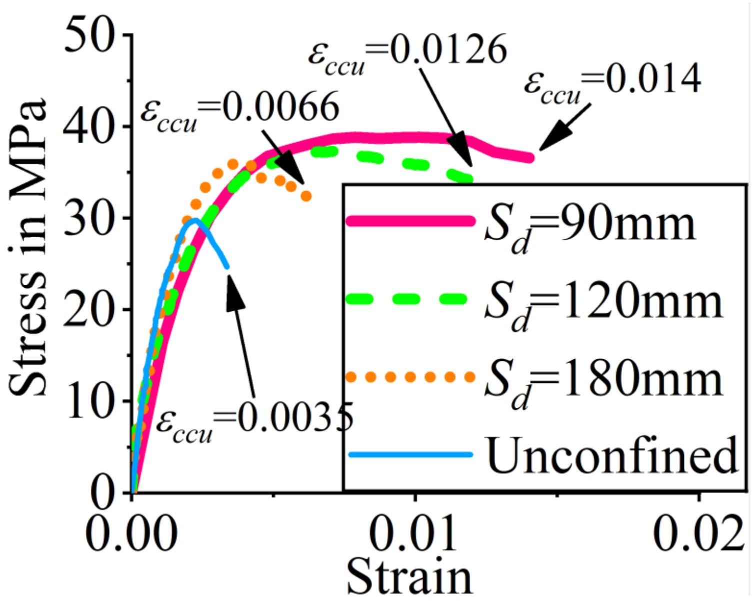




Research motivation

Published study: testing on concrete prisms confined by FRP laminate and spike anchors

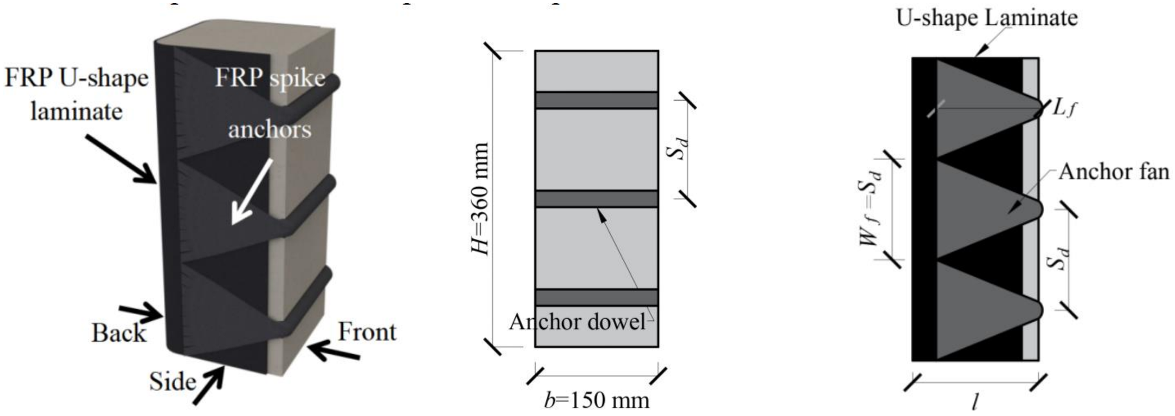




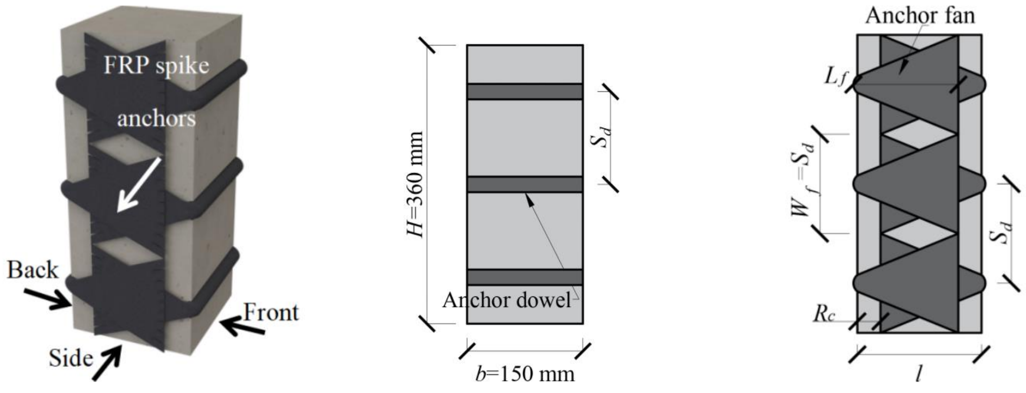
Key finding: the confined concrete exhibited an improved strength capacity by 1/3 and strain capacity by 4 times, when the anchor spacing was 90 mm.

Previous test data

Testing program: 75 prisms subjected to monotonic axial compression testing



Type A confinement



Type B confinement

Test variables:

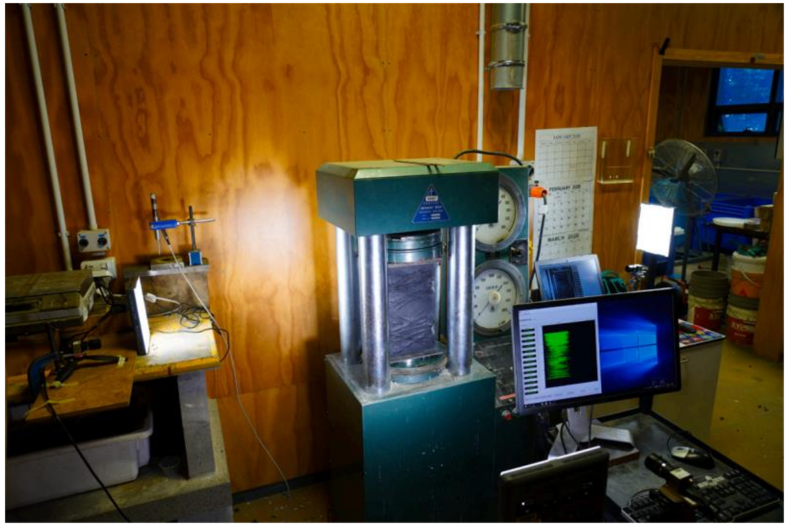
●**Anchor spacing (S_d)**:
90 mm, 120 mm and 180 mm;

●**Anchor cross-sectional area (A_d)**:
14 mm^2, 28 mm^2 and 56 mm^2;

●**Cross-sectional aspect ratio (*l*/*b*)**:
1 and 1.33.

Prism dimensions(mm):

•L=150, b=150, H=360
•L=200, b=150, H=360



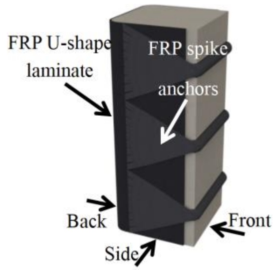
Previous test data

Failure modes:

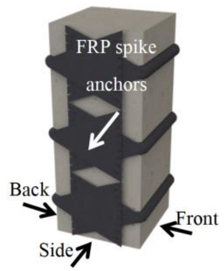
Tensile capacity of FRP fan insertion: $N_{fr} = 3.6 E_a \varepsilon_{afe} A_d^{0.56} \left(\frac{90^o - \alpha}{90^o} \right)$

Bond capacity of anchor fan: $N_{sd} = 0.122 \sigma_r A_f$

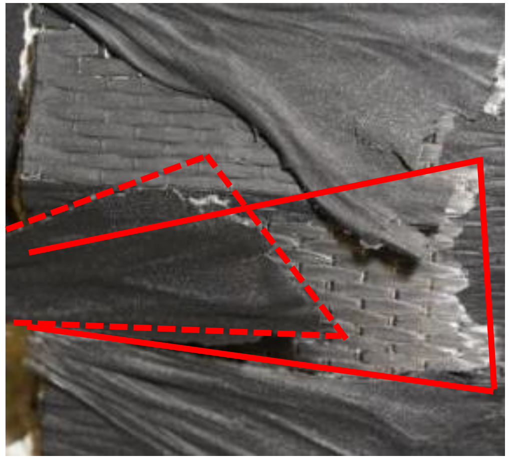
Concrete -control potential parameter: $M_{cl} = N_{fr} S_c^{0.5} \left(\frac{l}{b} \right)^{0.1}$

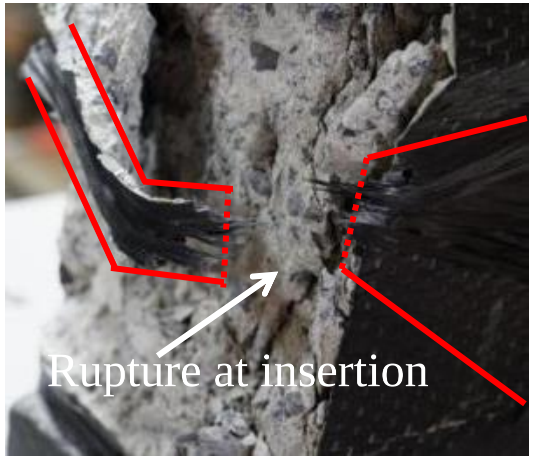


Type A confinement



Type B confinement





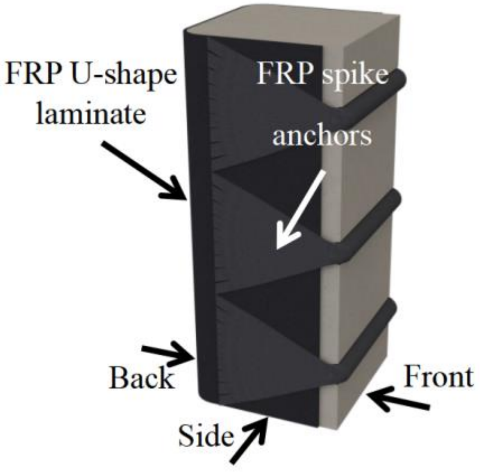
Debonding prevention:
$N_{fr} < N_{sd}$

Fiber rupture:
$M_{cl} > 0.31$ for type A
$M_{cl} > 0.25$ for type B

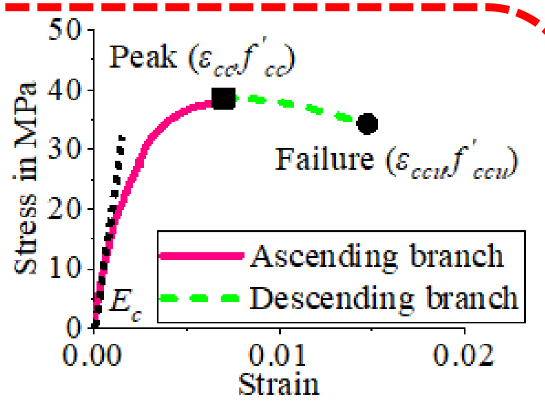
Concrete-controlled failure:
$M_{cl} < 0.31$ for type A
$M_{cl} < 0.25$ for type B

Research motivation

Research gap: guidelines currently unavailable in design codes or standards

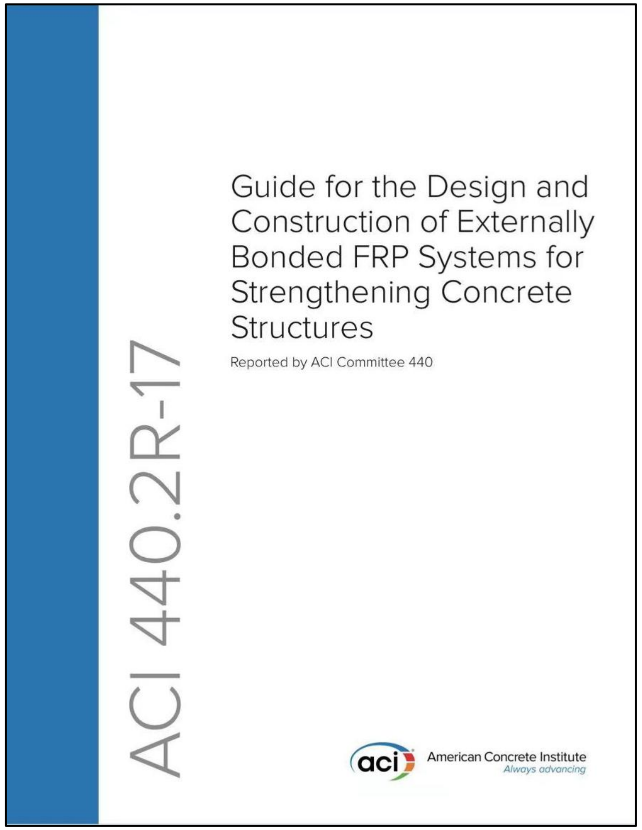


Stage 1: testing on prism



Stage 2: stress-strain model

Current work



Stage 3: Implementation into ACI code

Determination of the undecided parameters

Math connection: relations between the properties of the confined and unconfined concrete

Peak strength $f'_{cc} = (k_1 x_m + 1) f'_c$

Stress at failure $f'_{ccu} = (k_2 x_m + 0.85) f'_c$

Strain at peak $\varepsilon_{cc} = (k_3 x_g + 1)\varepsilon'_c$

Failure strain $\varepsilon_{ccu} = (k_4 x_g + 1.33)\varepsilon'_c$

$$x_m = \frac{\kappa_a f_p}{f'_c}$$

$$x_g = \left(\kappa_b \frac{f_p}{f'_c}\right)\left(\frac{\varepsilon_{afe}}{\varepsilon'_c}\right)^{0.45}$$

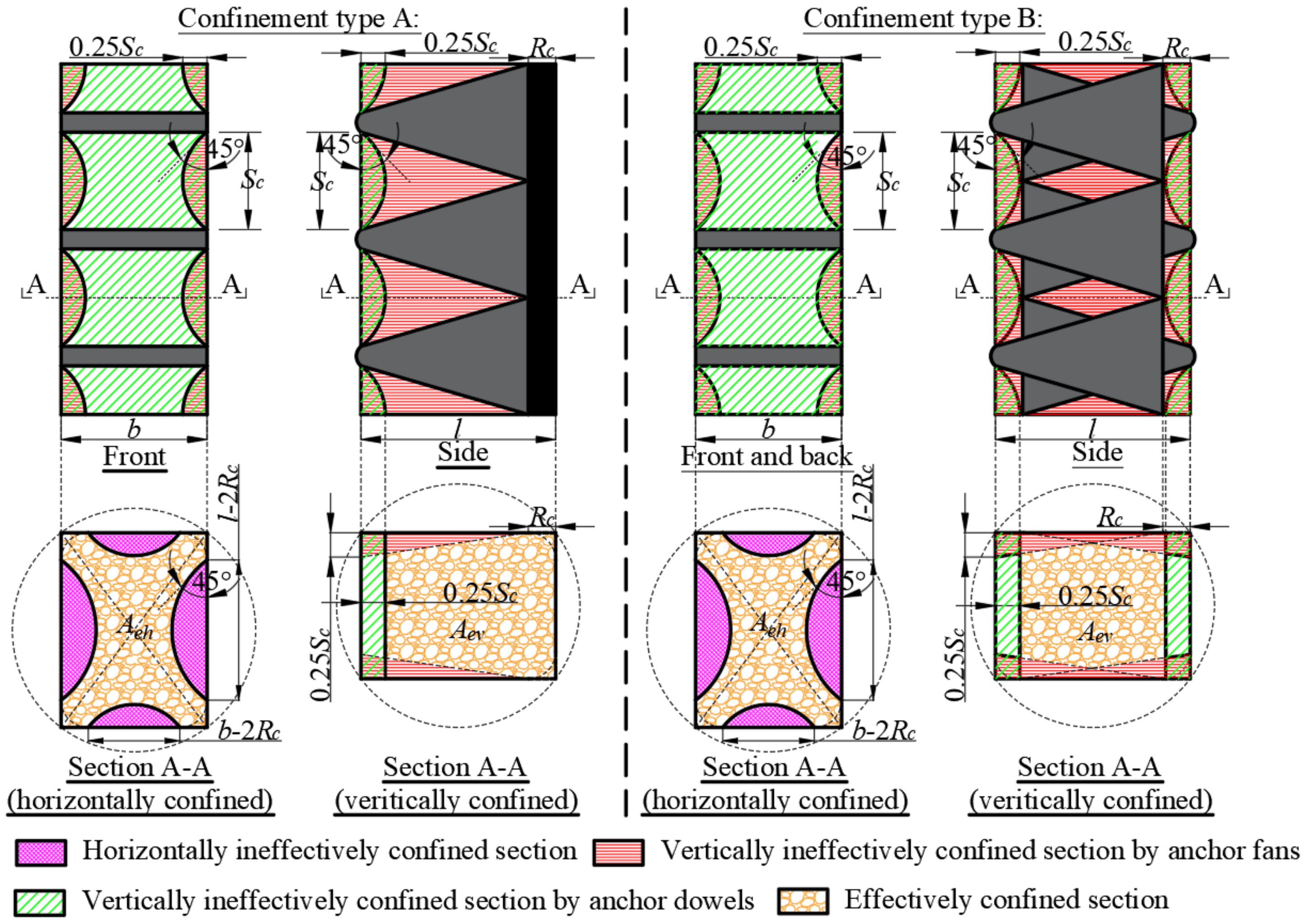
1. Max confining pressure f_p
2. Shape factor κ_a κ_b
3. k_1, k_2, k_3 and k_4

The mathematical forms follow the following publications:

1. Samaan M, Mirmiran A, Shahawy M. Model of concrete confined by fiber composites. Journal of structural engineering. 1998;124:1025-31.
2. Lam L, Teng J. Design-oriented stress-strain model for FRP-confined concrete in rectangular columns. Journal of reinforced plastics and composites. 2003;22:1149-86.

Determination of the undecided parameters

Shape factor κ_a and κ_b: calculated by introducing effectively/ineffectively confined sections



$$\kappa_a = \kappa_e \left(\frac{b}{l}\right)^2$$

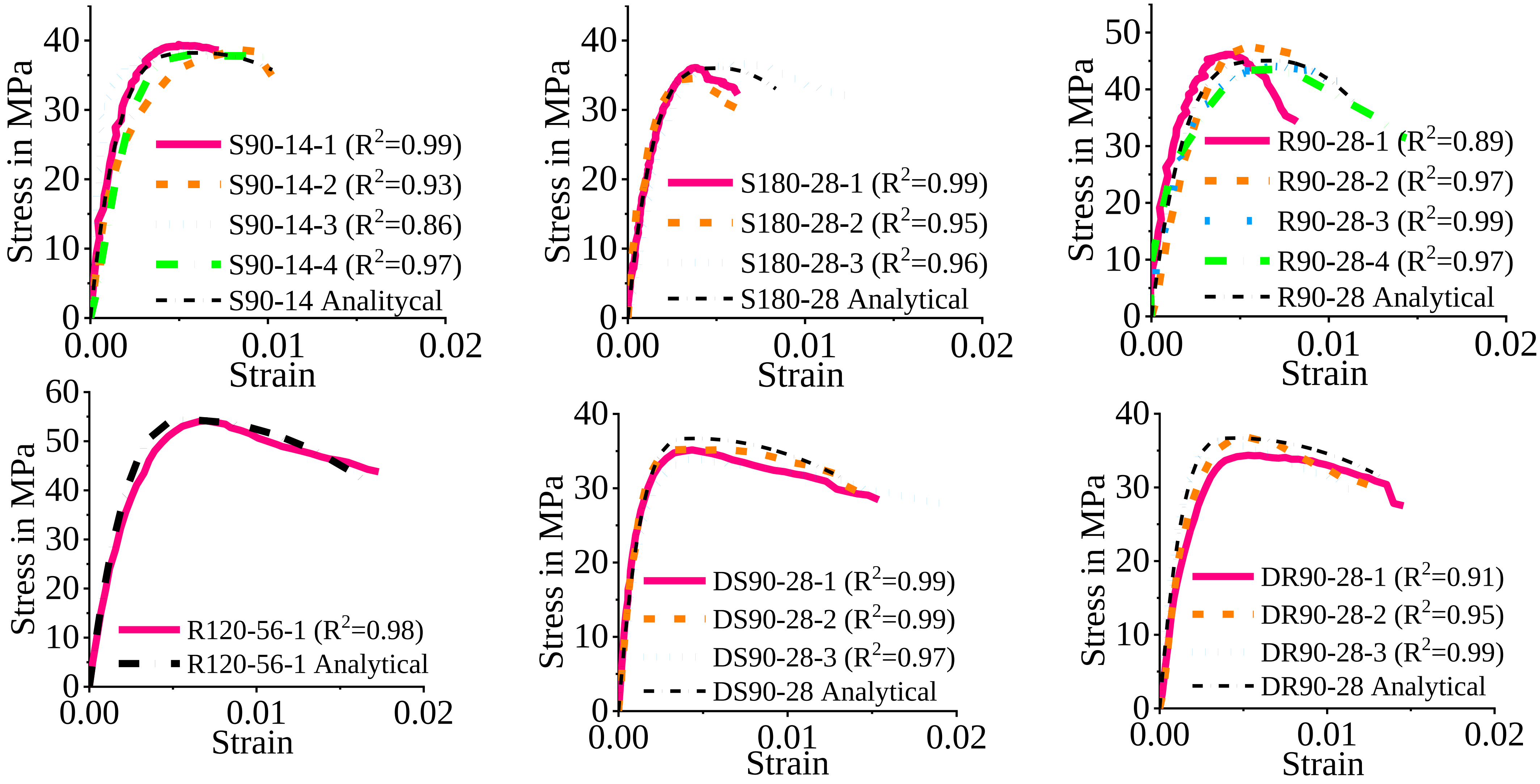
$$\kappa_b = \kappa_e \left(\frac{l}{b}\right)^{0.5}$$

$$\kappa_h = \frac{A_{eh}}{A_c}$$

$$\kappa_v = \frac{A_{ev}}{A_c}$$

$$\kappa_e = \kappa_h \kappa_v$$

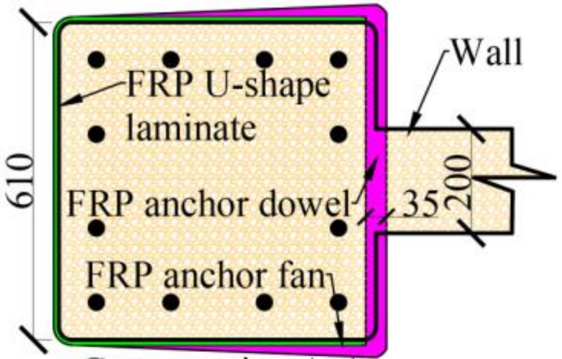
Comparison between tested and analytical results



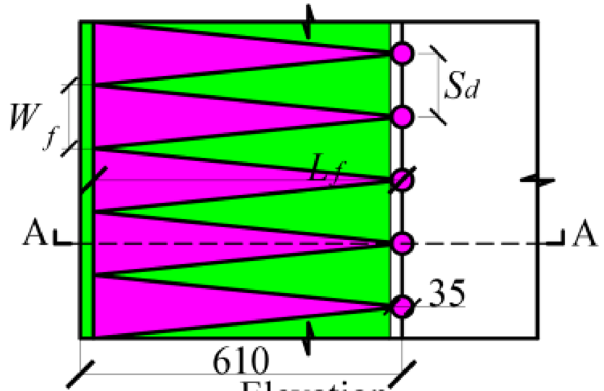
Design examples

Design example 1: enhancing column strength capacity (Section 16.8 of ACI PRC 440.2-17)

Example: a 610 mm square column requiring an additional 20% of axial load



Cross-section A-A



Elevation

Solution (confinement configurations):

- 6 plies FRP laminate
- Anchors spacing =120 mm
- Anchor cross-sectional area =254.5 mm^2 (diameter= 18 mm)

$$N_{fr} = 3.6\times 236.4\times 10^3\,\text{MPa}\times 0.00118\times(254.5)^{0.56}\,\text{mm}^2\times\frac{90^o-\frac{180^o}{\pi}\arctan(\frac{0.5\times 120}{610-25})}{90^o} = 208.8\text{kN}$$

$$N_{sd} = 0.122\times 50.6\text{MPa}\times 2\times 0.5\times 120\text{mm}\times(610-25)\text{mm} = 433.4\text{kN} > N_{fr} = 208.8\text{kN}$$

$$N_{fr} = 3.6\times 236.4\times 10^3\,\text{MPa}\times 0.95\times 0.55\times 0.00118\times(254.5)^{0.56}\,\text{mm}^2\times\frac{90^o-\frac{180^o}{\pi}\arctan(\frac{0.5\times 120}{610-25})}{90^o} = 109.1\text{kN}$$

$$M_{cl} = 109.1\text{kN}\times(85)^{0.5}\,\text{mm}\times\left(\frac{610}{610}\right)^{0.1} = 1.0\text{kNm} > 0.31\text{kNm}$$

$$A_{eh} = 610\text{mm}\times 610\text{mm} - \frac{1}{3}(610\text{mm}-2\times 25\text{mm})^2 - \frac{1}{3}(610\text{mm}-2\times 25\text{mm})^2 = 153233.3\text{mm}^2$$

$$A_{ev} = 610\text{mm}\times(610\text{mm} - 0.25\times 85\text{mm}) - 0.25\times 85\text{mm}\,\frac{(610\text{mm} - 25\text{mm} - 0.25\times 85\text{mm})^2}{610\text{mm} - 25\text{mm}} = 337793.0\text{mm}^2$$

$$\kappa_h = 153233.3\text{mm}^2 \div (610\text{mm}\times 610\text{mm}) = 0.412 \qquad \kappa_v = 337793.0\text{mm}^2 \div (610\text{mm}\times 610\text{mm}) = 0.908$$

$$\kappa_e = 0.412\times 0.908 = 0.374 \qquad \kappa_a = 0.374\times\left(\frac{610\text{mm}}{610\text{mm}}\right)^2 = 0.374$$

$$N_{dr} = 236.4\times 10^3\,\text{MPa}\times 0.95\times 0.55\times 0.00118\times 254.5\text{mm}^2 = 370.9\text{kN}$$

$$N_{lr} = 120\text{mm}\times 6\times 0.331\text{mm}\times 234.4\times 10^3\,\text{MPa}\times 0.95\times 0.55\times 0.0011 = 321.1\text{kN}$$

$$f_{p,l} = \frac{2\times 321.1\text{kN}}{120\text{mm}\times\sqrt{(610\text{mm})^2+(610\text{mm})^2}} = 6.2\text{MPa} \qquad f_{p,d} = \frac{2\times 208.8\text{kN}}{120\text{mm}\times\sqrt{(610\text{mm})^2+(610\text{mm})^2}} = 2.1\text{MPa}$$

$$f_{p,f} = \frac{370.9\text{kN}+321.1\text{kN}}{120\text{mm}\times\sqrt{(610\text{mm})^2+(610\text{mm})^2}} = 6.7\text{MPa} \qquad x_m = \frac{\kappa_a f_p}{f_c'} = \frac{0.374\times 5.4\text{MPa}}{45\text{MPa}} = 0.045$$

$$f_p = \frac{610\text{mm}\times 6.2\text{MPa} + 610\text{mm}\times 2.1\text{MPa} + 2\times 610\text{mm}\times 6.7\text{MPa}}{2\times 610\text{mm} + 2\times 610\text{mm}} = 5.4\text{MPa}$$

$$f_{cc}' = (6.0\times 0.045+1)\times 45\text{MPa} = 57.2\text{MPa} > 56.4\text{MPa}$$

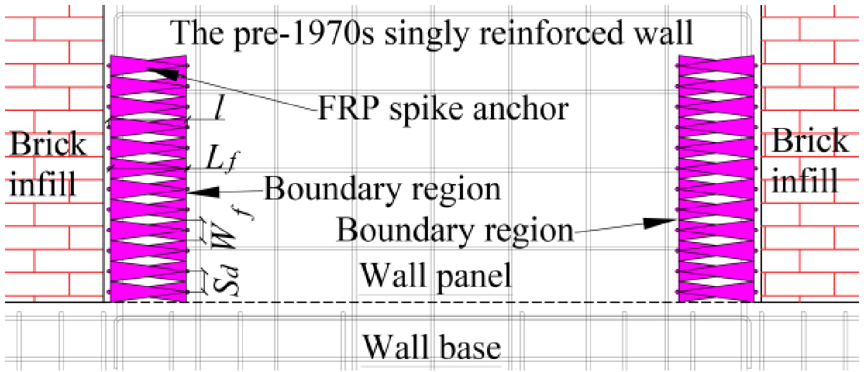
Design examples

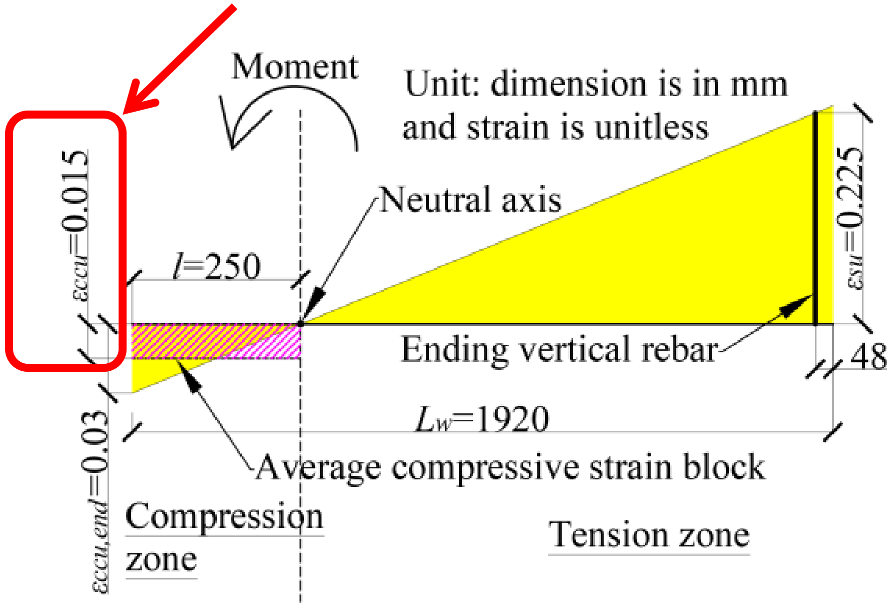
Design example 2: improving wall drift capacity

Example: A wall with axial failure of the boundary elements.

$$\varepsilon_{ccu} = 0.0158 > 0.0150$$

Solution (confinement configurations):
- b=200 mm and l=250 mm
- Anchors spacing =60 mm
- Anchor cross-sectional area =14 mm^2





Conclusions

The current work included:

1. Bi-parabola stress-strain model was developed based on 75 prism tests;

3. Design examples were given to assist the engineers to understand and use the model in practical design;

Future work will include:

1. Developing a calculation program/software utilizing the proposed model for industry (almost accomplished);

2. Implementation of the model into the ACI 440 code (?)

Thanks !

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