FDOT TRANSPORTATION SYMPOSIUM 2019

FRP-RC Design - Part 3c

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Adapted from…

Composites Australia, December 5, 2018

Design of concrete structures internally reinforced with FRP bars

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Course Description

Fiber-reinforced polymer (FRP) materials have emerged as an alternative for producing reinforcing bars for concrete structures. Due to other differences in the physical and mechanical behavior of FRP materials versus steel, unique guidance on the engineering and construction of concrete structures reinforced with FRP bars is necessary.

Learning Objectives

- Understand the mechanical properties of FRP bars
- Describe the behavior of FRP bars
- Describe the design assumptions
- Describe the flexural/shear/compression design procedures of concrete members internally reinforced with FRP bars
- Describe the use of internal FRP bars for serviceability & durability design including long-term deflection
- Review the procedure for determining the development and splice length of FRP bars.

Content of the Course

FRP-RC Design - Part 1, (50 min.)

This session will introduce concepts for reinforced concrete design with FRP rebar. Topics will address:

- Recent developments and applications
- Different bar and fiber types;
- Design and construction resources;
- Standards and policies;

FRP-RC Design - Part 2, (50 min.)

This session will introduce Basalt FRP rebar that is being standardized under FHWA funded project ***STIC-0004-00A*** with extended FDOT research under BE694, and provide training on the flexural design of beams, slabs, and columns for:

- Design Assumptions and Material Properties
- Ultimate capacity and rebar development length under strength limit states;
- Crack width, sustained load resistance, and deflection under service limit state;

Content of the Course

FRP-RC Design - Part 3, (50 min.)

This session continues with Basalt FRP rebar from Part II, covering shear and axial design of columns at the strength limit states for:

- Flexural behavior and resistance (Session 3a);
- Shear resistance of beams (Session 3b);
- Compression and biaxial column resistance (Session 3c);

FRP-RC Design - Part IV *(Not included at FTS - for future training)*:

This session continues with FRP rebar from Part III, covering detailing and plans preparation:

- Fatigue resistance under the Fatigue limit state
- Minimum Shrinkage and Temperature Reinforcing
- Bar Bends and Splicing
- Reinforcing Bar Lists
- General Notes & Specifications

Session 3c: Compression Behavior & Column Design

- Effect of Confinement
- Eccentric Loading
- Strength of FRP-RC columns
- Design Philosophy
- Design Examples

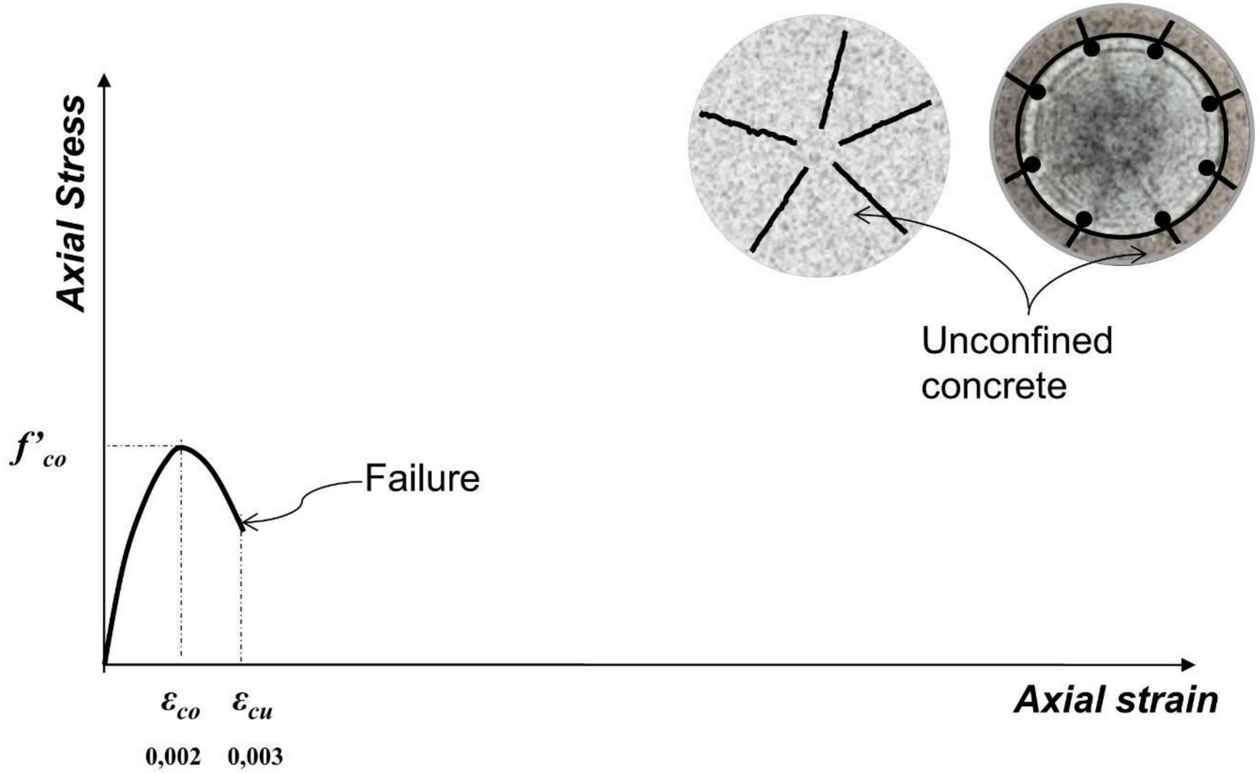
Session 3c: Compression Behavior

Role of reinforcement in columns?

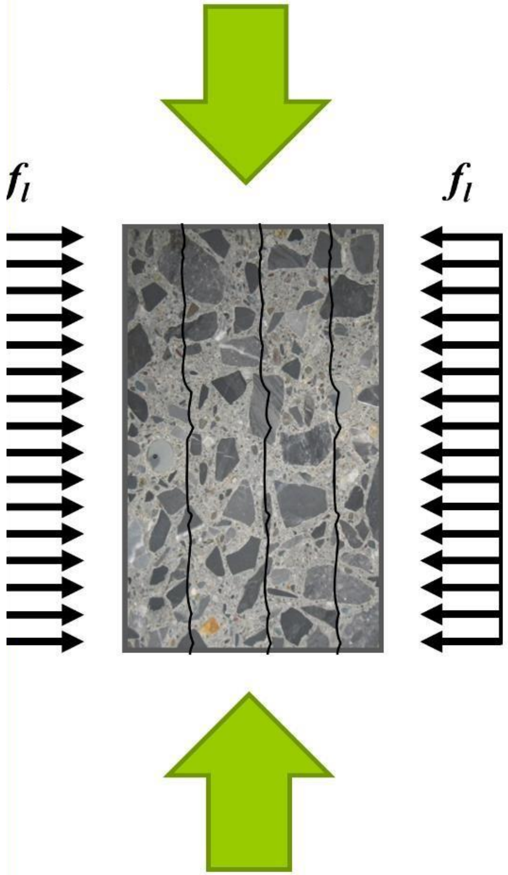
1. Longitudinal rebars
   - Compression, flexure, ductility.
2. Transverse ties/spirals
   - Shear, confinement.

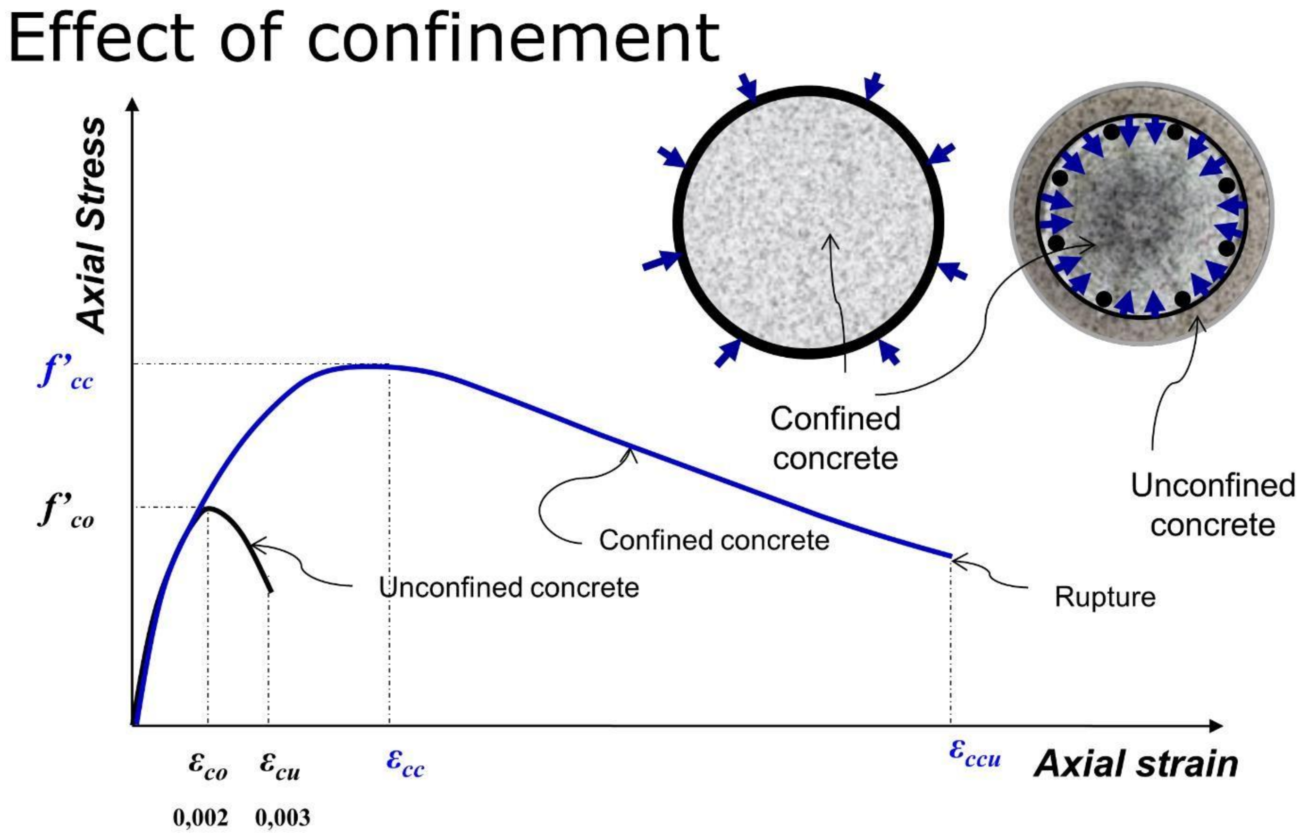
Session 3c: Compression Behavior

Effect of confinement



Session 3c: Compression Behavior



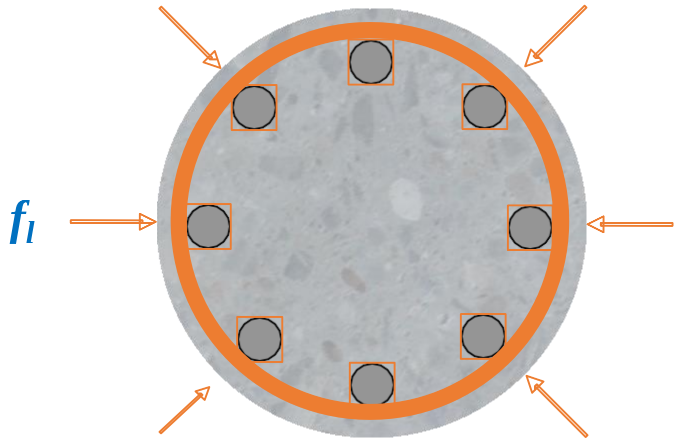


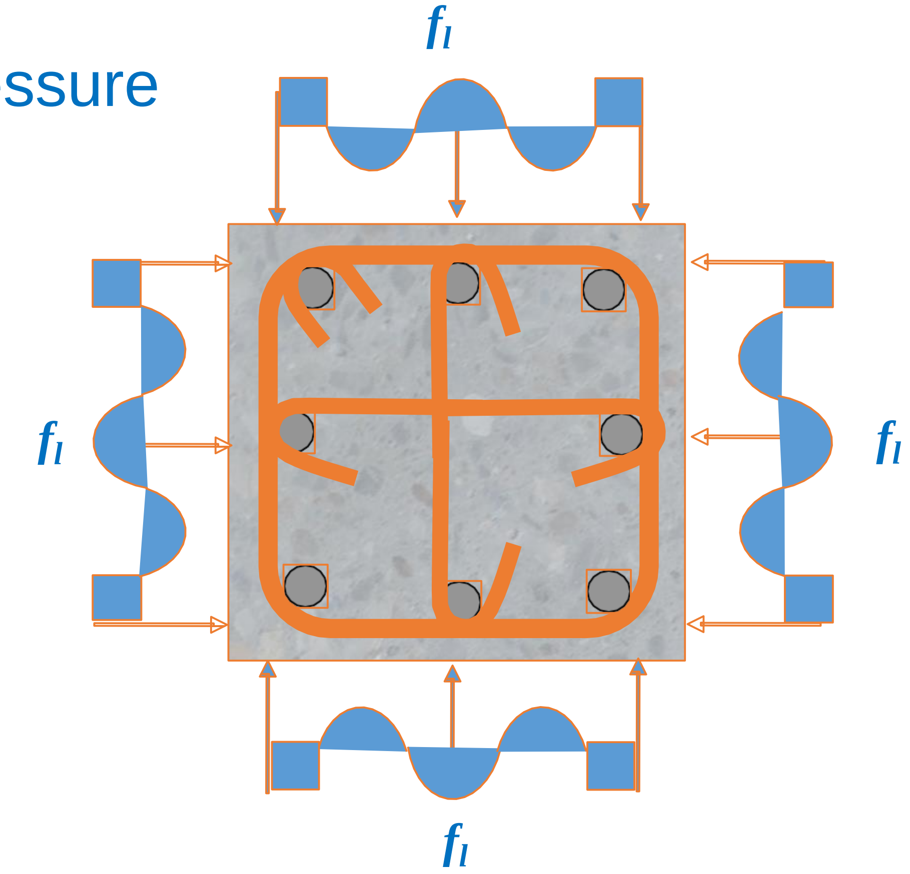
Session 3c: Compression Behavior

Effect of confinement

Principle of internal confinement

Lateral confining pressure

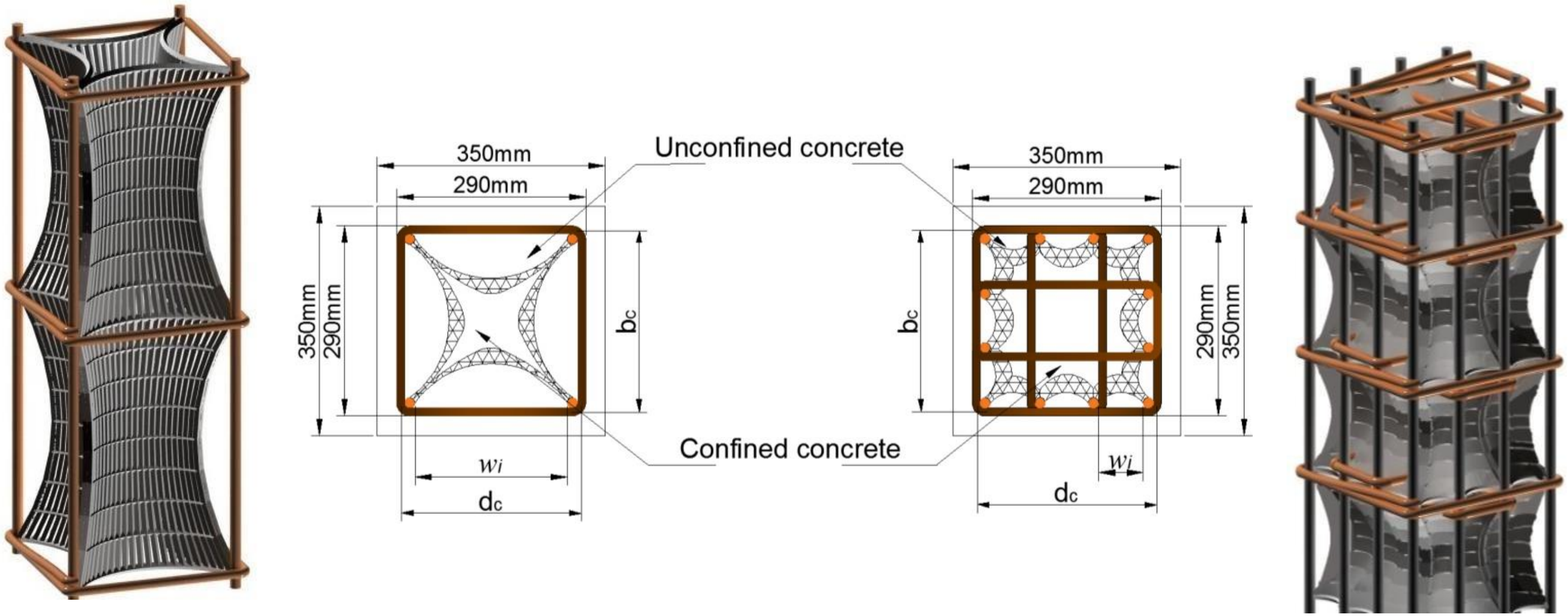




Session 3c: Compression Behavior

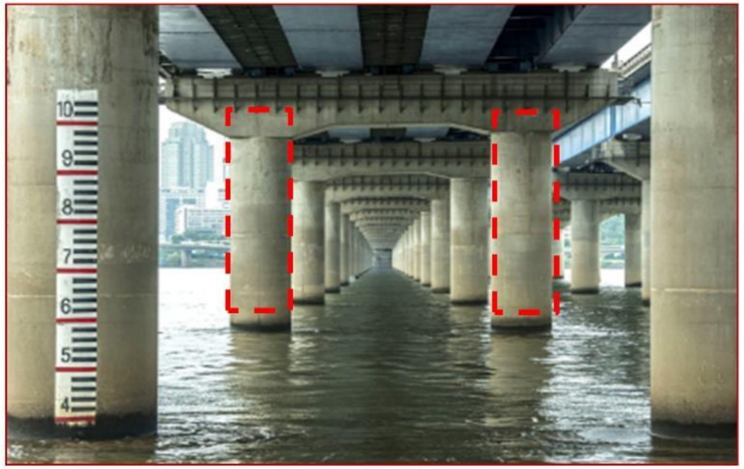
Effect of confinement

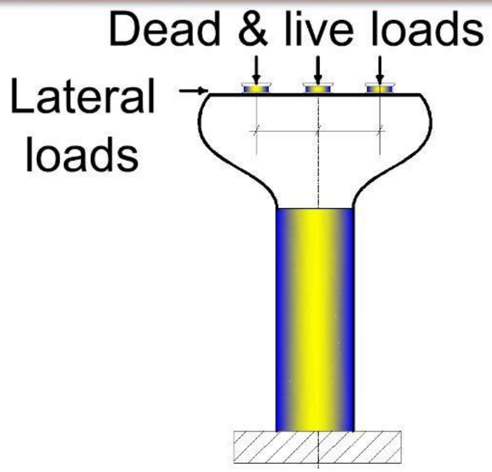
Principle of internal confinement

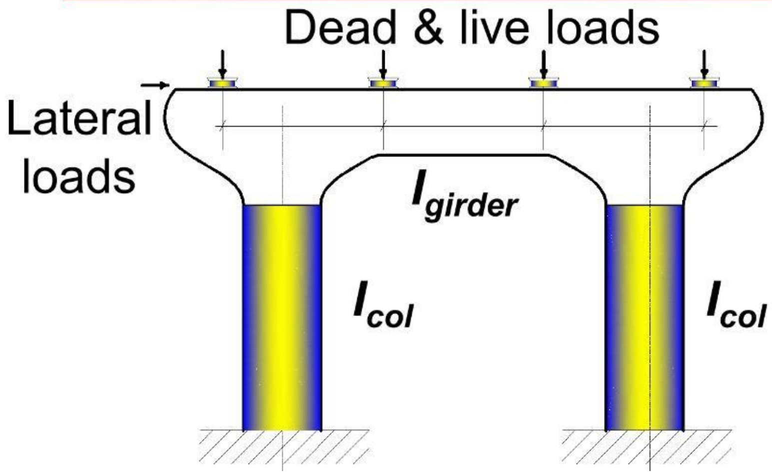


Session 3c: Compression Behavior

Interaction Diagram

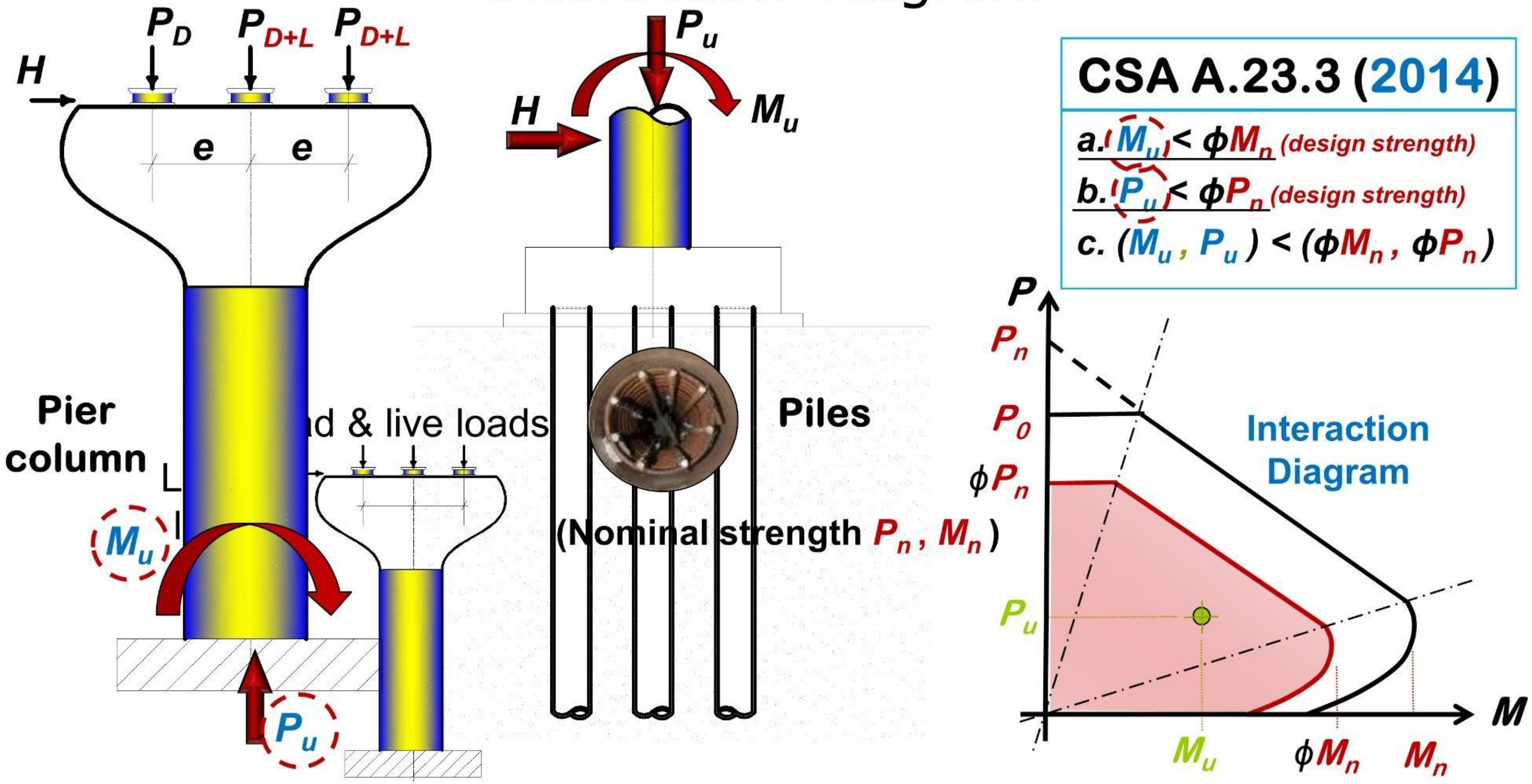






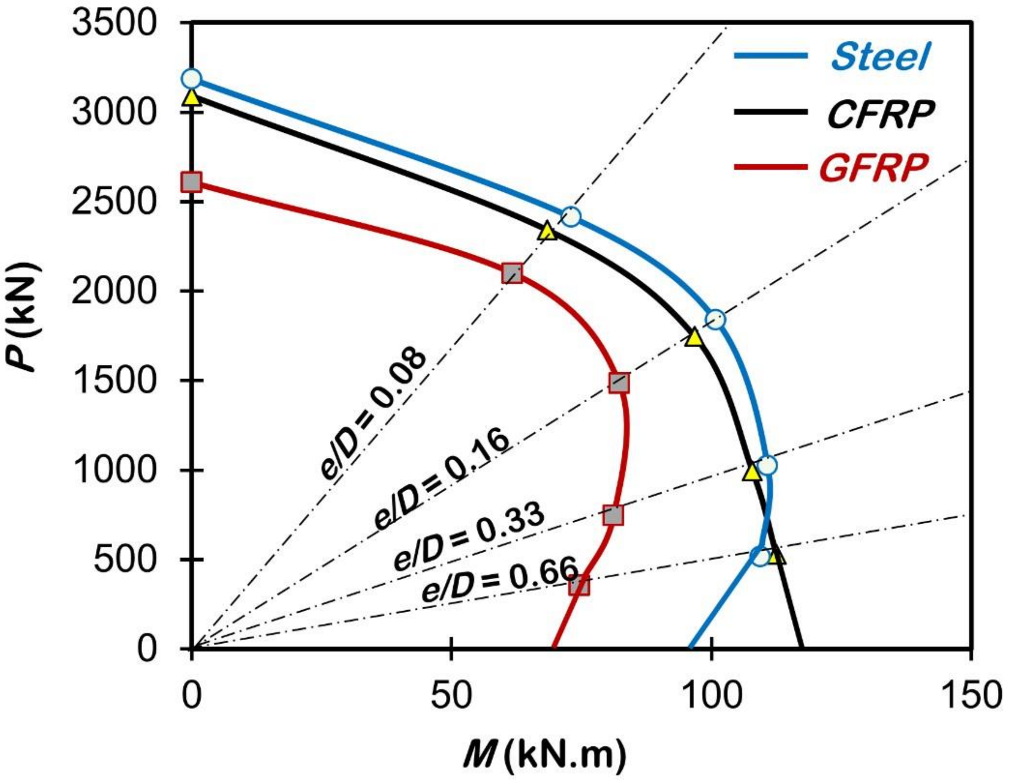
Session 3c: Column Design

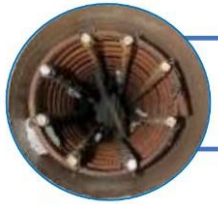
Interaction Diagram



Session 3c: Column Design

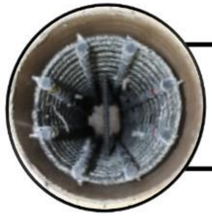
Eccentric loading (interaction diagrams)





8 No. 5 (2.2%)
Spirals No. 3 @ 80 mm

Steel



8 No. 5 (2.2%)
Spirals No. 3 @ 80 mm

CFRP

8 No. 5 (2.2%)
Spirals No. 3 @ 80 mm

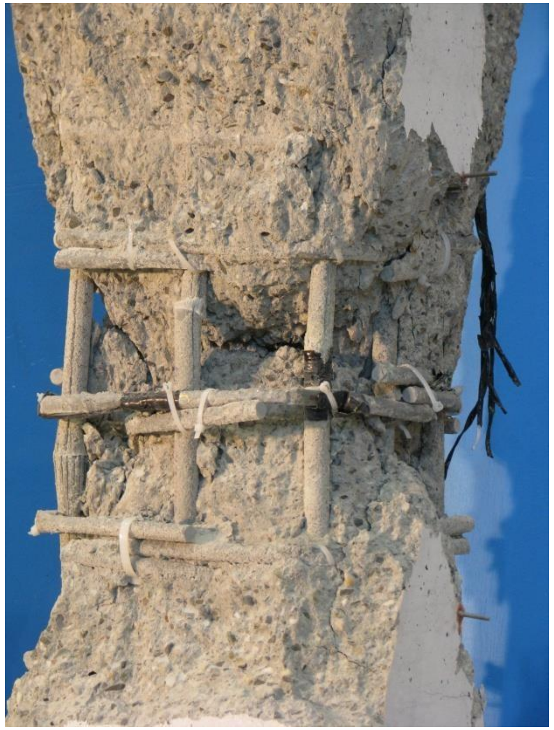
GFRP

Session 3c: Column Design

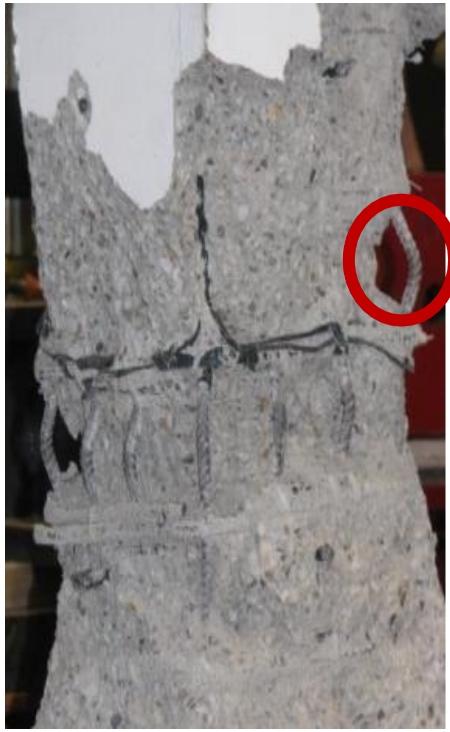
Effect of confinement

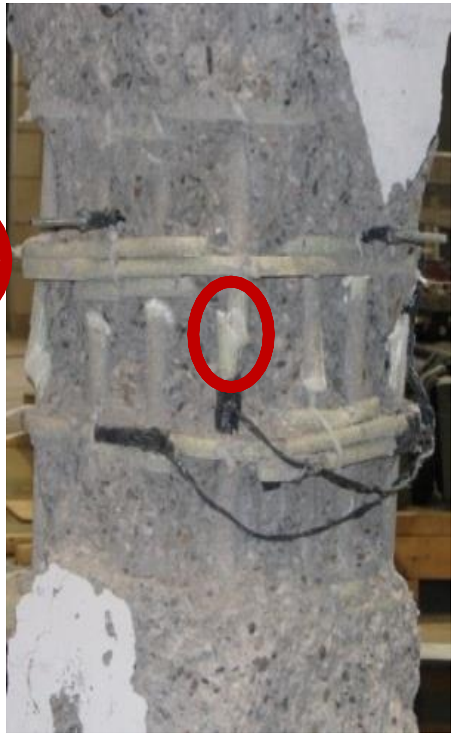
Low confinement

Moderate confinement



High confinement





Session 3c: Column Design

FRP Reinforcements

Carbon FRP Spirals

Glass FRP Spirals

Carbon & Glass FRP
Circular Ties

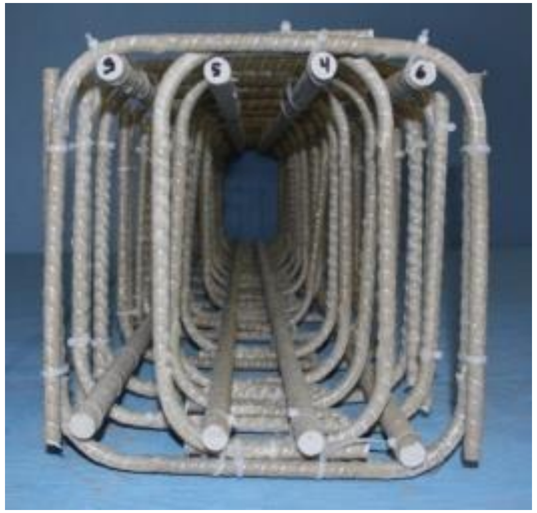
Carbon & Glass FRP
Straight Bars

Session 3c: Column Design

Square FRP-RC Columns

Type A

Type B



Session 3c: Strength of FRP-RC columns

Research projects at University of Sherbrooke

2011

2012

2011

2012

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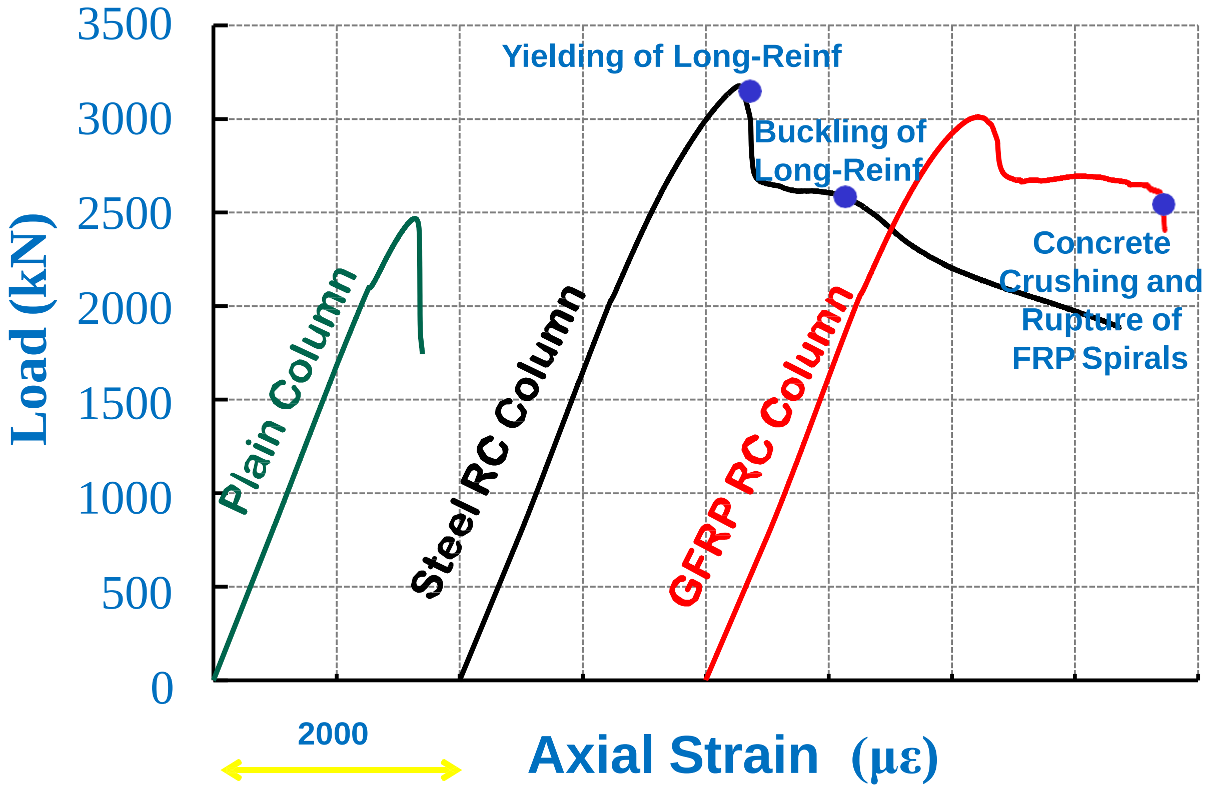
Session 3c: Strength of FRP-RC columns

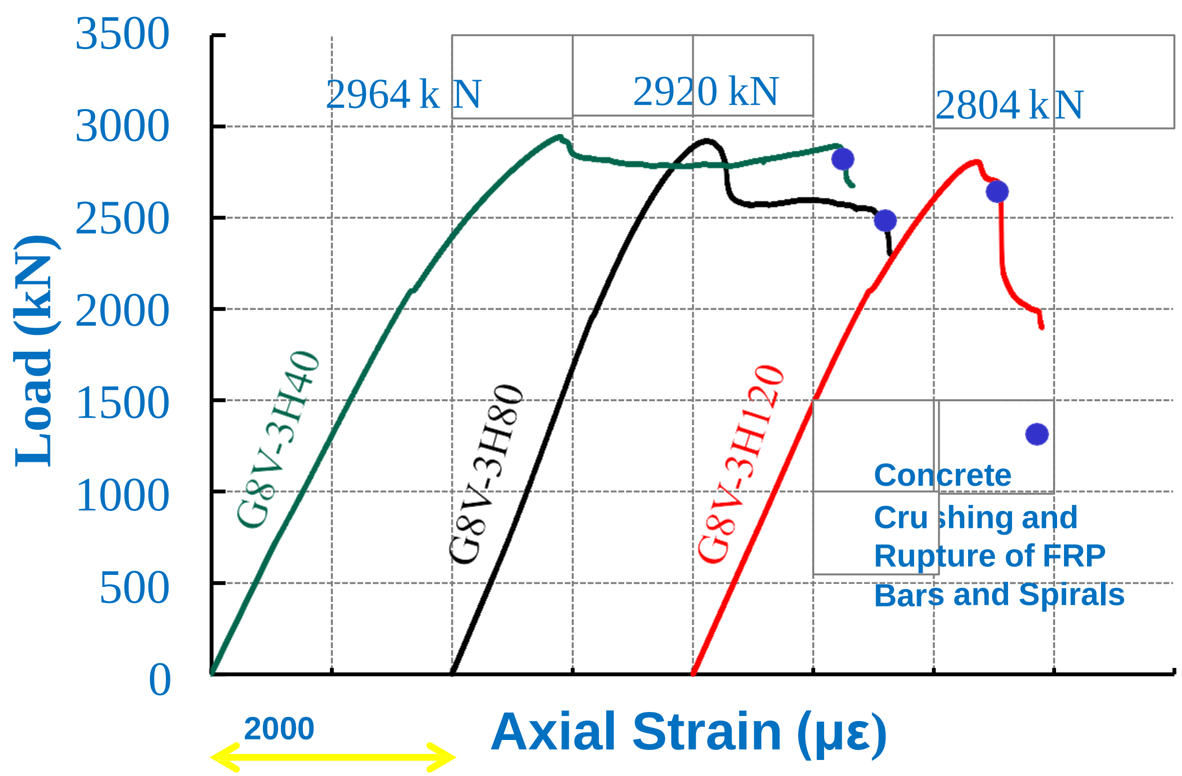
Axial Loading Results: Effect of Type of Reinforcement

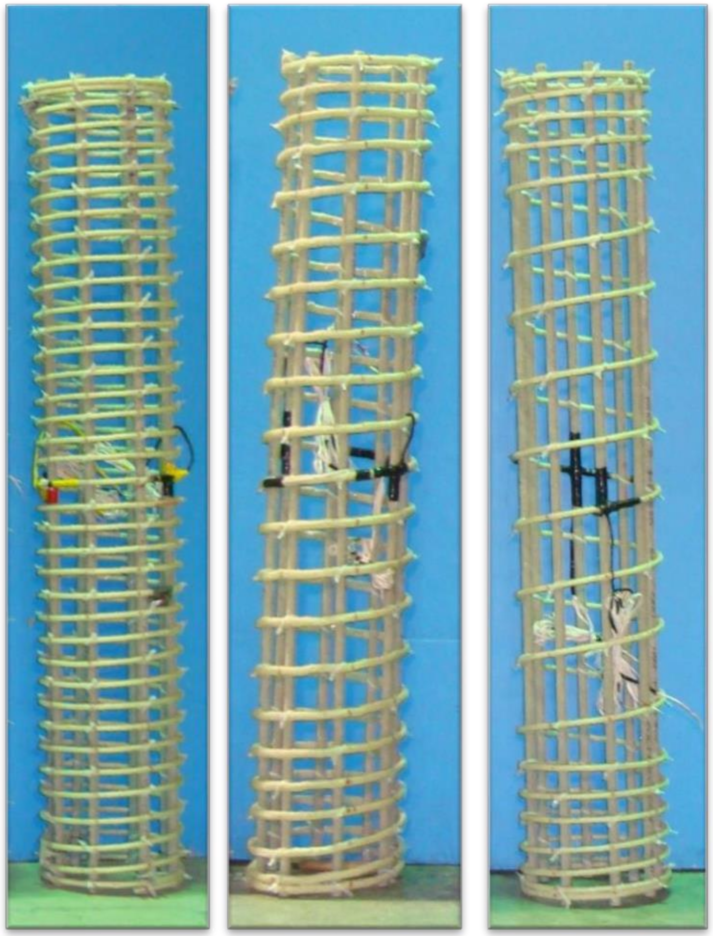


Plain Steel GFRP

Session 3c: Strength of FRP-RC columns

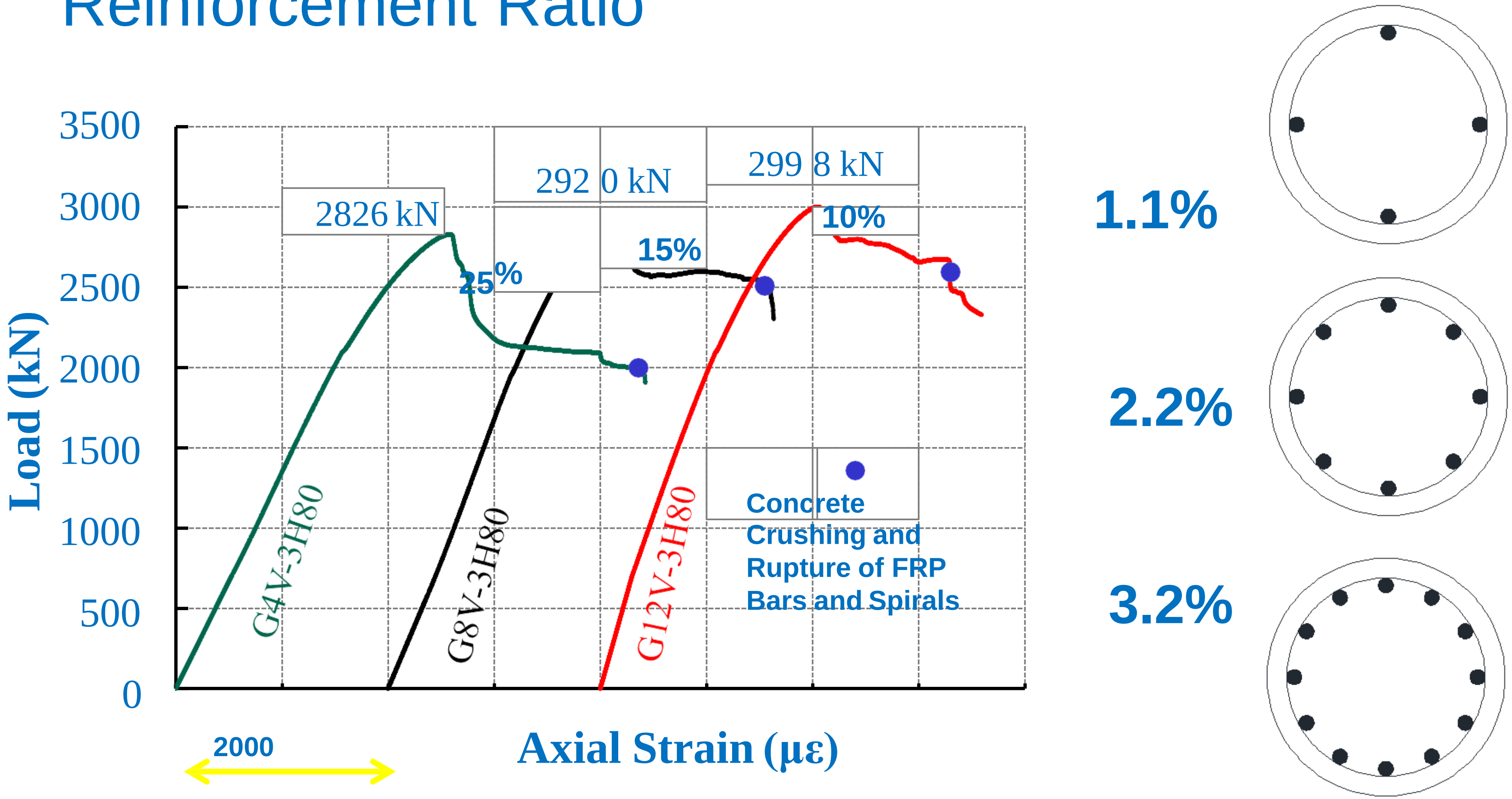
Axial Loading Results: Effect of Spiral Spacing





Session 3c: Strength of FRP-RC columns

Axial Loading Results: Effect of Longitudinal Reinforcement Ratio



Session 3c: Strength of FRP-RC columns

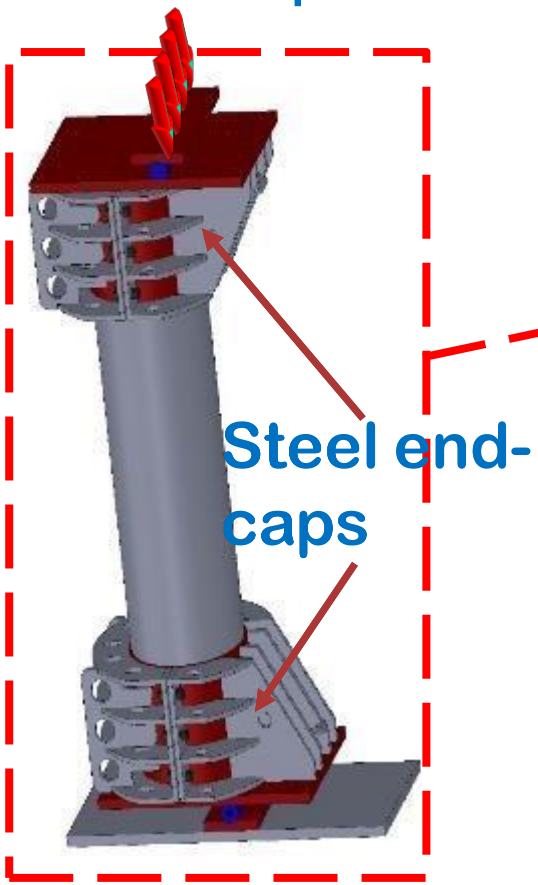
Axial loading (failure modes)

GFRP-RC columns

Session 3c: Strength of FRP-RC columns

Eccentric Loading

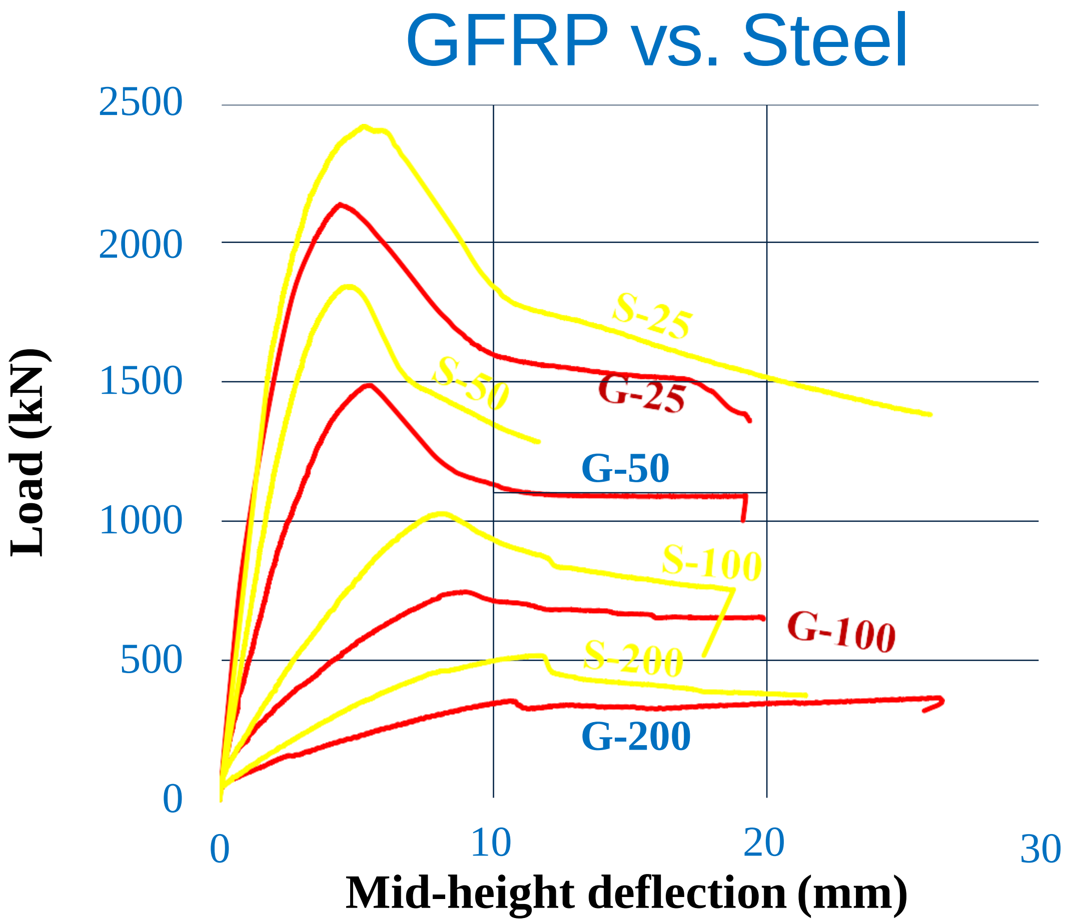
Test setup



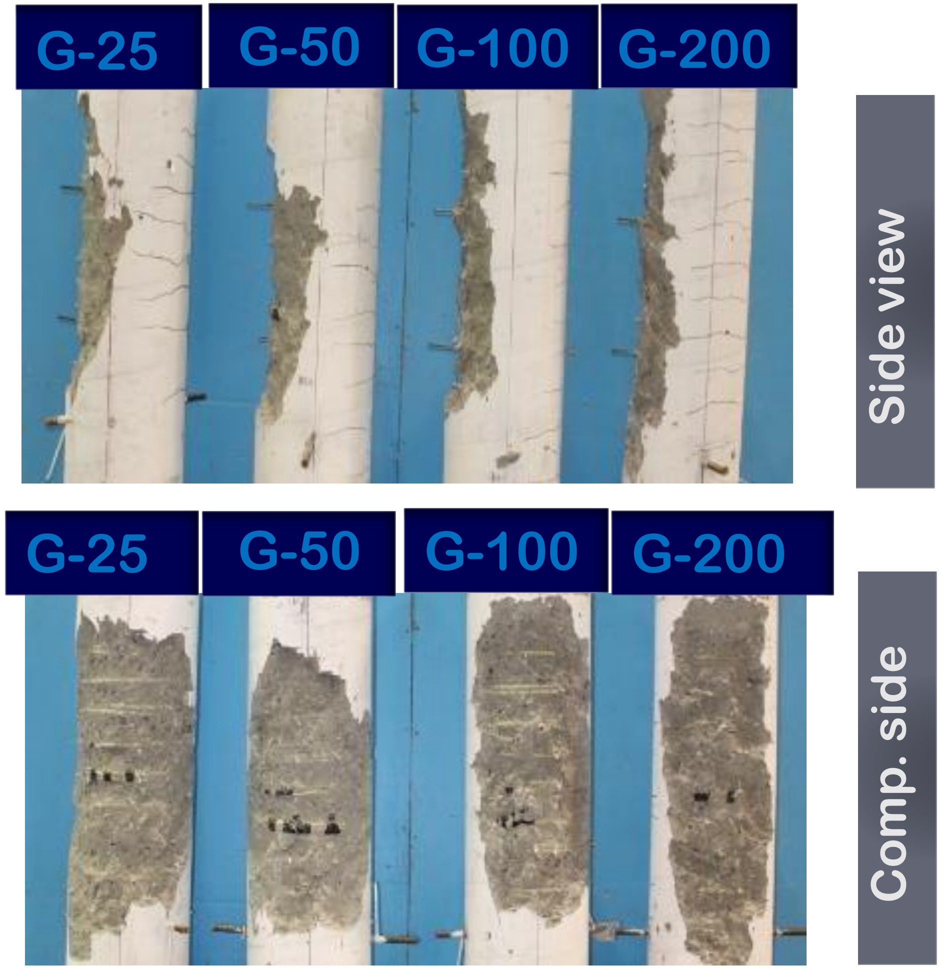
Forney machine (UdS)

Session 3c: Strength of FRP-RC columns

Results



Load-Deflection diagram

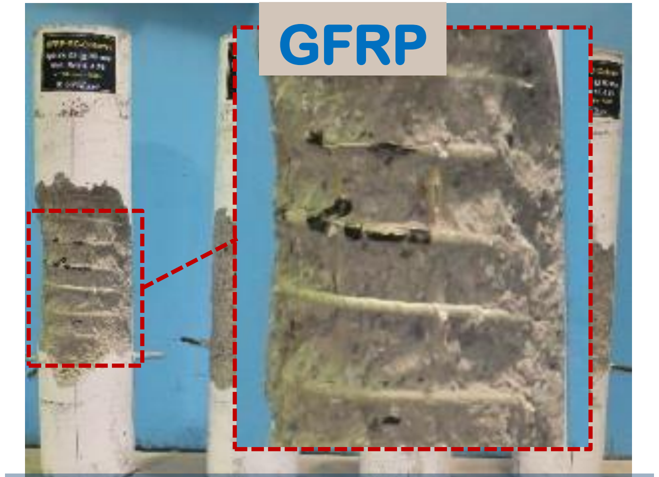


Overview of test region at failure

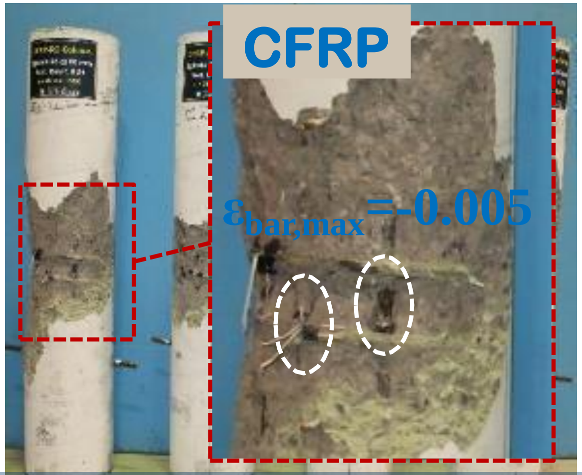
Session 3c: Strength of FRP-RC columns

Eccentric loading (failure modes)

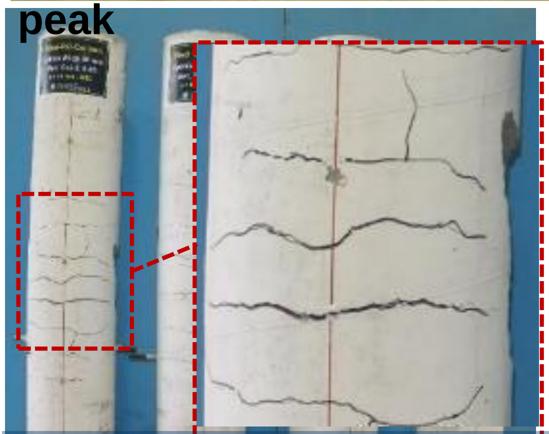
St bars yielded before peak



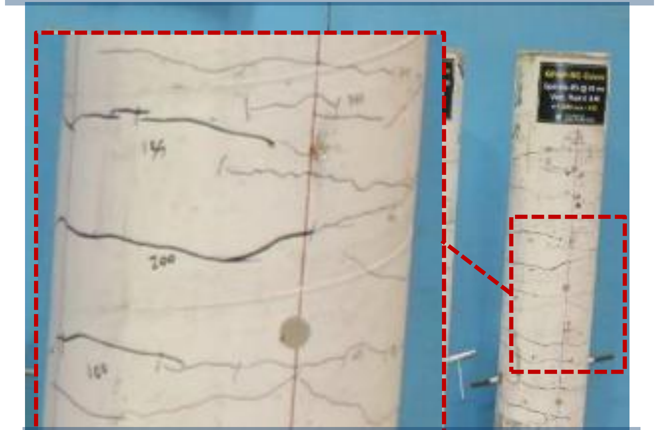
G bars were intact



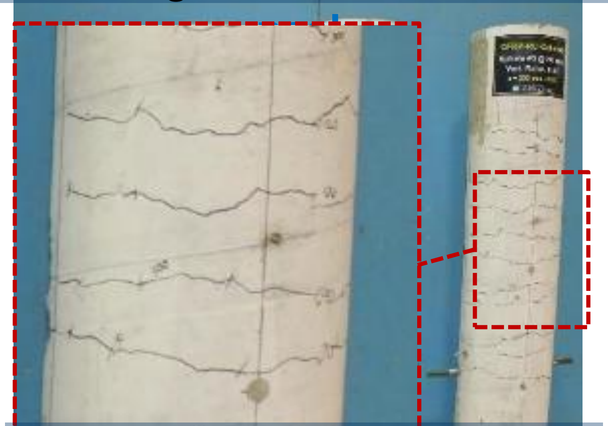
C bars got crushed after the



St bars yielded & wide cracks remained



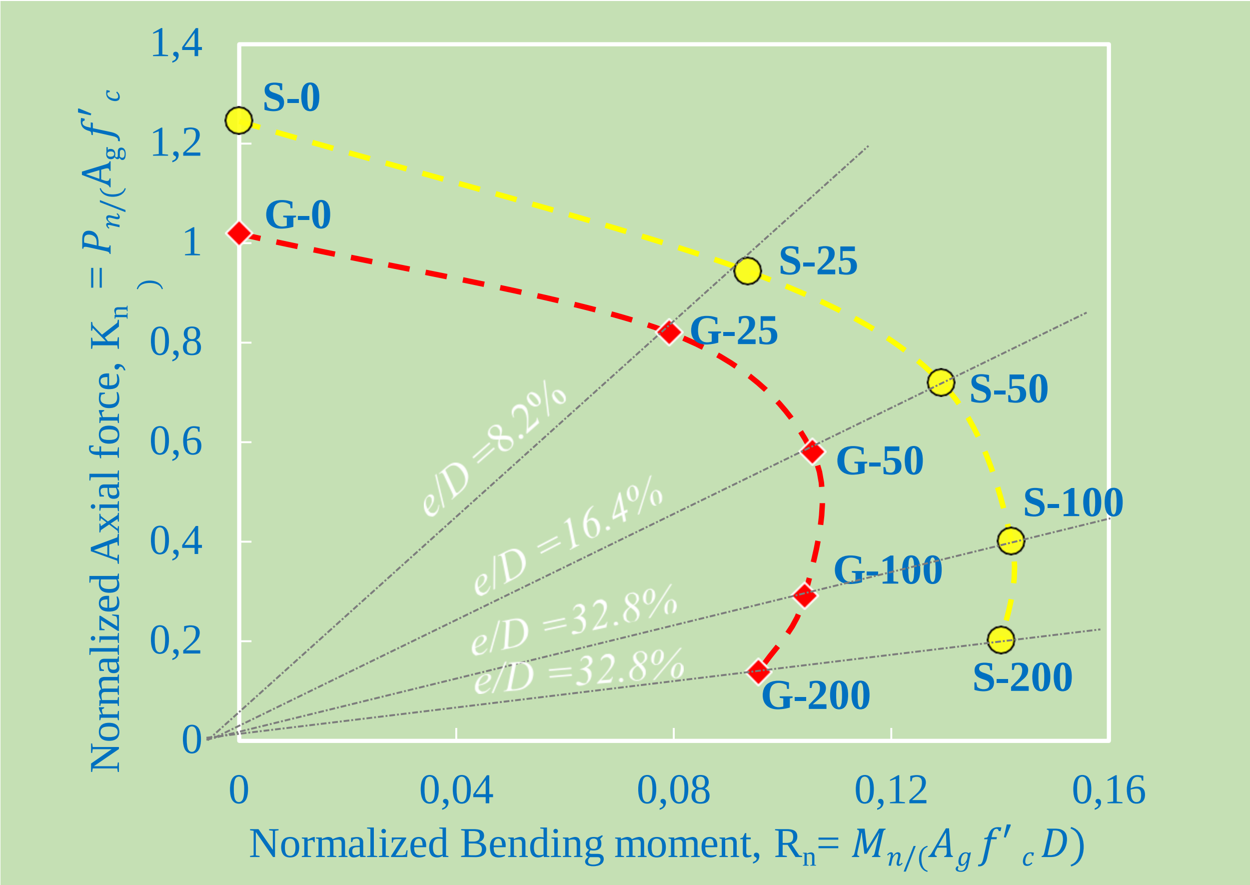
G bars were intact & wide cracks got closed



C bars were intact & wide cracks got closed

Session 3c: Strength of FRP-RC columns

Eccentric loading (interaction diagrams) **GFRP vs. Steel**



Normalised interaction diagram

Dia.=305 mm
f'_c= 35 MPa
f_{ftu}= 1190 MPa
E_{tu}= 54.9 GPa

Dia.=305 mm
f'_c = 35 MPa
f_{ftu}= 1190 MPa
E_{tu}= 54.9 GPa

Session 3c: Design Philosophy *(CSA S806)*

Members under Flexure and Axial Load (Clause 8.4.3)

Longitudinal FRP reinforcement may be used in members subjected to combined flexure and axial load. The FRP reinforcement in compression members of such members shall be deemed to have zero compressive strength and stiffness as per Clause 7.1.6.4.

Session 3c: Design Philosophy ***(CSA S806)***

Longitudinal Reinforcement

- **Limits for longitudinal reinforcement ratio is the same as those for steel reinforcement; Min: 1% and Max: 8% (8.4.3.7 to 8.4.3.9).**
- **Slender columns are not permitted when FRP longitudinal reinforcement is used (8.4.3.3).**
- **Flexural resistance of columns shall be computed in accordance with Clause 8.4.1 (like beams) with the effects of axial forces included in flexural analysis.**

Session 3c: Design Philosophy ***(CSA S806)***

Maximum Factored Axial Load Resistance

The maximum factored axial load resistance, $P_{r,max}$ shall be:

- **For spirally reinforced columns:**

  $P_{r,max} = 0.85\, P_{ro}$

- **For tied columns:**

  $P_{r,max} = 0.80\, P_{ro}$

$$P_{ro} = \alpha_1 \phi_c f_c'(A_g - A_{st}) + \phi_s f_y A_{st}$$ **For steel Re-bars**

$$P_{ro} = \alpha_1 \phi_c f_c'(A_g - A_f)$$ **For FRP bars**

Session 3c: Design Philosophy ***(CSA S806)***

FRP Spirals

FRP spirals shall conform to the following:

- **Minimum diameter of 6 mm;**
- **Pitch shall not exceed 1/6 of the core diameter;**
- **Clear distance between successive turns shall not exceed 75 mm nor be less than 25 mm.**

$$\rho_{Fs} = \frac{f_c'}{f_{Fh}}\left(\frac{A_g}{A_c} - 1\right)\left(\frac{P}{P_o}\right)$$

$$\frac{P}{P_o} \geq 0.2 \qquad \frac{A_g}{A_c} \geq 0.3 \qquad f_{Fh} = \phi_f f_{Fu} \text{ or } 0.006 E_F$$

Session 3c: Design Philosophy *(CSA S806)*

FRP Ties

FRP ties shall consist of one or more of the following:

- **Pre-shaped rectilinear ties with corners having an angle of not more than 135°;**
- **Prefabricated rectilinear grids;**
- **Crossties with hooks where the hooks engage peripheral longitudinal bars;**
- **Pre-shaped circular ties or rings;**
- **Others that perform as least as good as above.**

Session 3c: Design Philosophy ***(CSA S806)***

FRP Ties

The spacing of FRP ties shall not exceed the least of the following dimensions:

- **16 times the diameter of the smallest longitudinal bars or the smallest bar in a bundle;**
- **48 times the minimum cross-sectional dimension (or diameter) of FRP tie or grid;**
- **the least dimension of the compression member; or**
- **300 mm in compression members containing bundled bars.**

Session 3c: Design Philosophy ***(CSA S806)***

Assumptions

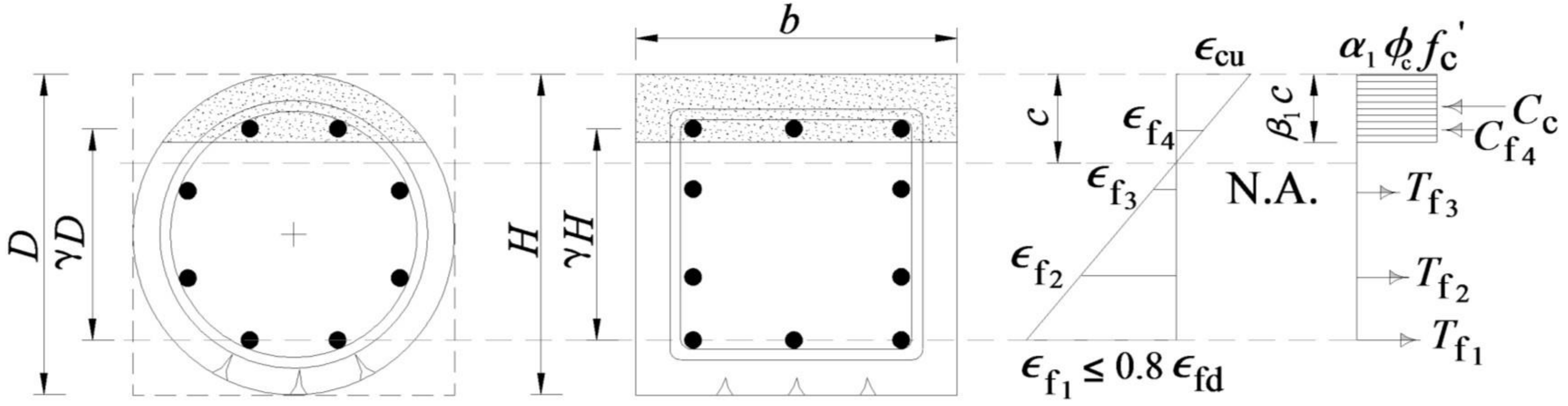
- Maximum strain at the concrete compression fibre is 3500 x 10-6;
- Tensile strength of concrete is ignored for cracked sections;
- The strain in concrete and FRP at any level is proportional to the distance from the neutral axis;
- The stress-strain relationship for FRP is linear up to failure;
- Perfect bond exists between the concrete and the FRP reinforcement;
- The maximum design tensile strain (ε_{fd}) for GFRP bars is the minimum of 0.01 and f_{fu}/E_f.

Session 3c: Design Philosophy *(CSA S806)*

- **Modes of failure**
  - ***Transition***, concrete crushing while GFRP bars have a strain level **greater than 0.8 ε_{fd}** and **smaller than ε_{fd}**;
  - ***Compression controlled***, concrete crushing while GFRP bars have a strain level **smaller than ε_{fd}**;
  - ***Tension controlled***, concrete crushing while GFRP bars have a strain level **equal to ε_{fd}**.

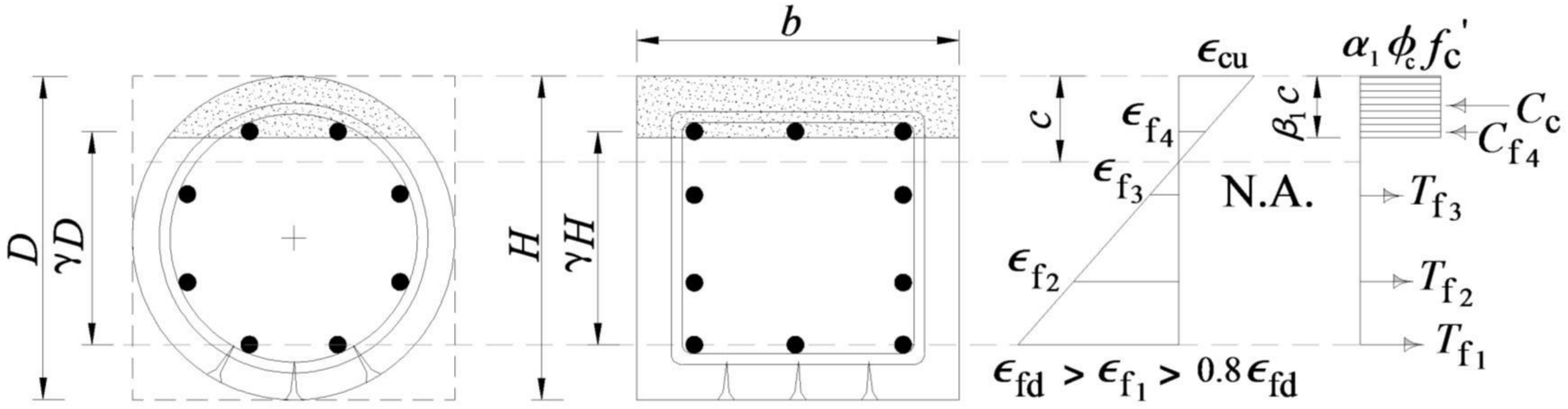
Session 3c: Design Philosophy ***(CSA S806)***

- **Compression controlled**



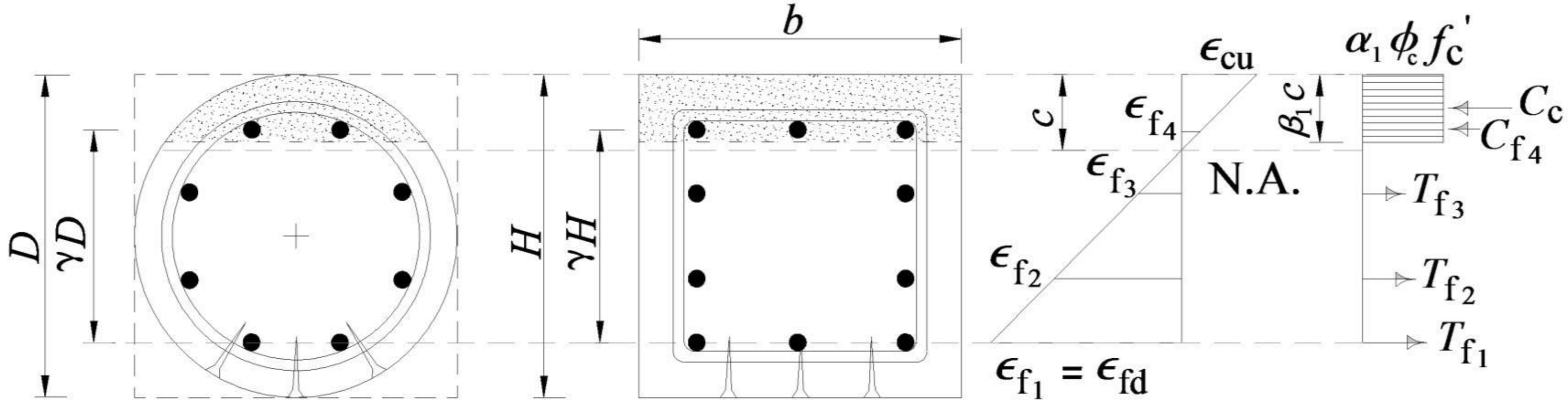
Session 3c: Design Philosophy ***(CSA S806)***

- **Transition**



Session 3c: Design Philosophy ***(CSA S806)***

- **Tension controlled**



Session 3c: Design Philosophy *(CSA S806)*

- **Developing interaction diagram**

  1. **Calculate ERSB (α_1 and β_1):**

$$\alpha_1 = 0.85 - 0.0015\, f_c' \geq 0.67$$

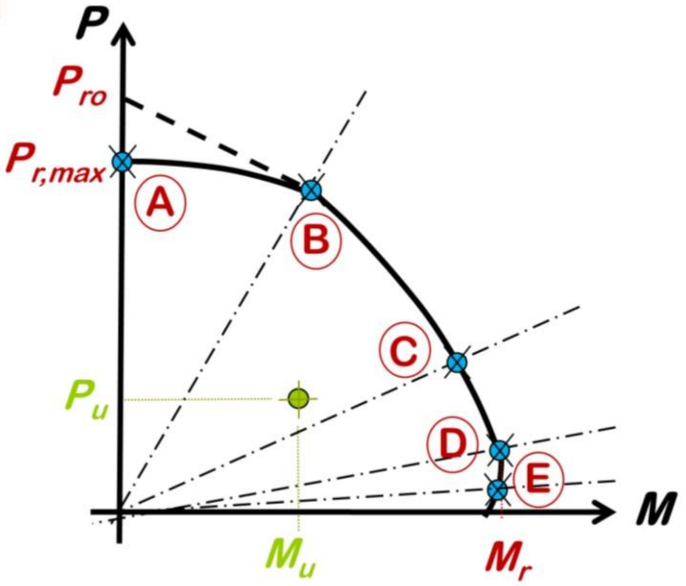
$$\beta_1 = 0.97 - 0.0025\, f_c' \geq 0.67$$

  2. **Calculate $P_{r,max}$ at point A:**

$$P_{ro} = \alpha_1 \phi_c f_c' (A_g - A_f)$$

$$P_{r,max} = 0.85\, P_{ro}$$ **(for spirally columns)**

$$P_{r,max} = 0.80\, P_{ro}$$ **(for tied columns)**



Session 3c: Design Philosophy *(CSA S806)*

Developing interaction diagram

3. Calculate P_r and M_r at point B:

- Take c=d
- Calculate strains in Tensile FRP bars

$$\varepsilon_{f1} = 0$$

- Calculate Forces C_c and $\sum T_f$

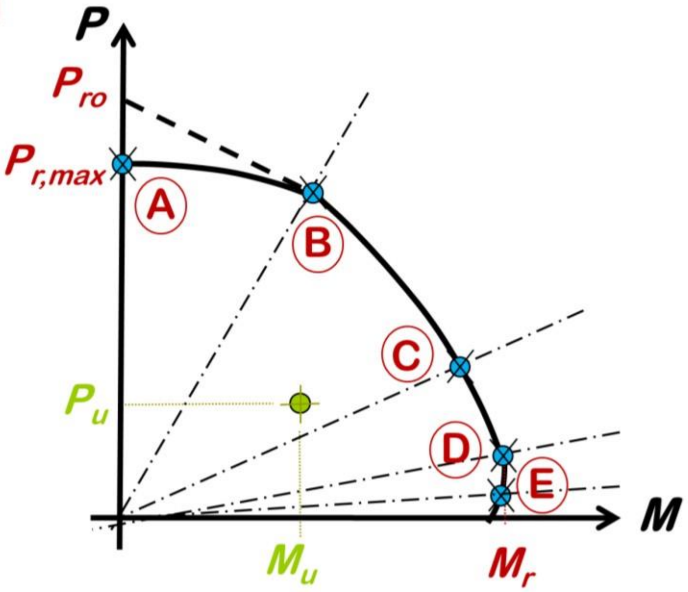
$$C_c = \alpha_1 \varphi_c f_c' \beta_1 c\, b$$

$$T_f = A_f\, \varphi_f\, E_f \sum \varepsilon_f$$

- Apply Equilibrium

$$P_r = C_c - T_f$$

$$M_r = C_c\left(\frac{h}{2} - \frac{\beta_1 c}{2}\right) \pm \sum T_f(y_f)$$



Session 3c: Design Philosophy *(CSA S806)*

Developing interaction diagram

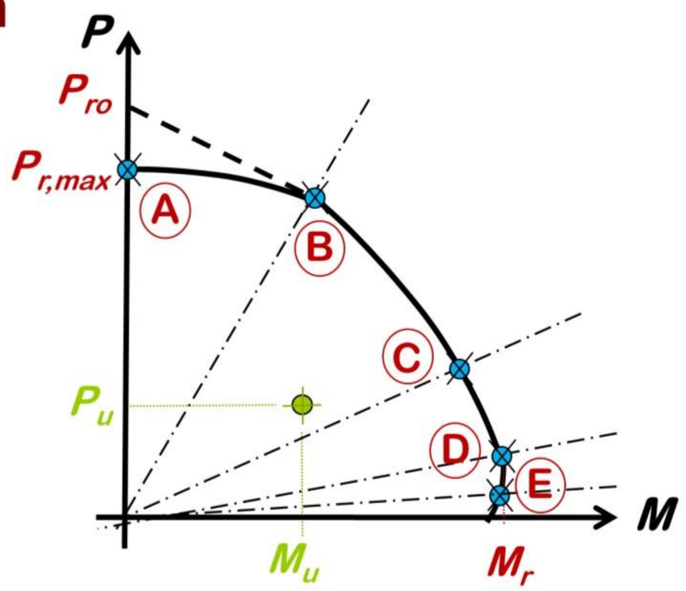
4. Calculate P_r and M_r at point C:

- **Take** $\varepsilon_{f1} = (0:0.8)\,\varepsilon_{fd} \approx 0.4\varepsilon_{fd}$
- **Calculate c**

$$\frac{c}{d} = \frac{0.0035}{0.0035 + \varepsilon_{f1}}$$

- **Calculate strains in all FRP rows**
- **Calculate Forces C_c and $\sum T_f$**
- **Apply Equilibrium**

$$P_r = C_c - T_f \qquad M_r = C_c\left(\frac{h}{2} - \frac{\beta_1 c}{2}\right) \pm \sum T_f(y_f)$$



Session 3c: Design Philosophy ***(CSA S806)***

Developing interaction diagram

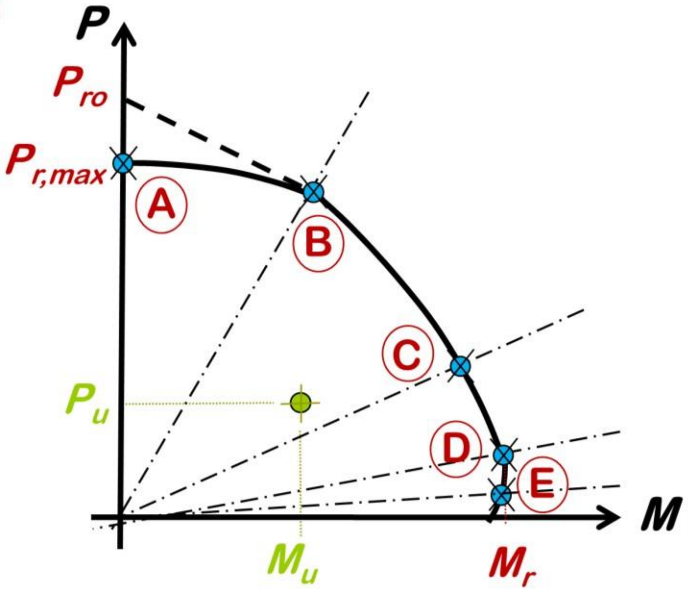
5. Calculate P_r and M_r at point D:

- **Take** $\varepsilon_{f1} = 0.8\,\varepsilon_{fd}$
- **Calculate c**

$$\frac{c}{d} = \frac{0.0035}{0.0035 + \varepsilon_{f1}}$$

- **Calculate strains in all FRP rows**
- **Calculate Forces C_c and $\sum T_f$**
- **Apply Equilibrium**

$$P_r = C_c - T_f \qquad M_r = C_c\left(\frac{h}{2} - \frac{\beta_1 c}{2}\right) \pm \sum T_f(y_f)$$



Session 3c: Design Philosophy *(CSA S806)*

- **Developing interaction diagram**

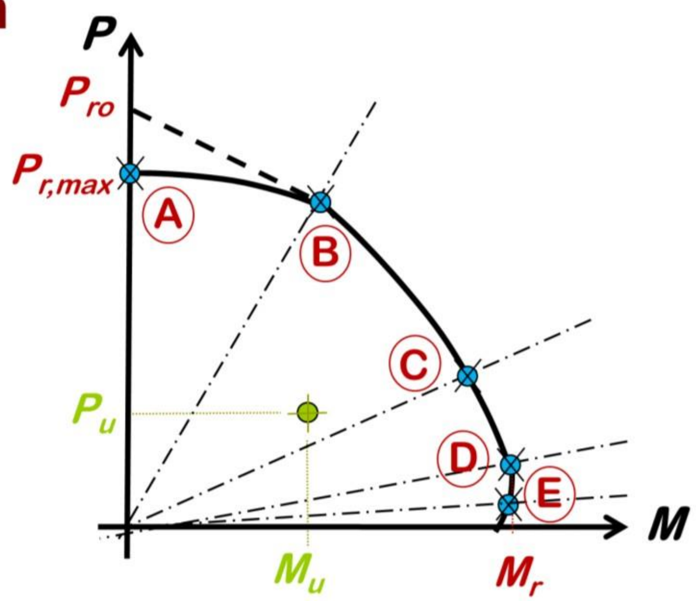
6. Calculate P_r and M_r at point E:

- **Take** $\varepsilon_{f1} = \varepsilon_{fd}$
- **Calculate c**

$$\frac{c}{d} = \frac{0.0035}{0.0035 + \varepsilon_{f1}}$$

- **Calculate strains in all FRP rows**
- **Calculate Forces C_c and $\sum T_f$**
- **Apply Equilibrium**

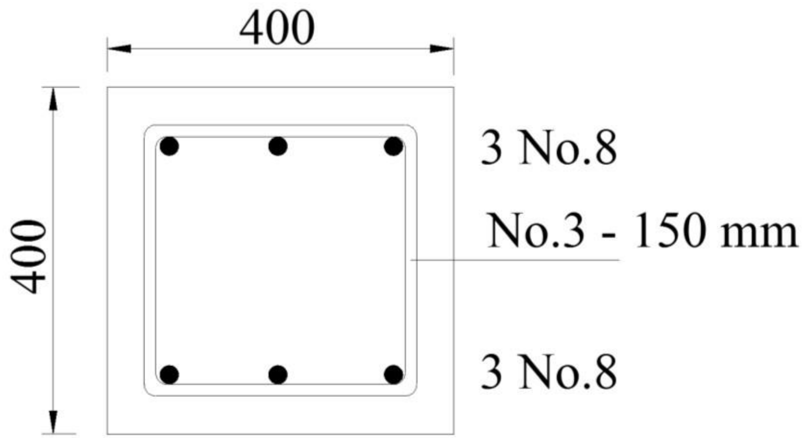
$$P_r = C_c - T_f \qquad M_r = C_c\left(\frac{h}{2} - \frac{\beta_1 c}{2}\right) \pm \sum T_f(y_f)$$



Session 3c: Design Examples

▫ Example 1

Develop the interaction strength diagram of a square concrete column with size and reinforcement as shown below. The concrete strength is 35 MPa. The ultimate tensile strength and Young's modulus are 1200 MPa and 50 GPa, respectively. The concrete clear cover is 25 mm.



Session 3c: Design Examples

- **Example 1**

1. **Calculate ERSB** (α_1 and β_1)**:**

$$\alpha_1 = 0.85 - 0.0015 \times (35) = 0.798$$

$$\beta_1 = 0.97 - 0.0025 \times (35) = 0.88$$

2. **Calculate $P_{r,max}$ at point A:**

$$P_{r,max} = 0.80 \times (0.798 \times 0.65 \times 35 \times (400^2 - 6 \times 510)) = 2278 \text{ kN}$$

Session 3c: Design Examples

Example 1

3. Calculate P_r and M_r at point B:

- **Take** $c = d = 400 - 25 - 10 - 25/2 = 352.5\,\text{mm}$
- **Calculate strains in Tensile FRP bars**

$$\varepsilon_{f1} = 0$$

- **Calculate C_c**

$$C_c = 0.798 \times 0.65 \times 35 \times 0.88 \times 352.5 \times 400 = 2253\,\text{kN}$$

- **Apply Equilibrium**

$$P_r = C_c = 2253\,\text{kN}$$

$$M_r = 2253\left(\frac{400}{2} - \frac{0.88 \times 352.5}{2}\right) = 101.14\,\text{kN.m}$$

Session 3c: Design Examples

Example 1

4. Calculate P_r and M_r at point C:

- **Take** $\varepsilon_{f1} = 0.4\varepsilon_{fd} = 0.4 \times 0.01 = 0.004$
- **Calculate *c*** $\dfrac{c}{352.5} = \dfrac{0.0035}{0.0035 + 0.004}$ ⇒ $c = 164.5\,\text{mm}$
- **Calculate C_c and T_f**

$$C_c = 0.798 \times 0.65 \times 35 \times 0.88 \times 164.5 \times 400 = 1051\,\text{kN}$$

$$T_f = 3 \times 510 \times 0.75 \times 50000 \times 0.004 = 229.5\,\text{kN}$$

- **Apply Equilibrium**

$$P_r = C_c - T_f = 821.5\,\text{kN}$$

$$M_r = 1051\left(\frac{400}{2} - \frac{0.88 \times 164.5}{2}\right) + 229.5\left(\frac{400}{2} - 47.5\right) = 169\,\text{kN.m}$$

Example 1

5. Calculate P_r and M_r at point D:

- **Take** $\varepsilon_{f1} = 0.8\varepsilon_{fd} = 0.8 \times 0.01 = 0.008$
- **Calculate c** $\frac{c}{352.5} = \frac{0.0035}{0.0035 + 0.008}$ ⇒ $c = 107\ \text{mm}$
- **Calculate C_c and T_f**

$$C_c = 0.798 \times 0.65 \times 35 \times 0.88 \times 107 \times 400 = 687\ \text{kN}$$

$$T_f = 3 \times 510 \times 0.75 \times 50000 \times 0.008 = 459\ \text{kN}$$

- **Apply Equilibrium**

$$P_r = C_c - T_f = 227\ \text{kN}$$

$$M_r = 687\left(\frac{400}{2} - \frac{0.88 \times 107}{2}\right) + 459\left(\frac{400}{2} - 47.5\right) = 175\ \text{kN.m}$$

Session 3c: Design Examples

Example 1

5. Calculate P_r and M_r at point D:

- **Take** $\varepsilon_{f1} = \varepsilon_{fd} = 0.01$
- **Calculate *c*** $\dfrac{c}{352.5} = \dfrac{0.0035}{0.0035 + 0.01}$ ⇒ $c = 91.3\,\text{mm}$
- **Calculate C_c and T_f**

$$C_c = 0.798 \times 0.65 \times 35 \times 0.88 \times 91.3 \times 400 = 585\,\text{kN}$$

$$T_f = 3 \times 510 \times 0.75 \times 50000 \times 0.01 = 575\,\text{kN}$$

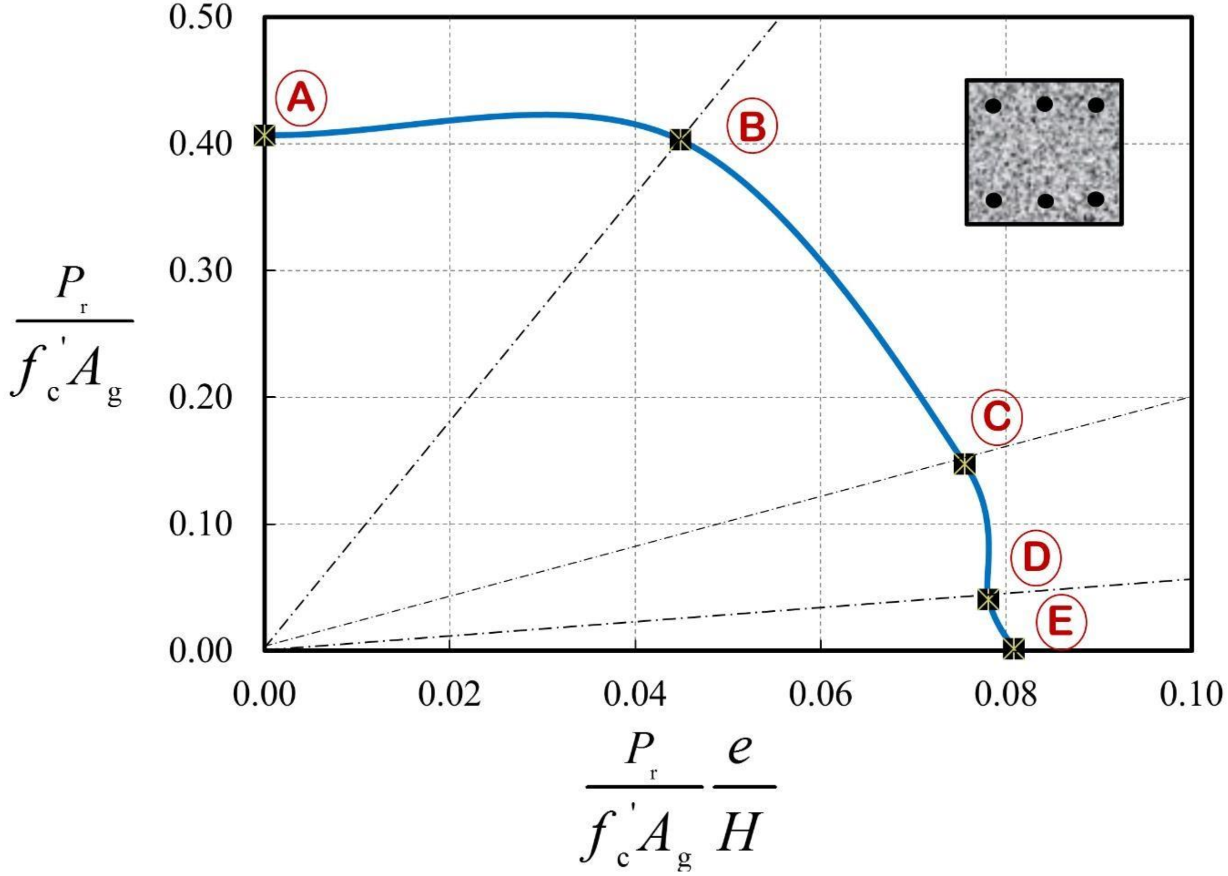
- **Apply Equilibrium**

$$P_r = C_c - T_f = 10\,\text{kN}$$

$$M_r = 585\left(\frac{400}{2} - \frac{0.88 \times 91.3}{2}\right) + 575\left(\frac{400}{2} - 47.5\right) = 181\,\text{kN.m}$$

Session 3c: Design Examples

- **Example 1**



Session 3c: Design Examples

- **Example 2**

Resolve Example 1 considering the compression contribution of GFRP bars. Show a comparison of the results in terms of interaction diagrams. Compare these diagrams with the interaction diagram of similar section reinforced with steel bars (F_y =460 MPa)

Session 3c: Design Examples

Example 2

Similar steps as Example 1 are followed while considering the compression contribution of GFRP bars as follows:

- **In step 2, $P_{r,max}$ at point A:**

$$P_{ro} = \alpha_1 \phi_c f_c^{'} (A_g - A_f) + 0.002\, \phi_f E_f A_f$$

- **In step 3-6, the forces are:**

$$C_c = \alpha_1 \varphi_c f_c^{'} \beta_1 c\, b$$

$$C_f = A_f\, \varphi_f\, E_f \sum \varepsilon_f \quad \text{(for FRP bars in compression)}$$

$$T_f = A_f\, \varphi_f\, E_f \sum \varepsilon_f \quad \text{(for FRP bars in tension)}$$

Session 3c: Design Examples

◻ Example 2

Similar steps as Example 1 are followed while considering the compression contribution of GFRP bars as follows:

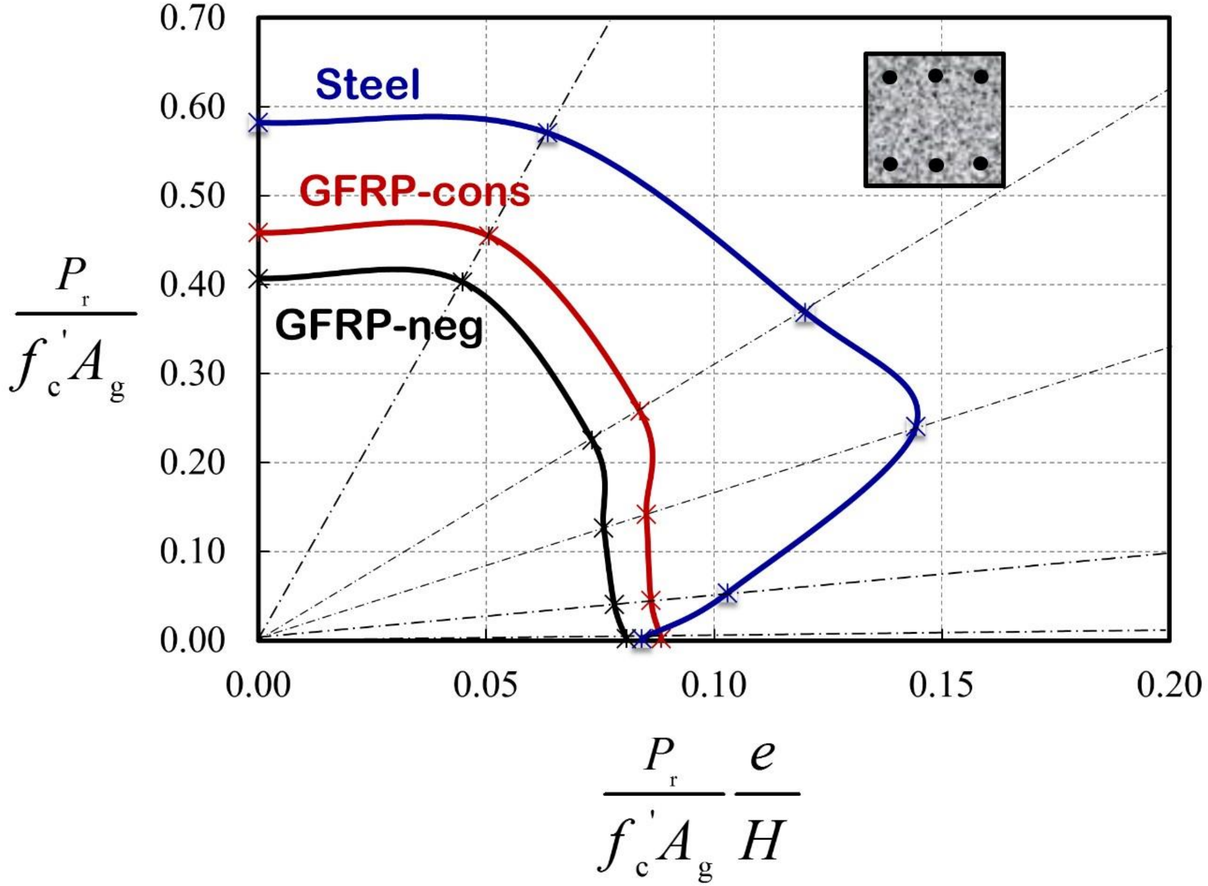
- **In step 3-6, apply equilibrium as:**

$$P_r = C_c + C_f - T_f$$

$$M_r = C_c\left(\frac{h}{2} - \frac{\beta_1 c}{2}\right) \pm \sum C_f(y_f) \pm \sum T_f(y_f)$$

Session 3c: Design Examples

- **Example 2**



End of Session

Questions

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