FDOT TRANSPORTATION SYMPOSIUM 2019

FRP-RC Design - Part 3

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Design of concrete structures internally reinforced with FRP bars

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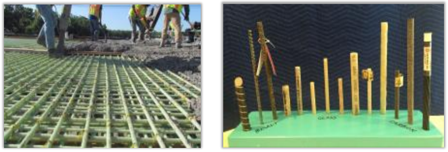
Course Description

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 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-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 Complete Course

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

Session 3a: Flexural Behavior

Flexural behavior:

- Balance failure
- Tension failure
- Compressive failure
- Design examples

Session 3a: Flexural Behavior

Failure Modes:

- 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: Flexural Behavior

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.

Session 3a: Flexural Behavior

Ultimate Flexural Strength:

- M_n = nominal capacity
- M_u = factored moment

$\phi M_n \geq M_u$

ϕ = strength reduction factor

As an examples:

$M_u = 1.2M_{DL} + 1.6M_{LL}$ *(CSA)*

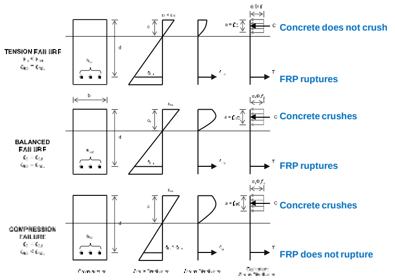
$M_u = 1.25M_{DC} + 1.75M_{LL}$ *(AASHTO)*

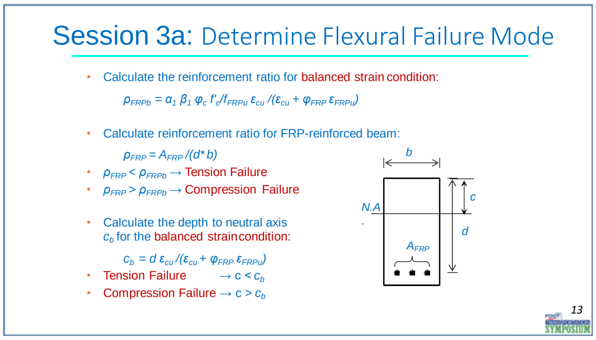
Session 3a: Flexural Behavior

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.

Flexural Failure Modes for FRP Reinforced Beams





Session 3a: Determine Flexural Failure Mode

- Calculate the reinforcement ratio for balanced strain condition:

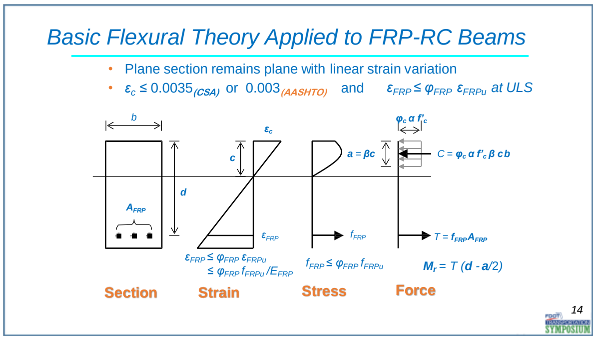
  $\rho_{FRPb} = \alpha_1\, \beta_1\, \varphi_c\, f'_c/f_{FRPu}\, \varepsilon_{cu}\, /(\varepsilon_{cu} + \varphi_{FRP}\, \varepsilon_{FRPu})$

- Calculate reinforcement ratio for FRP-reinforced beam:

  $\rho_{FRP} = A_{FRP}\, /(d^*\, b)$
- $\rho_{FRP} < \rho_{FRPb}$ → Tension Failure
- $\rho_{FRP} > \rho_{FRPb}$ → Compression Failure

- Calculate the depth to neutral axis c_b for the balanced strain condition:

  $c_b = d\, \varepsilon_{cu}\, /(\varepsilon_{cu} + \varphi_{FRP}\, \varepsilon_{FRPu})$
- Tension Failure → $c < c_b$
- Compression Failure → $c > c_b$



Basic Flexural Theory Applied to FRP-RC Beams

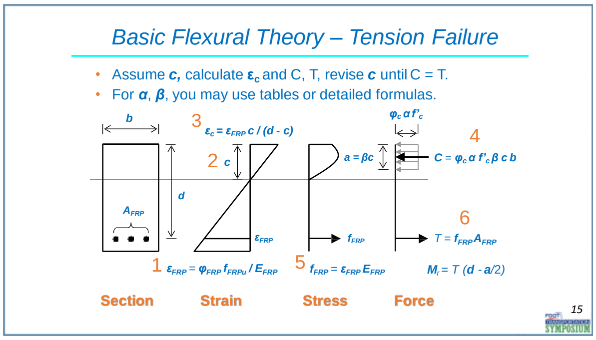
- Plane section remains plane with linear strain variation
- $\varepsilon_c \leq 0.0035_{(CSA)}$ or $0.003_{(AASHTO)}$ and $\varepsilon_{FRP} \leq \varphi_{FRP}\, \varepsilon_{FRPu}$ *at ULS*

$\varepsilon_{FRP} \leq \varphi_{FRP}\, \varepsilon_{FRPu}$
$\leq \varphi_{FRP}\, f_{FRPu}\, /E_{FRP}$

$f_{FRP} \leq \varphi_{FRP}\, f_{FRPu}$

$M_r = T\, (d - a/2)$

Section **Strain** **Stress** **Force**



Basic Flexural Theory – Tension Failure

- Assume ***c,*** calculate ε_c and C, T, revise ***c*** until C = T.
- For ***α***, ***β***, you may use tables or detailed formulas.

3 $\varepsilon_c = \varepsilon_{FRP}\, c\, /\, (d - c)$

4 $C = \varphi_c\, \alpha\, f'_c\, \beta\, c\, b$

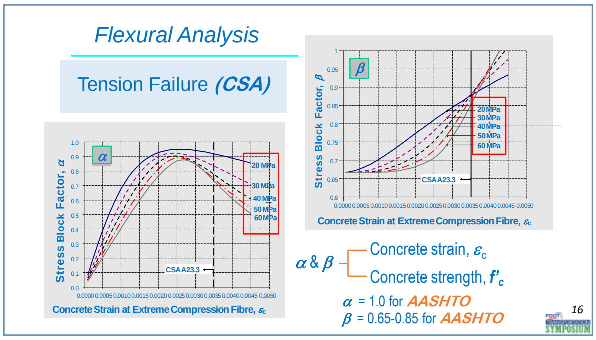
6 $T = f_{FRP} A_{FRP}$

1 $\varepsilon_{FRP} = \varphi_{FRP}\, f_{FRPu}\, /\, E_{FRP}$

5 $f_{FRP} = \varepsilon_{FRP}\, E_{FRP}$

$M_r = T\, (d - a/2)$

Section **Strain** **Stress** **Force**

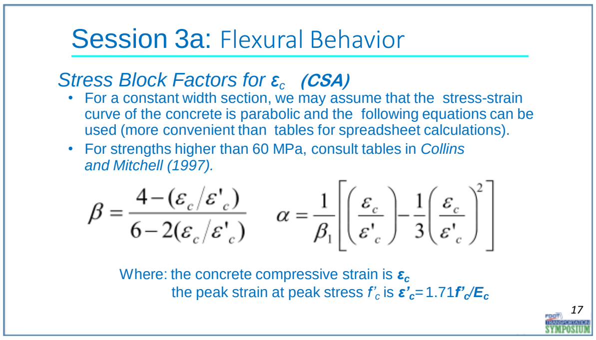


Flexural Analysis

Tension Failure ***(CSA)***

$\alpha\, \&\, \beta$ — Concrete strain, ε_c
— Concrete strength, ***f'c***

α = 1.0 for ***AASHTO***
β = 0.65-0.85 for ***AASHTO***



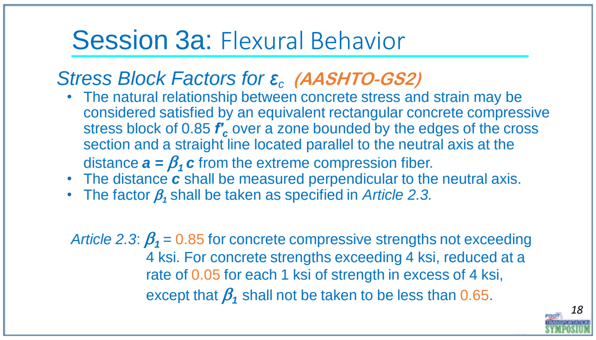
Session 3a: Flexural Behavior

Stress Block Factors for ε_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).*

$$\beta = \frac{4-(\varepsilon_c/\varepsilon'_c)}{6-2(\varepsilon_c/\varepsilon'_c)} \qquad \alpha = \frac{1}{\beta_1}\left[\left(\frac{\varepsilon_c}{\varepsilon'_c}\right)-\frac{1}{3}\left(\frac{\varepsilon_c}{\varepsilon'_c}\right)^2\right]$$

Where: the concrete compressive strain is ε_c
the peak strain at peak stress f'_c is $\varepsilon'_c = 1.71 f'_c/E_c$



Session 3a: Flexural Behavior

Stress Block Factors for ε_c (AASHTO-GS2)

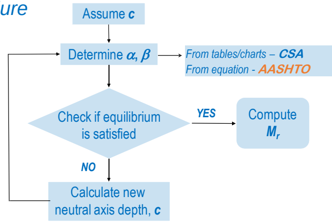
- The natural relationship between concrete stress and strain may be considered satisfied by an equivalent rectangular concrete compressive stress block of 0.85 ***f'c*** over a zone bounded by the edges of the cross section and a straight line located parallel to the neutral axis at the distance ***a*** = β_1 ***c*** from the extreme compression fiber.
- The distance ***c*** shall be measured perpendicular to the neutral axis.
- The factor β_1 shall be taken as specified in *Article 2.3*.

Article 2.3: β_1 = 0.85 for concrete compressive strengths not exceeding 4 ksi. For concrete strengths exceeding 4 ksi, reduced at a rate of 0.05 for each 1 ksi of strength in excess of 4 ksi, except that β_1 shall not be taken to be less than 0.65.

Session 3a: Flexural Analysis

Tension Failure

To summarize:



Assume c

Determine α, β

*From tables/charts – **CSA***
*From equation - **AASHTO***

Check if equilibrium is satisfied

YES

Compute M_r

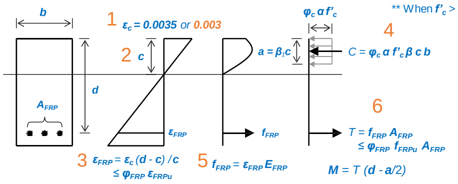
NO

Calculate new neutral axis depth, c

Basic Flexural Theory – Compression Failure

- Assume c, calculate ε_{FRP}, f_{FRP} and C, T, revise c until C = T.
  - Use $\alpha_1 = 0.85 - 0.0015f'_c$, $\beta_1 = 0.97 - 0.0025f'_c$ for $\varepsilon_c = 0.0035$ ***(CSA);***
  - Use $\alpha_1 = 1.0$, $\beta_1 = 0.85 – [0.05\ (f'_c - 4\ \text{ksi}]$** and $\varepsilon_c = 0.003$ ***(AASHTO)***.

** When $f'_c > 4$ ksi



1 $\varepsilon_c = 0.0035$ *or* *0.003*

2 c

3 $\varepsilon_{FRP} = \varepsilon_c (d - c) / c \le \varphi_{FRP}\, \varepsilon_{FRPu}$

4 $C = \varphi_c\, \alpha\, f'_c\, \beta\, c\, b$

5 $f_{FRP} = \varepsilon_{FRP} E_{FRP}$

6 $T = f_{FRP} A_{FRP} \le \varphi_{FRP}\, f_{FRPu}\, A_{FRP}$

$M = T\,(d - a/2)$

Section **Strain** **Stress** **Force**

Session 3a: Flexural Failure

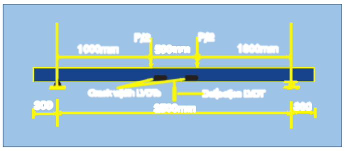
	Tension	Balanced	Compression
Behavior	FRP Rupture	FRP Rupture and Concrete crushing	Concrete crushing
Desirability	Least desirable : rupture is sudden and violent		Most desirable : sufficient warning
Reinf. Ratio	$\rho_{frp} < \rho_{bal}$	$\rho_{frp} = \rho_{bal}$	$\rho_{frp} > \rho_{bal}$
Strains	$\varepsilon_{frp} = \varepsilon_{frpu}$ $\varepsilon_c < \varepsilon_{cu}$	$\varepsilon_{frp} = \varepsilon_{frpu}$ $\varepsilon_c = \varepsilon_{cu}$	$\varepsilon_{frp} < \varepsilon_{frpu}$ $\varepsilon_c = \varepsilon_{cu}$

Session 3a: Flexural Behaviour

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

Test Set-up

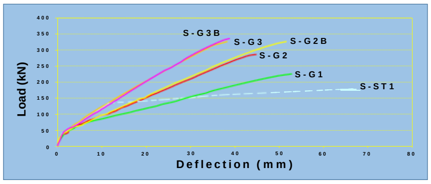
4-point bending over a clear span of 2.5 m.



Session 3a: Flexural Behaviour

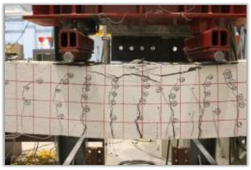
Load-Deflection of FRP-Reinforced Concrete Beams & One-Way Slabs under Flexure Load

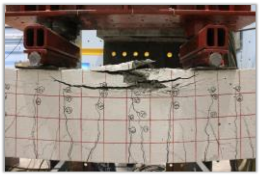
Effect of GFRP reinforcement ratio



Session 3a: Flexural Behaviour

Mode of failure: Compression failure (gradual concrete crushing)





Session 3a: Flexural Behaviour

Compression failure – GFRP RC Beam

GFRP RC Beam at failure

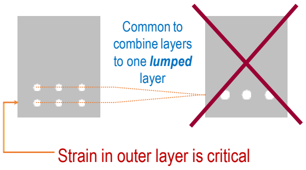
Release of Applied Load

When the applied load was released, the FRP RC beam recovered most of their deflection during the unloading process, because the FRP bars on the tension side did not reach rupture strain; In contrast, the steel specimen retained deflection after unloading

(Elastic behavior of FRP: Resilient structural element which maintains its functionality)

Flexural Analysis - Additional Considerations

Beams with FRP reinforcement in multiple layers



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

Strain in outer layer is critical

Lumping of reinforcement not allowed, strain compatibility is used to design on the basis of tensile failure of the outermost FRP layer

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Flexural Analysis - Additional Considerations

Minimum Flexural Resistance

- Minimum reinforcement required to prevent brittle failure when concrete cracks on tensile face:
  $M_r \geq 1.5\, M_{cr}$ ***(CSA-S6)*** | $M_r \geq 1.6\, M_{cr}$ ***(AASHTO-GS2)***
- If the ULS resistance of the section is governed by FRP rupture (*tension failure*):
  $M_r \geq 1.5\, M_f$ ***(CSA-S6)*** | $M_r \geq 1.6\, M_{cr}$ ***(AASHTO-GS2)***
- For tension failure, the code requires a purposely conservative design to ensure that ample deformation and cracks will develop before failure of the beam.
- Neglect compression FRP.

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 c/d requirement shown below:

$$\frac{c}{d} \geq \frac{7}{7 + 2000\,\varepsilon_{Fu}}$$

Flexural Analysis - Additional Considerations

*Flexure Design **(CSA S806)***

- **Assumptions**
  - – Minimum Flexural Reinforcement Requirement

$$M_r \geq 1.5 M_{cr} = 1.5 f_r \frac{I_g}{y_t}$$

  - – For Slabs:
    - $A_{F.min} = 400 E_F / A_g \geq 0.0025 A_g$
    - Spacing of $A_{F.min} \leq$ 300mm or 3 times slab thickness

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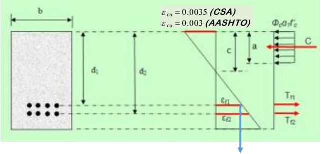
Flexural Analysis - Additional Considerations

Flexure Design

Strain Compatibility Analysis:



(CSA S806)

$\varphi_c = 0.65$
$\varphi_F = 0.75$
$\alpha_1 = 0.85 - 0.0015 f'c \geq 0.67$
$\beta_1 = 0.97 - 0.0025 f'c \geq 0.67$
$a = \beta_1 c$

$T_{f1} = \alpha_F \varepsilon_{f1} E_f A_{f1}$
$T_{f2} = \alpha_F \varepsilon_{f2} E_f A_{f2}$

(AASHTO-GS2)

$\varphi_c = 0.65$
$\varphi_F = 0.55$
$\alpha_1 = 0.85$
$\beta_1 = 0.85 - 0.05 (f'c - 4\ ksi) \geq 0.65$
$a = \beta_1 c$

$T_{f1} = \varepsilon_{f1} E_f A_{f1}$
$T_{f2} = \varepsilon_{f2} E_f A_{f2}$

$$\varepsilon_{fi} = \frac{d_i - c}{c} \varepsilon_{cu} = \frac{d_i - c}{c} 0.0035$$

(CSA S806)

$$\varepsilon_{fi} = \frac{d_i - c}{c} \quad \varepsilon_{cu} = \frac{d_i - c}{c} 0.003$$

(AASHTO-GS2)

Flexural Analysis - Additional Considerations

*Flexure Design **(CSA S806)***

Resisting Moment:

$$M_r = C\left(c - \frac{a}{2}\right) + T_{f1}(d_1 - c) + T_{f2}(d_2 - c) \geq M_f$$

Session 3a: Flexural Analysis

Analysis at Service Limit State

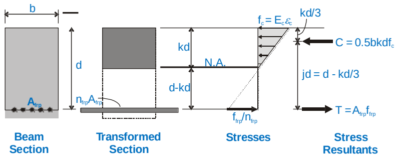
- Serviceability considerations (stresses, crack widths, and deflections) may govern the design of FRP-reinforced concrete members
- Analysis at Service Limit State can be performed assuming linear-elastic behavior (straight-line theory)
  - FRP materials are linear-elastic to failure
  - Concrete stress-strain relationship is linear for compression stresses less than 60% of ***f'$_c$***

Session 3a: Flexural Analysis

Analysis at Service Limit State

- Linear-elastic cracked transformed section analysis:

A_{FRP} transformed to equivalent area of concrete



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

(See Example #1 & #2 – Attachment 3a)

Session 3b: Shear Behaviour

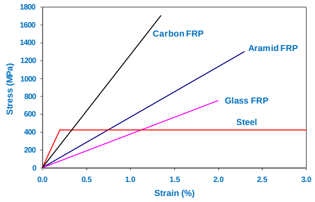
Session 4: (1:30 pm - 2:30 pm)

Shear behaviour

- \- Design philosophy
- \- Shear strength
- \- Design examples

Session 3b: Shear Behaviour

Stress-Strain Relationships for FRP Bars



Session 3b: Shear Behaviour

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

Session 3b: Shear Behaviour

Shear Strength of FRP Reinforced Members

- Concrete reinforced with FRP has a lower shear strength than concrete with steel reinforcement

Increased crack width	⟶	Less aggregate interlocking
Small compressive zone depth	⟶	Less concrete resistance in the zone compressive

Session 3b: Shear Behaviour

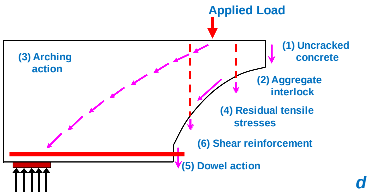
Most of the design codes and design guidelines recommend the following simplified approach for shear design:

$$V_n = V_{cf} + V_{sf} + V_p$$

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

Session 3b: Shear Behaviour



Session 3b: Shear Behaviour

Shear Behaviour of FRP RC Beams

Beam CN-3 **Beam GN-3**

Diagonal tension failure mode

Session 3b: Shear Behaviour

Size Effect

Session 3b: Shear Behaviour

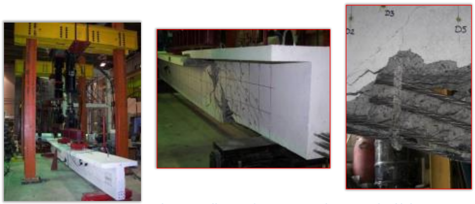
Beam B1-1

Beam B1-2

Diagonal Tension Failure Mode

Session 3b: Shear Behaviour

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)

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

Reinforcing Cage and Concrete Casting

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

Curing and transportation

Session 3b: Shear Behaviour

Shear Behaviour of FRP RC Beams

GFRP-Cages

Session 3b: Shear Behaviour

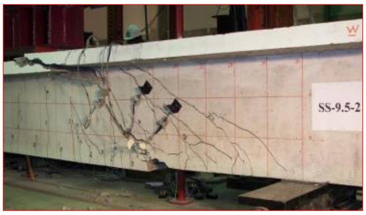
Shear Behaviour of FRP RC Beams; GFRP & CFRP Stirrups

CFRP Stirrups

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

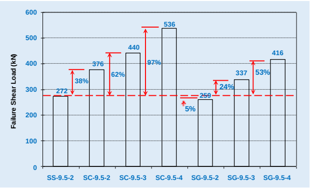
Shear Failure of SC-9.5-3 (CFRP @ d/3)

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)



Shear Capacity

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_c 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**

$$V_{r,\max} = 0{,}22\varphi_c f_c' b_w d_v + 0{,}5V_p + \left[\frac{M_{dc}V_f}{M}\right]$$

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

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

$$V_c = 0.05\lambda\varphi_c k_m k_r \left(f_c'\right)^{1/3} b_w d_v$$

where

$$k_m = \sqrt{\frac{V_f d}{M_f}} \leq 1$$

$$k_r = 1 + (E_F \rho_{Fw})^{1/3}$$

BUT

$$V_c \leq 0.22\varphi_c \sqrt{f'_c} b_w d_v$$

$$V_c \geq 0.11\varphi_c \sqrt{f'_c} b_w d_v$$

$$f_c' \leq 60 MPa$$

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

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 $A_{v,min}$

$$V_c = 0.05\lambda\varphi_c k_m k_r k_s \left(f_c^{'}\right)^{1/3} b_w d_v$$

where

$$k_s = \frac{750}{450 + d} \leq 1$$

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

- Shear Carried by Transverse Reinforcement
  - For Members with FRP Transverse Reinforcement

$$V_{s,F} = \frac{0.4\varphi_F A_{Fv} f_{Fu} d_v}{s} \cot\theta$$

  - For Members with Steel Transverse Reinforcement

$$V_{s,s} = \frac{\varphi_S A_v f_y d_v}{s} \cot\theta$$

f_{Fu} 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

$V_f > 0.5V_c + \Phi_F V_p$, or $T_f > 0.5T_{cr}$.

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 are of FRP shear reinforcement shall be such that

$$A_{vF} = 0.07\sqrt{f_c^{'}} \frac{b_w s}{0.4 f_{Fu}}$$

f_{Fu} shall not be greater than 1200MPa or $0.005E_F$.

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

- **Shear resistance is calculated as:**

$$V_r = V_c + V_{sf} \leq 0.25\phi_c f_c^{'} b_w d_{long}$$

Where $V_c = 2.5\ \beta\ \phi_c\ f_{cr}\ b_v\ d_{long}$

$$V_{sf} = \frac{\phi_{frp}\ A_{fv}\ f_{fv}\ d_{long} \cot\theta}{s}$$

$$d_{long} = 0.72h \quad or \quad 0.9d$$

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

Simplified Method

For sections with at least minimum shear reinforcement

$$\theta = 42^o$$
$$\beta = 0.18$$

For sections without minimum shear reinforcement

$$\theta = 42^o$$
$$\beta = \frac{230}{1000 + d_{long}}$$

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

General Method

$$\beta = \frac{0.4}{(1+1500\,\varepsilon_x)} \cdot \frac{1300}{(1000+S_{ze})}$$

$$\theta = (29+7000\,\varepsilon_x)(0.88+S_{ze}/2500)$$

$$S_{ze} = 300mm$$

$$\varepsilon_x = \frac{(M_f/d_{long})+V_f}{2\,E_{fl}A_{fl}}$$

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

The stress in FRP stirrup, f_{fv} , is calculated as:

$$f_{fv} = 0.004\,E_{fv} \le f_{bend}$$

$$f_{bend} = \left(0.3+0.05\frac{r_b}{d_b}\right) f_{fuv} \le f_{fuv}$$

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

- **Minimum Shear Reinforcement**

$$A_{fv\,,\min} = 0.06\sqrt{f_c'}\,\frac{b_w\,s}{f_{fv}}$$

$$s \le 0.75\,d_v \quad or \quad 600mm \quad if \quad V_f < 0.1\phi_c f_c' b_w d_{long}$$

$$s \le 0.33\,d_v \quad or \quad 300mm \quad if \quad V_f > 0.1\phi_c f_c' b_w d_{long}$$

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

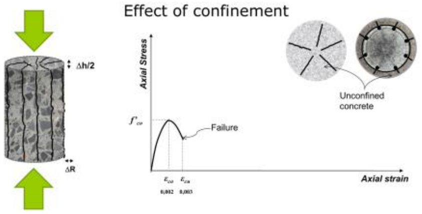
Session 3c: Compression Behavior

Role of reinforcement in columns?

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

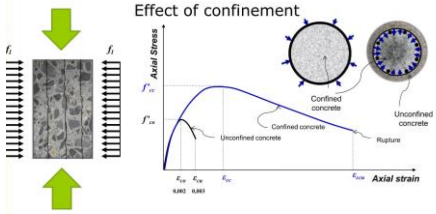
Session 3c: Compression Behavior

Effect of confinement



Session 3c: Compression Behavior

Effect of confinement

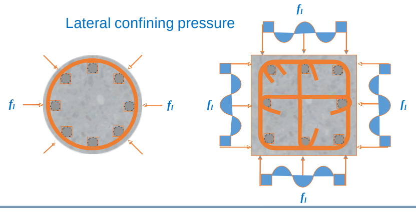


Session 3c: Compression Behavior

Effect of confinement

Principle of internal confinement

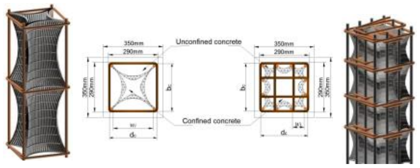
Lateral confining pressure



Session 3c: Compression Behavior

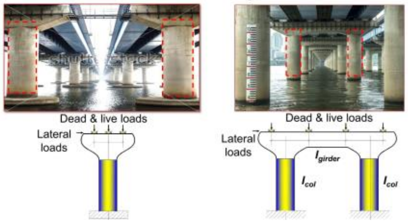
Effect of confinement

Principle of internal confinement



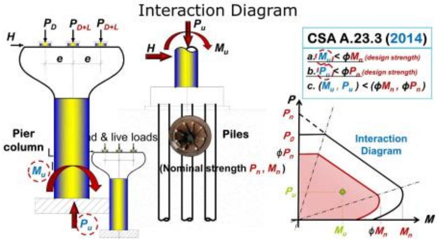
Session 3c: Compression Behavior

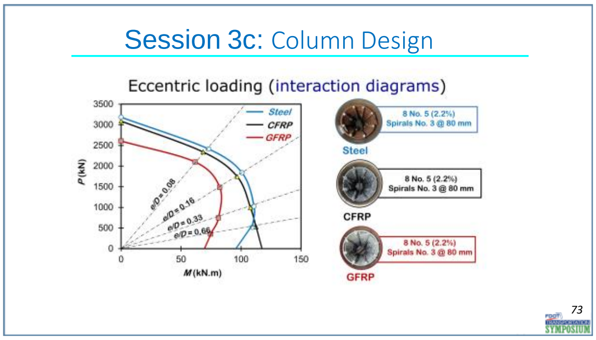
Interaction Diagram



Session 3c: Column Design

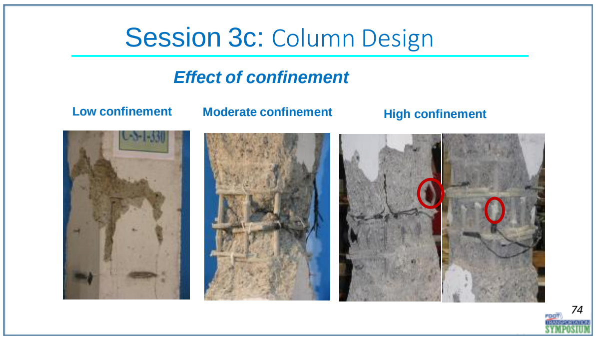
Interaction Diagram





Session 3c: Column Design

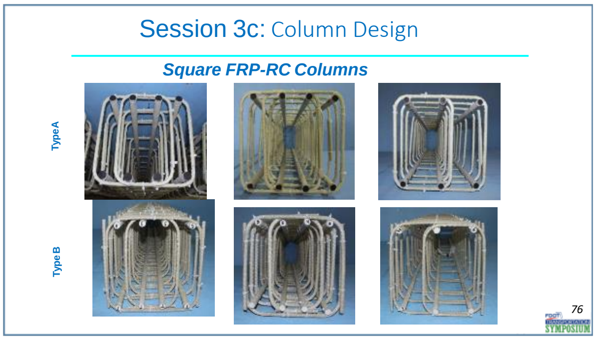
Eccentric loading (interaction diagrams)



Session 3c: Column Design

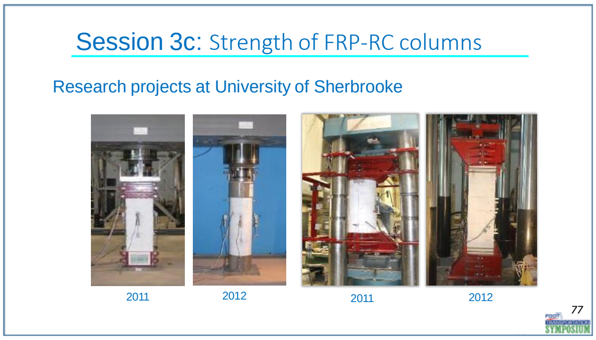
Effect of confinement

Session 3c: Column Design



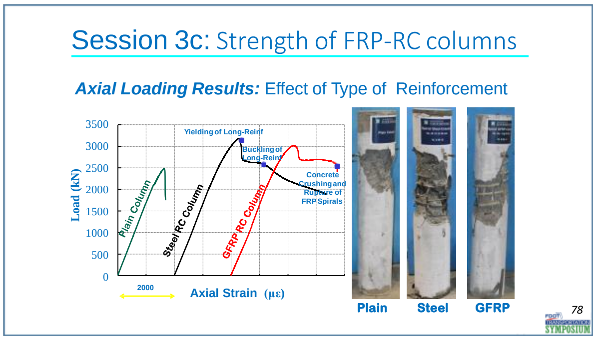
Session 3c: Column Design

Square FRP-RC Columns



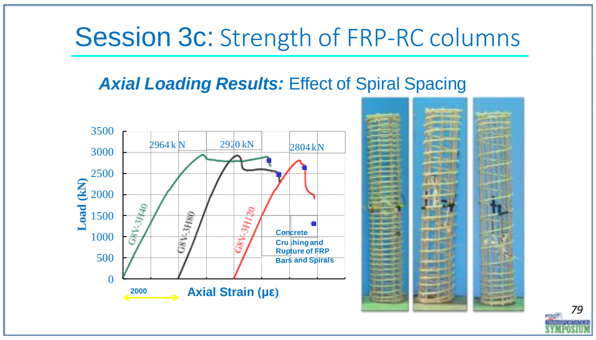
Session 3c: Strength of FRP-RC columns

Research projects at University of Sherbrooke



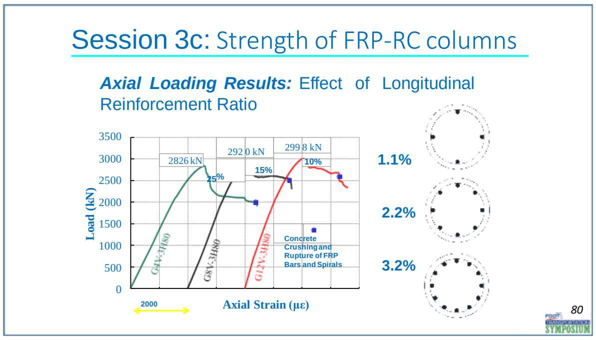
Session 3c: Strength of FRP-RC columns

Axial Loading Results: Effect of Type of Reinforcement



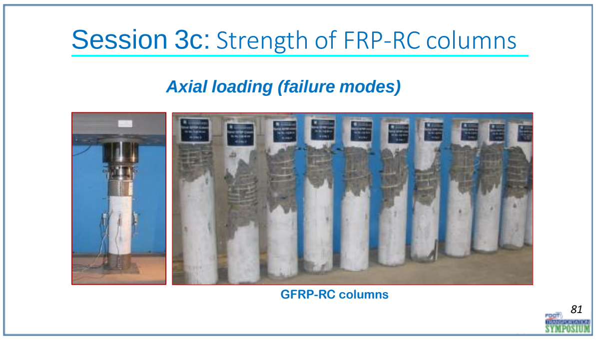
Session 3c: Strength of FRP-RC columns

Axial Loading Results: Effect of Spiral Spacing



Session 3c: Strength of FRP-RC columns

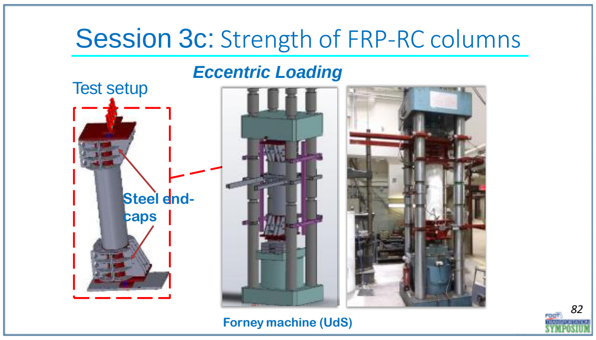
Axial Loading Results: Effect of Longitudinal Reinforcement Ratio



Session 3c: Strength of FRP-RC columns

Axial loading (failure modes)

GFRP-RC columns

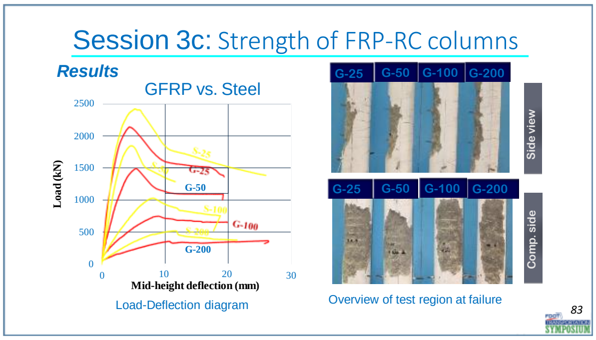


Session 3c: Strength of FRP-RC columns

Eccentric Loading

Test setup

Forney machine (UdS)



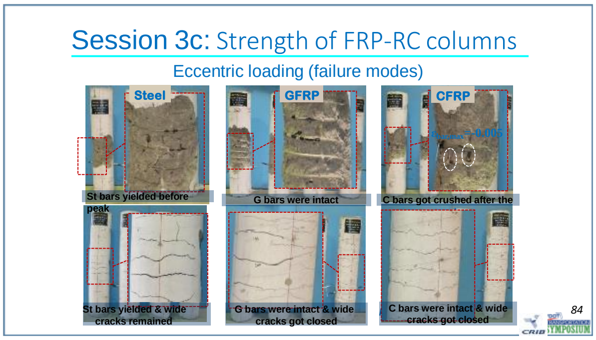
Session 3c: Strength of FRP-RC columns

Results

GFRP vs. Steel

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

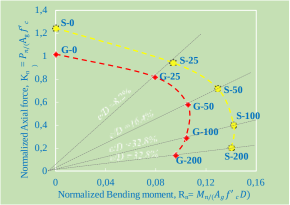
St bars yielded & wide cracks remained

G bars were intact & wide cracks got closed

C bars were intact & wide cracks got closed

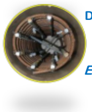
Session 3c: Strength of FRP-RC columns

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**

$P_{ro} = \alpha_1 \phi_c f'_c (A_g - A_t)$ **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.**

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

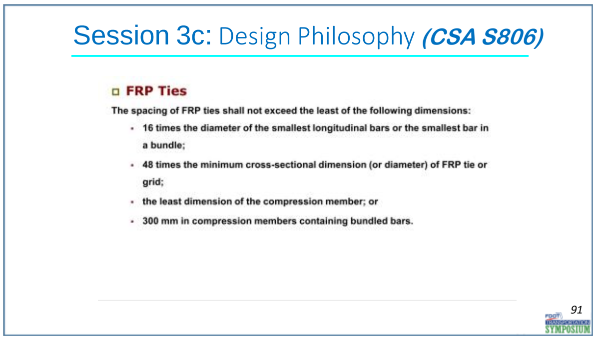
$$\frac{P}{P_o} \geq 0.2 \qquad \frac{A_g}{A_c} \geq 0.3 \qquad f_{Fh} = \phi_f f_{Fu} \text{ or } 0.006E_F$$

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.**

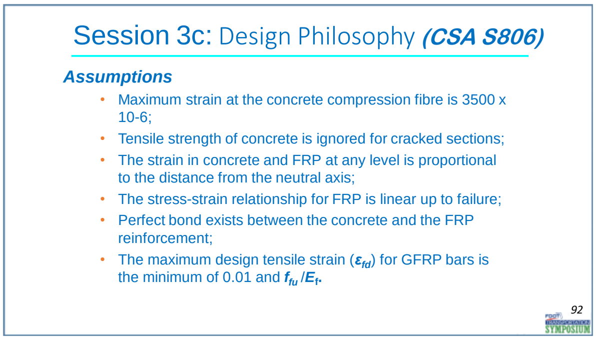


Session 3c: Design Philosophy *(CSA S806)*

□ FRP Ties

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

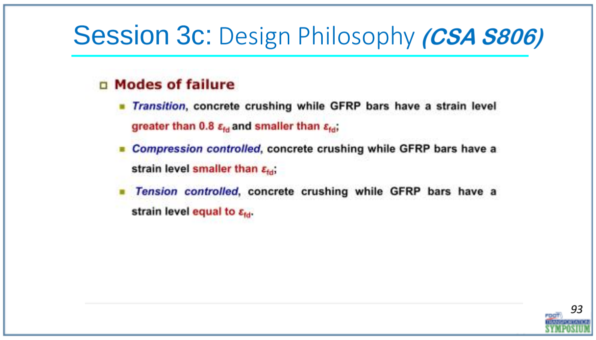
- **16 times the diameter of the smallest longitudinal bars or the smallest bar in a bundle;**
- **48 times the minimum cross-sectional dimension (or diameter) of FRP tie or grid;**
- **the least dimension of the compression member; or**
- **300 mm in compression members containing bundled bars.**



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

Assumptions

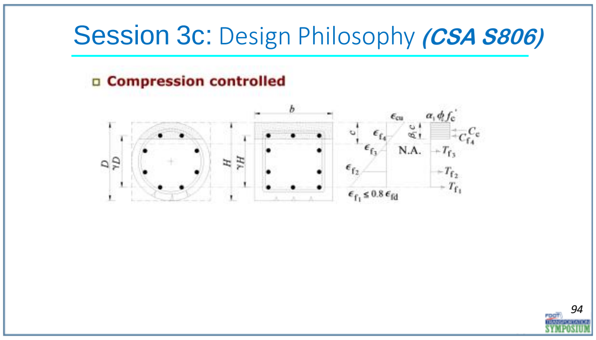
- Maximum strain at the concrete compression fibre is 3500 x 10-6;
- Tensile strength of concrete is ignored for cracked sections;
- The strain in concrete and FRP at any level is proportional to the distance from the neutral axis;
- The stress-strain relationship for FRP is linear up to failure;
- Perfect 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)*

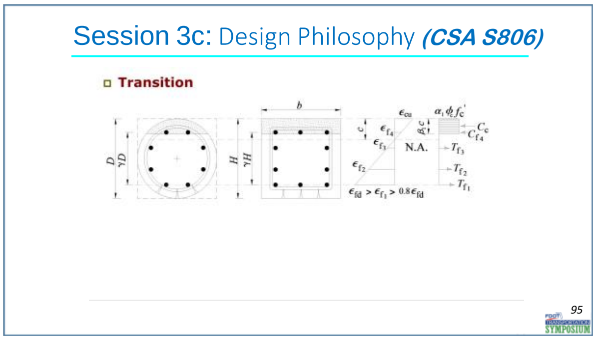
□ Modes of failure

- ***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}.**



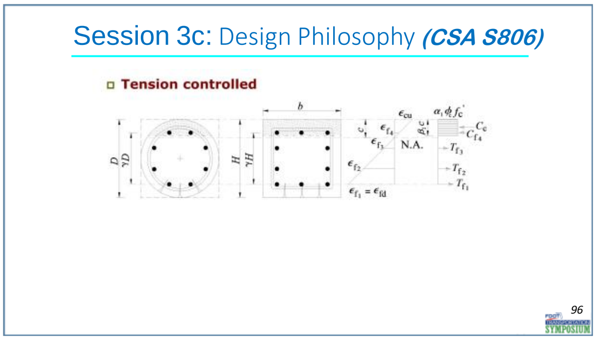
Session 3c: Design Philosophy *(CSA S806)*

□ Compression controlled



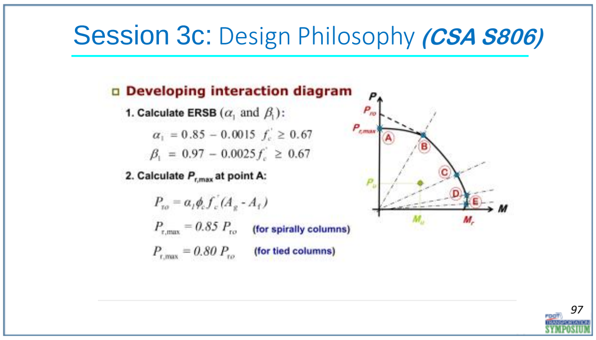
Session 3c: Design Philosophy *(CSA S806)*

□ Transition



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

□ Tension controlled



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

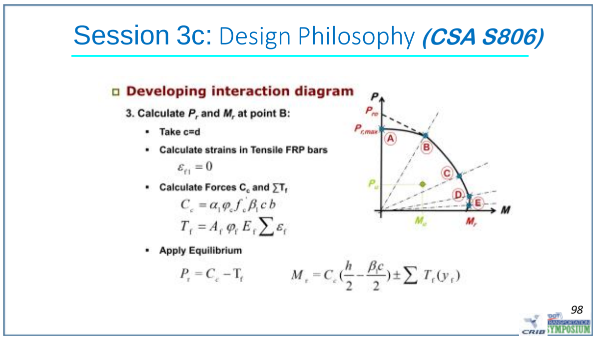
Developing interaction diagram

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

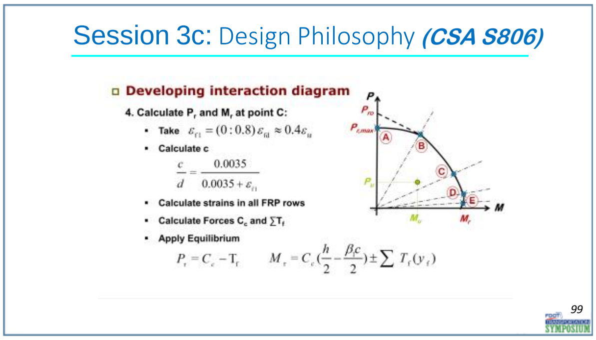
$$\varepsilon_{f1} = 0$$

- 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

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



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

Developing interaction diagram

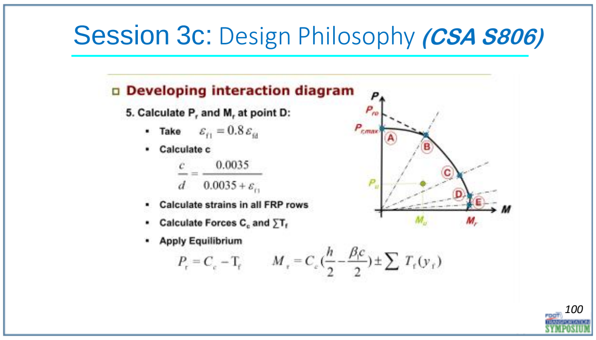
4. Calculate P_r and M_r at point C:

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

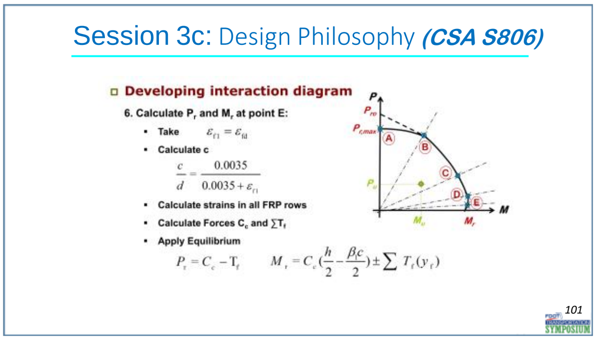
5. Calculate P_r and M_r at point D:

- 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

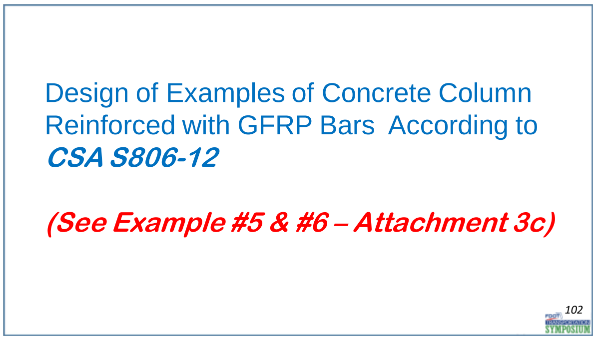
6. Calculate P_r and M_r at point E:

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

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

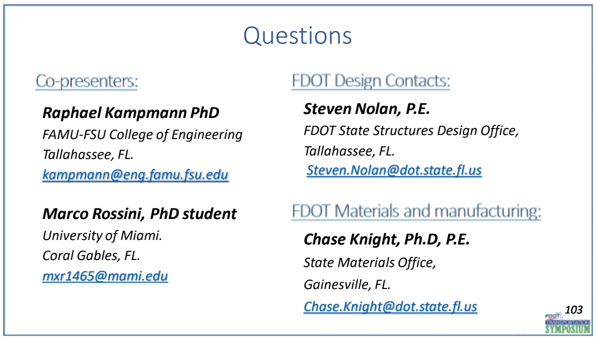
- Calculate strains in all FRP rows
- Calculate Forces C_c and $\sum T_f$
- Apply Equilibrium

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



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

(See Example #5 & #6 – Attachment 3c)



Questions

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