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.

Course Description

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 Complete 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-004-00A 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.

FRP-RC Design - Part 3, (50 min.)
This session continues with Basalt FRP rebar from Part 2, covering shear and axial design of columns at the strength limit states for:
- Flexural Behavior and Resistance (Session 3a);
- Shear Behavior and Resistance of beams and slabs (Session 3b);
- Axial Behavior of columns & Combined axial and flexure resistance (Session 3c).

FRP-RC Design - Part 4 (Not included at FTS - for future training):
This session continues with FRP rebar from Part 3, 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
Flexural behavior:
- Balance failure
- Tension failure
- Compressive failure
- Design examples

Assumptions:
- Maximum strain at the concrete compression fiber is 0.0035 (CSA) or 0.003 for AASHTO/ACI;
- 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.

Modes of Failure:
- Balanced failure - simultaneous rupture of FRP and crushing of concrete;
- Compression failure - concrete crushing while FRP remains in the elastic range with a strain level smaller than the ultimate strain;
- Tension failure - rupture of FRP before crushing of concrete.

Ultimate Flexural Strength:
\[ M_u = \phi M_n \]
\[ M_n = M_{DL} + 1.6 M_{LL} \text{ (CSA)} \]
\[ M_u = 1.25 M_{DC} + 1.75 M_{LL} \text{ (AASHTO)} \]

As an examples:
- Under-reinforced sections may fail suddenly
  - FRP bars do not yield;
- There will be warning in the form of cracking and large deflection;
- Over-reinforced may be desirable to avoid sudden collapse of members;
- Over or under-reinforced sections are acceptable provided that the strength and serviceability criteria are satisfied;
- Flexural behavior is not ductile; therefore, safety factors are larger than in steel-RC.
Session 3a: Determine Flexural Failure Mode

- Calculate the reinforcement ratio for balanced strain condition:
  \[ \beta_a = \frac{\alpha_a \beta_f \phi_f (\sigma_c + \phi_f \epsilon_{fr})}{E_f} \]

- Calculate reinforcement ratio for FRP-reinforced beam:
  \[ \beta_{fr} \leq \beta_f \phi_f \]

- Calculate the depth to neutral axis \( c_0 \) for the balanced strain condition:
  \[ c_0 = \frac{\beta_f \phi_f}{(\sigma_c + \phi_f \epsilon_{fr})/E_f} \]

- Tension Failure: \( c < c_0 \)

- Compression Failure: \( c > c_0 \)

Basic Flexural Theory – Tension Failure

- Assume \( c_0 \), calculate \( c_0 \) and \( C \). If \( C > c_0 \), revise \( c \) until \( C = c_0 \).
- For \( a, \beta \), you may use tables or detailed formulas.

Session 3a: Flexural Behavior

**Stress Block Factors for \( \epsilon_c \) (CSA)**

- For a constant width section, we may assume that the stress-strain curve of the concrete is parabolic and the following equations can be used (more convenient than tables for spreadsheet calculations).
- For strengths higher than 60 MPa, consult tables in Collins and Mitchell (1997).

\[ \begin{align*}
\beta &= \frac{4 - (\epsilon_c / \epsilon_{c'})}{6 - 2(\epsilon_c / \epsilon_{c'})} \\
\alpha &= \frac{1}{\beta} \left( 1 - \frac{1}{3} \left( \frac{\epsilon_c}{\epsilon_{c'}} \right)^2 \right)
\end{align*} \]

Where: concrete compressive strain is \( \epsilon_c \)

The peak stress at peak strain \( \epsilon_{c'} = 1.71f_c/E_c \)

Basic Flexural Theory Applied to FRP-RC Beams

- Plane section remains plane with linear strain variation

**Flexural Analysis**

Session 3a: Flexural Behavior

**Stress Block Factors for \( \epsilon_c \) (AASHTO-GS2)**

- The natural relationship between concrete stress and strain may be considered satisfied by an equivalent rectangular concrete compressive stress block of 0.85 \( f_c \), over a zone bounded by the edges of the cross section and a straight line located parallel to the neutral axis at the distance \( a = 0.65 \) from the extreme compression fiber.
- The distance \( c \) shall be measured perpendicular to the neutral axis.
- The factor \( \beta_t \) shall be taken as specified in Article 2.3.

**Article 2.3:** \( \beta_t = 4 \) for concrete compressive strengths not exceeding 4 ksi. For concrete strengths exceeding 4 ksi, reduced at a rate of 0.06 for each 1 ksi of strength in excess of 4 ksi, except that \( \beta_t \) shall not be taken to be less than 0.65.
### Session 3a: Flexural Analysis

**Tension Failure**

To summarize:

1. Assume \( c \)
2. Determine \( \alpha \) and \( \beta \)
3. Check if equilibrium is satisfied
4. If NO, calculate new neutral axis depth, \( c \)
5. From tables/charts - CSA
6. From equation - AASHTO

**Compression Failure**

Assume \( c \), calculate \( \varepsilon_{FRP} \), \( f_{FRP} \), and \( C \), consume \( c \) until \( C = T \).

- \( \alpha_1 = 0.85 - 0.0015f'_c \)
- \( \beta_1 = 0.97 - 0.0025f'_c \)

**Basic Flexural Theory – Compression Failure**

- Assume \( c \), calculate \( \varepsilon_{FRP} \) and \( C, T \), revise \( c \) until \( C = T \).
- Use \( \alpha_1 = 0.85 - 0.0015f'_c \), \( \beta_1 = 0.97 - 0.0025f'_c \)

**Session 3a: Flexural Behaviour**

**FRP-Reinforced Concrete Beams & One-Way Slabs under Flexure Load**

**Test Set-up**

4-point bending over a clear span of 2.5 m.

**Load-Deflection of FRP-Reinforced Concrete Beams & One-Way Slabs under Flexure Load**

Effect of GFRP reinforcement ratio

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### Table: Flexural Failure

<table>
<thead>
<tr>
<th>Behavior</th>
<th>Tension</th>
<th>Balanced</th>
<th>Compression</th>
</tr>
</thead>
<tbody>
<tr>
<td>Desirability</td>
<td>FRP Rupture</td>
<td>FRP Rupture and Concrete crushing</td>
<td>Concrete crushing</td>
</tr>
<tr>
<td>Rein. Ratio</td>
<td>( \rho_{FRP} &gt; \rho_{bal} )</td>
<td>( \rho_{FRP} = \rho_{bal} )</td>
<td>( \rho_{FRP} &lt; \rho_{bal} )</td>
</tr>
<tr>
<td>Strains</td>
<td>( \varepsilon_{FRP} &lt; \varepsilon_{cu} )</td>
<td>( \varepsilon_{FRP} = \varepsilon_{cu} )</td>
<td>( \varepsilon_{FRP} &gt; \varepsilon_{cu} )</td>
</tr>
</tbody>
</table>

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### Graph: Load-Deflection of FRP-Reinforced Concrete Beams & One-Way Slabs under Flexure Load

Effect of GFRP reinforcement ratio
Flexural Analysis - Additional Considerations

**Flexure Design (CSA S806)**

- **Assumptions**
  - Minimum Flexural Reinforcement Requirement
  
  \[ M_f \geq 1.5M_{cr} \]

- For Slabs:
  - \( A_{cr,0} = 0.0025A_0 \)
  - Spacing of \( A_{cr,0} \leq 300\text{mm} \) or 3 times slab thickness

- **Strain Compatibility Analysis:**
  - \( \varepsilon_s - \frac{A_{cr,0}}{A_s} \leq 0.0035 \) (CSA S806)
  - \( \varepsilon_s - \frac{A_{cr,0}}{A_s} \leq 0.0015 \) (AASHTO-GS2)

- **Common to combine layers to one lumped layer**

- **Strain in outer layer is critical**

Flexural Analysis - Additional Considerations

**Flexure Design (CSA S806)**

- **Assumptions**
  - Compressive strength of FRP shall be ignored when calculating the resistance of a member
  - Strain compatibility method shall be used to calculate the factored resistance of a member
  - Flexural members shall be designed such that failure at ultimate is initiated by the failure of concrete at the extreme compression fiber. This condition is satisfied by the critical requirement shown below:

- **Lumping of reinforcement not allowed, strain compatibility is used to design on the basis of tensile failure of the outermost FRP layer**
Flexural Analysis - Additional Considerations

**Flexure Design (CSA S806)**

Resisting Moment:

\[ M_r = C f_{,cd} \left( \frac{1}{2} + \frac{d - k_d}{2d} \right) \geq M_f \]

---

**Session 3a: Flexural Analysis**

**Analysis at Service Limit State**

- Serviceability considerations (stresses, crack widths, and deflections) may govern the design of FRP-reinforced concrete members

- Analysis at Service Limit State can be performed assuming linear-elastic behavior (straight-line theory)

- FRP materials are linear-elastic to failure

- Concrete stress-strain relationship is linear for compression stresses less than 60% of \( f'_c \)

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**Session 3b: Shear Behaviour**

**Session 4: (1:30 pm - 2:30 pm)**

Shear behaviour

- Design philosophy
- Shear strength
- Design examples

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**Flexural Design Examples of Concrete Beam Reinforced with GFRP Bars According to CSA S806-12**

*(See Example #1 & #2 – Attachment 3a)*
Shear Strength of FRP Reinforced Members

- FRP has a relatively low modulus of elasticity
- FRP has a high tensile strength and no yielding point
- Tensile strength of a bent portion of an FRP bar is significantly lower than a straight portion
- FRP has low dowel resistance

Shear Behaviour of FRP RC Beams

Nominal shear strength $V_n = V_{cf} + V_{sf} + V_p$

where

- $V_n$ = nominal shear strength
- $V_{cf}$ = concrete contribution to shear strength
- $V_{sf}$ = shear reinforcement contribution to shear strength
- $V_p$ = prestressing resisting component

Size Effect
Session 3b: Shear Behaviour

Beam B1-1
Beam B1-2
Diagonal Tension Failure Mode

Shear Behaviour of Concrete Bridge Girders Reinforced with FRP Stirrups (T-Section) – MTQ Research Project (2007-2009)

Shear Failure of SC-9.5-2 (CFRP @ d/2)

Reinforcing Cage and Concrete Casting

Curing and transportation

Session 3b: Shear Behaviour

Shear Behaviour of FRP RC Beams

GFRP-Cages

Session 3b: Shear Behaviour

Shear Behaviour of FRP RC Beams; GFRP & CFRP Stirrups

CFRP Stirrups
Shear Failure of SC-9.5-3 (CFRP @ d/3)

Shear Behaviour of Concrete Bridge Girders Reinforced with FRP Stirrups (T-Section) – MTQ Research Project (2007-2009)

Shear Failure of SS-9.5-2 (Steel @ d/2)

Shear Behaviour of Concrete Bridge Girders Reinforced with FRP Stirrups (T-Section) – MTQ Research Project (2007-2009)

Session 3b: Shear Design (CSA-S806)

Shear design is similar to the simplified method of CSA A23.3-14, i.e.

\[ V_r \geq V_c + V_{s,F} \]

- \( V_r \) accounts for
  - Shear resistance of uncracked concrete
  - Aggregate interlock
  - Dowel action of the longitudinal reinforcement
  - Arching action

\( V_{s,F} = \) Shear carried by the FRP shear reinforcement

Session 3b: Shear Design (CSA-S806)

- For FRP Stirrups
  \[ V_r = V_c + V_{s,F} \]

- For Steel Stirrups
  \[ V_r = V_c + V_{s,F} \]

- However, \( V_r \) shall not exceed
  \[ V_{r,\text{max}} = 0.22 f_c b_d + 0.5 V_c + \frac{M_r V_c}{M} \]

Session 3b: Shear Design (CSA-S806)

If the member effective depth does not exceed 300 mm and there is no axial load:

\[ V_c = 0.05 f_c b_d \]

where

\[ k_c = \sqrt{\frac{M}{V_c}} \leq 1 \]

\[ k_c = 1 + (E_F \rho_F)^{1/3} \]

\[ V_r \geq 0.22 f_c b_d \]

\[ V_r \geq 0.11 f_c b_d \]

\[ f_c \leq 60 \, \text{MPa} \]

or if the member effective depth exceeds 300 mm and transverse shear reinforcements are equal or greater to \( A_{\text{min}} \) (Clause 8.4.4.8)

\[ V_r \geq 0.11 f_c b_d \]
Session 3b: Shear Design (CSA-S806)

To account for size effect, for sections with an effective depth greater than 300mm and with less transverse reinforcement than $A_{v,min}$:

$$V' = 0.05 \lambda_f k_h k_v \left( f' \right)^{1/3} b_d d_c$$

where

$$k_v = \frac{750}{450 + d_c} \leq 1$$

---

Session 3b: Shear Design (CSA-S806)

- Shear Carried by Transverse Reinforcement
  - For Members with FRP Transverse Reinforcement
    $$V_{frp} = \frac{0.4 f_{c} A_{v} f_{u}}{V_{pl} \cot \theta}$$
  - For Members with Steel Transverse Reinforcement
    $$V_{st} = \frac{0.4 f_{c} A_{v} f_{u}}{V_{pl} \cot \theta}$$
  
  $f_{u}$ shall not be greater than $0.005E_f$

---

Session 3b: Shear Design (CSA-S806)

- Minimum Shear Reinforcement
  - A minimum area of shear reinforcement shall be provided in all regions of flexural members where
    $$V_{f} > 0.5V_{c} + \Phi V_{p} \text{ or } T_{f} > 0.5T_{c}$$

This requirement may be waived for:
- Slabs and footings
- Concrete joist construction
- Beams with total depth not greater than 250 mm
- Beams cast integrally with slabs where overall depth is not greater than one-half the width of the web or 600 mm.

---

Session 3b: Shear Design (CSA-S806)

- Minimum Shear Reinforcement
  - The minimum area of FRP shear reinforcement shall be such that
    $$A_{v} = 0.07 \frac{f_{c}}{f_{u}}$$

  $f_{u}$ shall not be greater than 1200MPa or $0.005E_f$.

---

Session 3b: Shear Design (CSA-S806)

- Shear resistance is calculated as:
  $$V_s = V_{c} + V_{sf} \leq 0.25 \phi f' c b_d d_{k} \alpha_{kng}$$

Where

$$V_{c} = 2.5 \phi f' c b_d d_{k} \alpha_{kng}$$

$$V_{sf} = \phi f_{u} A_{v} f_{u} d_{k} \alpha_{kng} \cot \theta$$

$$\alpha_{kng} = 0.72 h \text{ or } 0.9d$$

---

Session 3b: Shear Design (CSA-S806)

**Simplified Method**

For sections with at least minimum shear reinforcement

$$\theta = 42^\circ \text{ and } \beta = 0.18$$

For sections without minimum shear reinforcement

$$\theta = 42^\circ \text{ and } \beta = \frac{230}{1000 + d_{kng}}$$
Session 3b: Shear Design *(CSA-S806)*

**General Method**

\[
\beta = \frac{0.4}{(1 + 1500 \varepsilon_y) (1000 + S_{sw})}
\]

\[
\theta = (29 + 7000 \varepsilon_y)(0.88 + S_{sw} / 2500)
\]

\[
S_{sw} = 300\text{mm}
\]

\[
\varepsilon_y = \left( \frac{M_f d_{long}}{2E_f A_f} \right) + V_f
\]

The stress in FRP stirrup, \( f_{sv} \), is calculated as:

\[
f_{sv} = 0.004E_{sv} \leq f_{bend}
\]

\[
f_{bend} = \left(0.3 + 0.05 \frac{f_{sv}}{d_b}\right)f_{uv} \leq f_{uv}
\]

Session 3b: Shear Design *(CSA-S806)*

- Minimum Shear Reinforcement

\[
A_{sv, min} = 0.06 \sqrt{f_{sv}} \frac{b_v s}{f_{sv}}
\]

\[ s \leq 0.75 d_v \text{ or } 600\text{mm} \quad \text{if} \quad V_f < 0.1A'f_v b_v d_{long}
\]

\[ s \leq 0.33 d_v \text{ or } 300\text{mm} \quad \text{if} \quad V_f > 0.1A'f_v b_v d_{long}
\]

Shear Design of Examples of Concrete Beam Reinforced with GFRP Bars According to *CSA S806-12*

(See Example #3 & #4 – Attachment 3b)

Session 3c: Compression Behavior & Column Design

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

Role of reinforcement in columns?

1. Longitudinal rebars
   - Compression, flexure, ductility.

2. Transverse ties/spirals
   - Shear, confinement.
Lateral confining pressure

Effect of confinement

Principle of internal confinement

Interaction Diagram
**Session 3c: Column Design**

**Eccentric loading (interaction diagrams)**

- **Effect of confinement**
  - Low confinement
  - Moderate confinement
  - High confinement

**FRP Reinforcements**
- Carbon FRP Spirals
- Glass FRP Spirals
- Carbon & Glass FRP Circular Ties
- Carbon & Glass FRP Straight Bars

**Square FRP-RC Columns**

**Session 3c: Strength of FRP-RC columns**

Research projects at University of Sherbrooke

**Axial Loading Results:** Effect of Type of Reinforcement

- Load (kN)
- Axial Strain (με)
- Concrete Crushing and Rupture of FRP Spirals
- Concrete Buckling of Long-Reinf
- Yielding of Long-Reinf

**Materials**
- Plain
- Steel
- GFRP
**Session 3c: Strength of FRP-RC columns**

**Axial Loading Results:** Effect of Spiral Spacing

- Load (kN) vs. Axial Strain (με)
- Load-Deflection diagram

**Session 3c: Strength of FRP-RC columns**

**Axial Loading Results:** Effect of Longitudinal Reinforcement Ratio

- Load (kN) vs. Axial Strain (με)

**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**

- GFRP vs. Steel
- Load-Deflection diagram

**Session 3c: Strength of FRP-RC columns**

**Eccentric loading (failure modes)**

- Steel bars yielded & wide cracks remained
- G bars were intact & wide cracks got closed
- C bars were intact & wide cracks got closed
**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.

**Maximum Factored Axial Load Resistance**

The maximum factored axial load resistance, \( P_{\text{max}} \), shall be:
- For spirally reinforced columns: \( P_{\text{max}} = 0.85 P_n \)
- For tied columns: \( P_{\text{max}} = 0.90 P_n \)

\[ P_n = \sigma_s f_c (A_c - A_t) + \phi f_t A_t \] For steel Re-bars

\[ P_n = \sigma_s f_c (A_c - A_t) \] For FRP bars

**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 35 mm.

\[ \rho_s = \frac{f_t}{f_c} \] \( \frac{2.82}{A_t} \geq \frac{d}{A_c} \geq 0.3 \) \( f_t = \phi f_c \) or 0.096\( f_c \)

**FRP Ties**
FRP ties shall consist of one or more of the following:
- Pre-shaped rectangular ties with corners having an angle of not more than 135°;
- Pretabulated rectangular grids;
- Crossover 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 level of the following dimensions:
    - 14 times the diameter of the smallest longitudinal bar or the smallest bar in a bundle;
    - All times the minimum cross-sectional dimension (or diameter) of FRP tie or grid;
    - The least dimension of the compression member; or
    - 306 mm in compression members containing bundled bars.

**Assumptions**
- Maximum strain at the concrete compression fibre is $3500 \times 10^{-6}$;
- 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 ($\varepsilon_{fd}$) 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 $\varepsilon_{sp}$ and smaller than $\varepsilon_{sa}$;
- **Compression controlled**, concrete crushing while GFRP bars have a strain level smaller than $\varepsilon_{sp}$;
- **Tension controlled**, concrete crushing while GFRP bars have a strain level equal to $\varepsilon_{sp}$.

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 ERS (αi and βi):
     \[ α_i = 0.85 - 0.0015 f_y / 0.67 \]
     \[ β_i = 0.87 + 0.0025 f_y / 0.67 \]
  2. Calculate \( P_{min} \) at point A:
     \[ P_{min} = α_i β f_y (A_y - A_c) \]
     \[ P_{min} = 0.85 P_{min} \text{ (for spandrel columns)} \]
     \[ P_{min} = 0.80 P_{min} \text{ (for lintel columns)} \]

Session 3c: Design Philosophy (CSA S806)

- Developing interaction diagram
  3. Calculate \( P_i \) and \( M_i \) at point B:
    - Take
    - Calculate strains in Tensile FRP bars
      \[ ε_{frp} = 0 \]
    - Calculate forces \( C_i \) and \( \Sigma f_i \)
      \[ C_i = α_i β f_y \]
      \[ \Sigma f_i = A_i \phi_f E_i ε_{frp} \]
    - Apply Equilibrium
      \[ P_i = C_i - \Sigma f_i \]
      \[ M_i = C_i \left( \frac{b}{2} \right) - \frac{B E_i}{2} \sum f_i(x_i) \]

Design of Examples of Concrete Column Reinforced with GFRP Bars According to CSA S806-12

(See Example #5 & #6 – Attachment 3c)
Questions

Co-presenters:
- Raphael Kampmann PhD
  FAMU-FSU College of Engineering
  Tallahassee, FL.
  kampmann@eng.famu.fsu.edu

- Marco Rossini, PhD student
  University of Miami
  Coral Gables, Fl.
  mxr1465@miami.edu

FDOT Design Contacts:
- Steven Nolan, P.E.
  FDOT State Structures Design Office
  Tallahassee, FL.
  Steven.Nolan@dot.state.fl.us

FDOT Materials and Manufacturing:
- Chase Knight, Ph.D, P.E.
  State Materials Office
  Gainesville, FL.
  Chase.Knight@dot.state.fl.us