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An Introduction to FRP-Reinforced Concrete

According to Canadian Code

Book 'Composites for Construction', L. Bank, Chapters 5, 6 and 7

ACI 440.1R-03

Emerging Technology Series

Guide for the Design and Construction of Concrete Reinforced with FRP Bars

Reported by ACI Committee 440

ACI encourages the development and appropriate use of new and emerging technologies through the publication of the ***Emerging Technology Series****. This series presents information and recommendations based on available test data, technical reports, limited experience with field applications, and the opinions of committee members. The presented information and recommendations, and their basis, may be less fully developed and tested than those for more mature technologies. This report identifies areas in which information is believed to be less fully developed, and describes research needs. The professional using this document should understand the limitations of this document and exercise judgment as to the appropriate application of this emerging technology.*

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Note: The committee acknowledges the contribution of associate member Tarek Alkhrdaji.

Fiber-reinforced polymer (FRP) materials have emerged as a practical alternative material for producing reinforcing bars for concrete structures. FRP reinforcing bars offer advantages over steel reinforcement in that FRP bars are noncorrosive, and some FRP bars are nonconductive. 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 needed. Several countries, such as Japan and Canada, have already established design and construction guidelines specifically for the use of FRP bars as concrete reinforcement. This document offers general information on the history and use of FRP reinforcement, a description of the unique material properties of FRP, and committee recommendations on the engineering and construction of concrete reinforced with FRP bars. The proposed guidelines are based on the knowledge gained from worldwide experimental research, analytical work, and field applications of FRP reinforcement.

Keywords: aramid fibers; carbon fibers; concrete; development length; fiber-reinforced polymers; flexure; glass fibers; moment; reinforced concrete; reinforcement; shear; slab; strength.

CONTENTS

ACI 440.1R-03 supersedes ACI 440.1R-01 and became effective March 27, 2003.

European Standardisation

- EC2 (EN 1992-1-1) does not include FRP materials
- Design clauses for composite rebars as internal reinforcement as well as external reinforcement will be included/added to the new EN 1992-1-1 2020
- No European material standard for FRP rebars or Laminates; only for pultrusion profiles EN 13706

European Technical Approval

- No Standard for reinforcing bars
- EAD European assessment document = testing and quality rules
- ETA defines material properties

FRP Materials

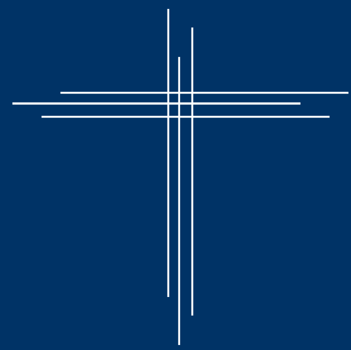
General

- Wide range of FRP products available:
  - Unidirectional bars

Fibres along axis

  - Orthogonal grids

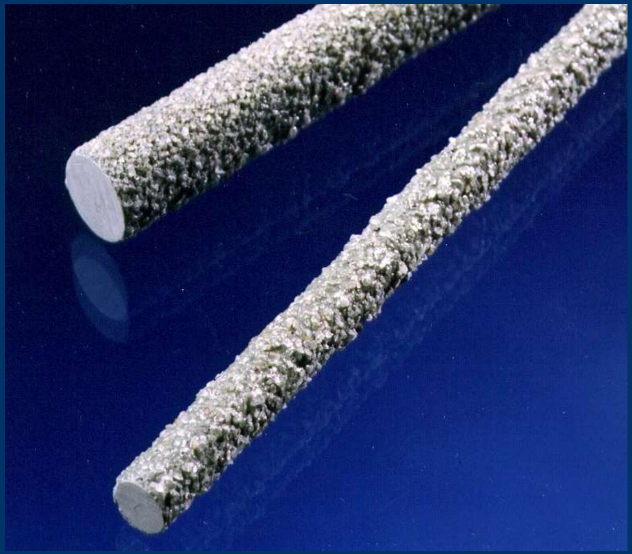
Unidirectional bars in two directions



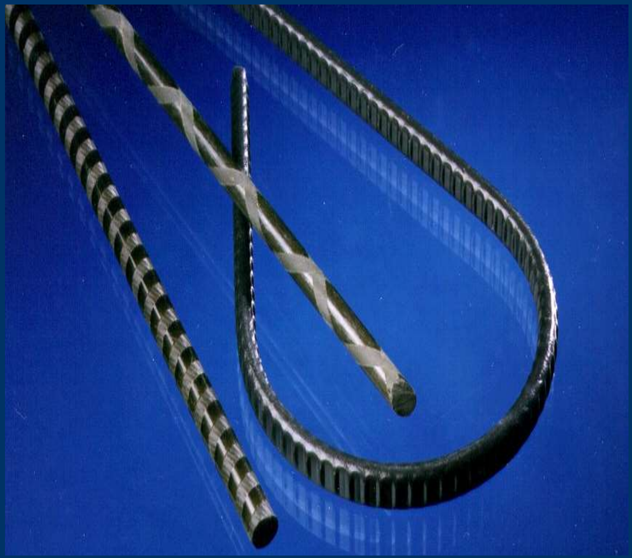
  - Prestressing tendons

FRP Materials

- To enhance FRP bar's mechanical bond with concrete:



Incorporate sand on the surface…



…or a fibre braid

FRP Materials

Add'l Info

❶CTE: - Coefficient of thermal expansion

- FRP value different from steel and concrete
- Varies considerably from product to product
- Difference in CTE may cause cracks, spalling

❷Fire: - High temperature adversely affects mechanical and bond properties of FRPs

- Maintain temperature below glass transition temperature (GTT) of polymer matrix

FRP Materials

Add'l Info

❸Bond: Strength depends on:

- Surface treatment of bar
- Environmental conditions
- Strength of FRP

❹Creep: Constant stress level over time can cause sudden failure

Carbon - least ⟵ *Susceptibility* ⟶ Glass - most

A stress limit is imposed to prevent this occurrence

FRP Materials

Add'l Info

❺Durability: - Complex topic

- Research ongoing
- FRPs are performing well to date

Design for Flexure

Assumptions

- FRP-reinforced concrete design uses a limit states design philosophy
- Material resistance factors:
  - Concrete, ϕ_c = 0.65 (precast), 0.6 (cast-in-place), 0.75 (bridges)
  - FRP, ϕ_{frp} = 0.8 (carbon), 0.4 (aramid), 0.6 (glass)
- Material related assumptions:

➊ Failure strain of concrete = 0.0035

➋ Concrete has no tensile strength

➌ Strain is proportional to distance from neutral axis

➍ FRPs are perfectly linear-elastic

➎ FRP has no compressive strength

➏ Perfect bond between FRPs and concrete

Design for Flexure

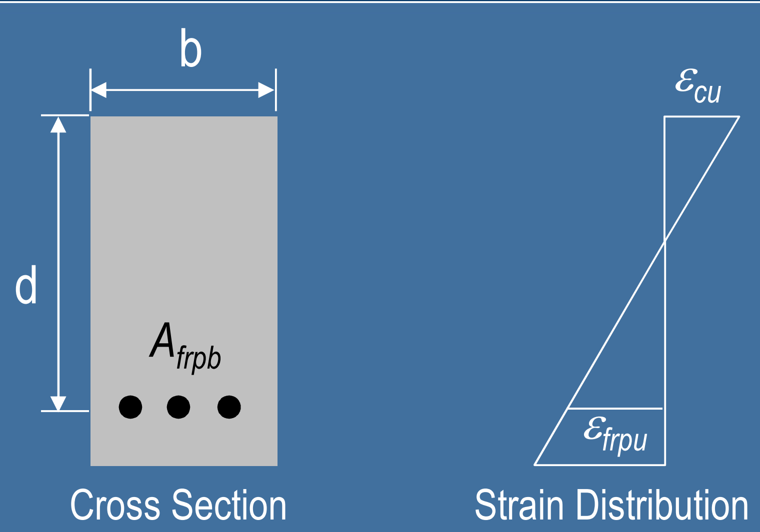
Types of Failure

Failure Modes

	Tension	Balanced	Compression
Behaviour	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	$\varepsilon_{frp} = \varepsilon_{frpu}$ $\varepsilon_{c} < \varepsilon_{cu}$	$\varepsilon_{frp} = \varepsilon_{frpu}$ $\varepsilon_{c} = \varepsilon_{cu}$	$\varepsilon_{frp} < \varepsilon_{frpu}$ $\varepsilon_{c} = \varepsilon_{cu}$

Design for Flexure

Balanced



Objective: Solve for balanced reinforcement ratio (ρ_{frpb})

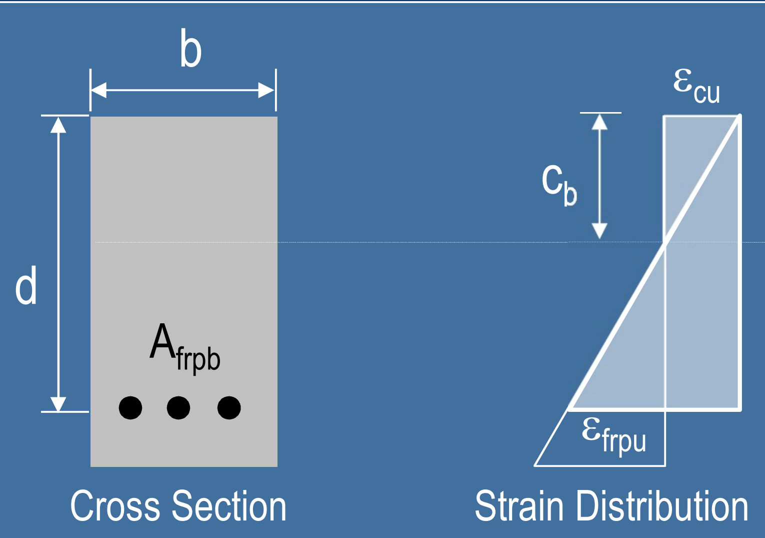
Step 1: Strains

Concrete: $\varepsilon_c = \varepsilon_{cult} = 0.0035$

FRP: $\varepsilon_{frp} = \varepsilon_{frpult} = f_{frp}/E_{frp}$

Design for Flexure

Balanced

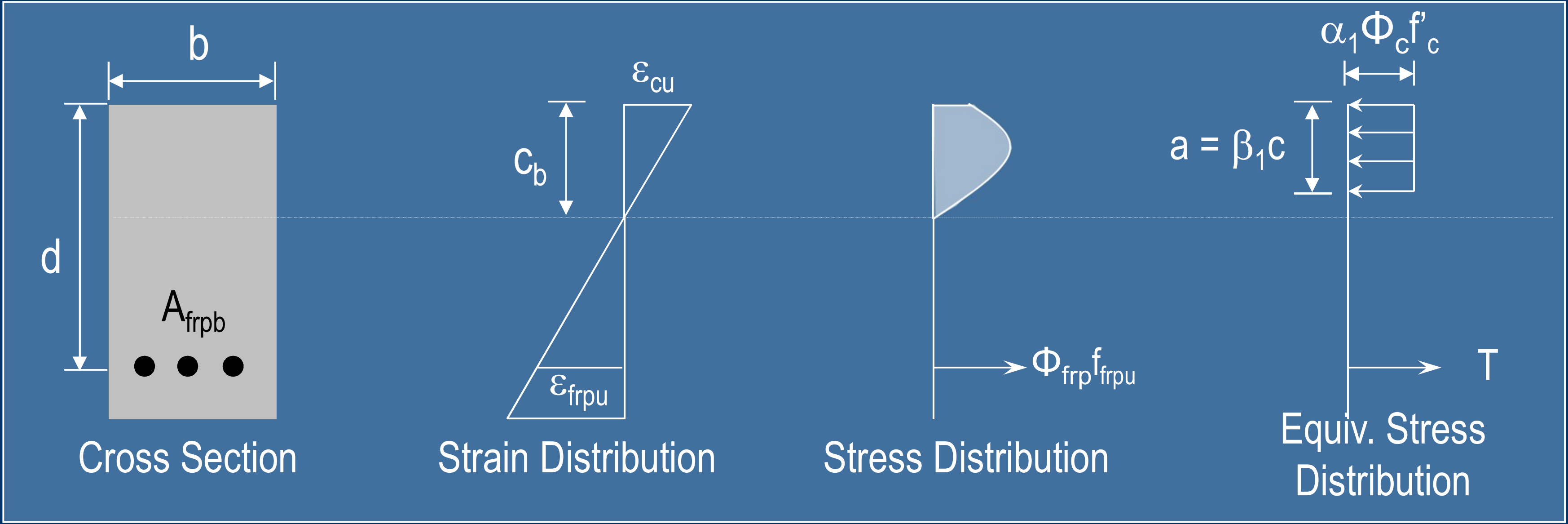


Step 2: Strain compatibility

$$\frac{c_b}{d} = \frac{\varepsilon_{cu}}{\varepsilon_{cu} + \varepsilon_{frpu}}$$

Design for Flexure

Balanced



Step 3: Stress distribution

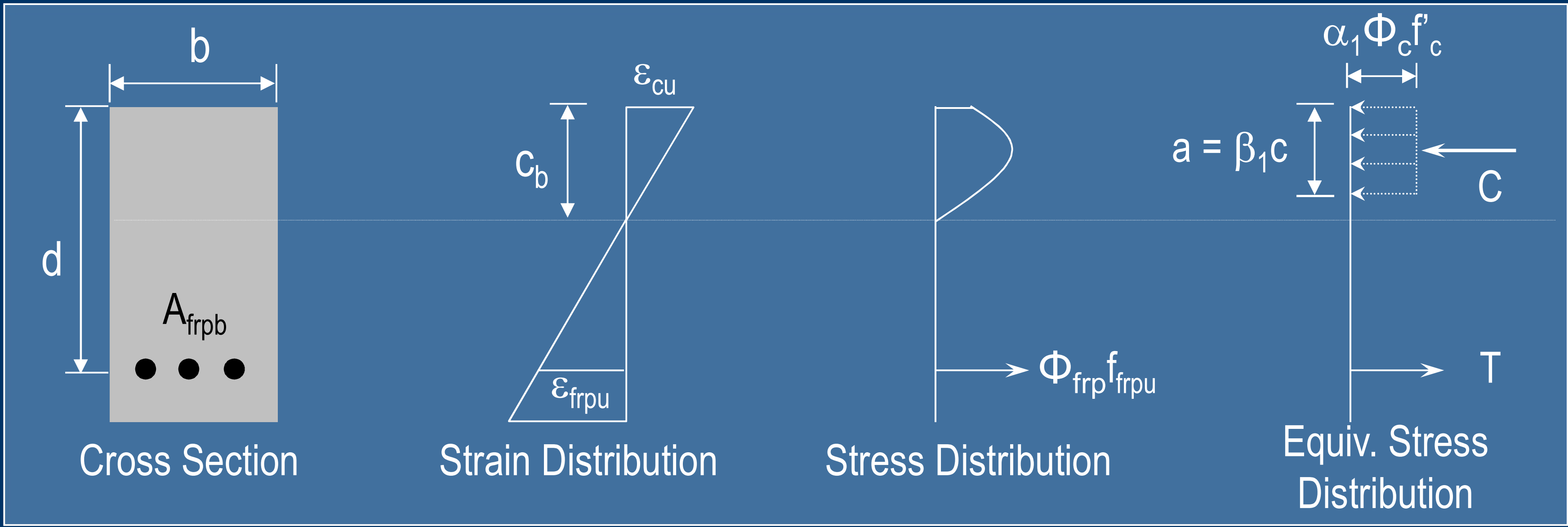
True stress block is non-linear

Instead, replace with equivalent rectangular stress block

Use same α_1, β_1 as for steel-reinforced concrete

Design for Flexure

Balanced



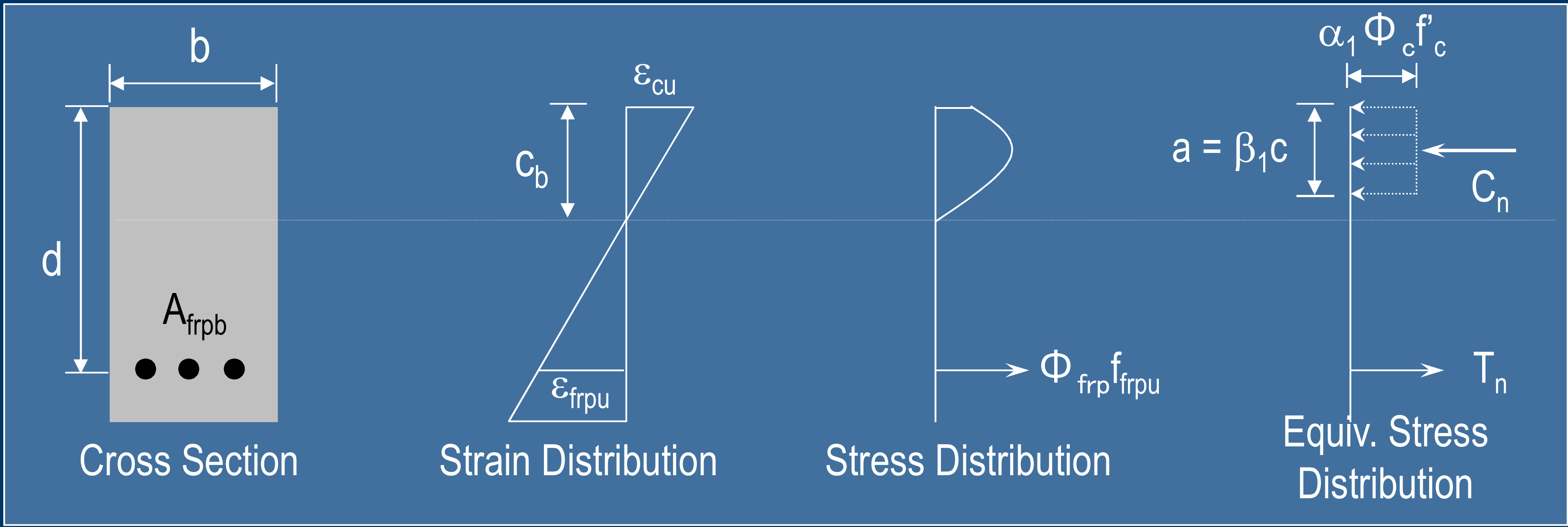
Step 4: Equilibrium

$$T = C$$

$$\Phi_{frp}\varepsilon_{frpu}E_{frp}A_{frp} \qquad \Phi_c\alpha_1 f'_c\beta_1 cb$$

Design for Flexure

Balanced



<u>Step 5</u>: Solution of ρ_{frpb}

$$\rho_{frpb} = \frac{A_{frpb}}{b\,d} = \alpha_1 \beta_1 \frac{\phi_c}{\phi_{frp}} \frac{f'_c}{f_{frpu}} \left(\frac{\varepsilon_{cu}}{\varepsilon_{cu} + \varepsilon_{frpu}} \right)$$

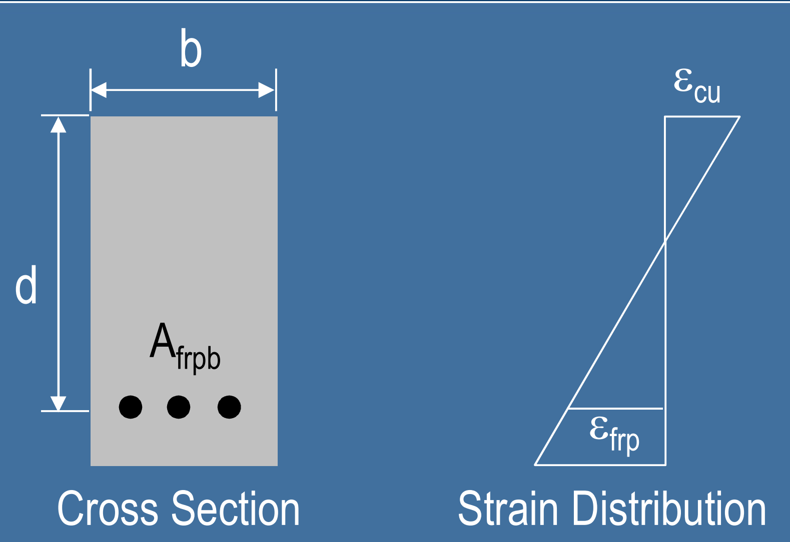
Design for Flexure

- When $\rho_{frp} > \rho_{frpb}$ → Compression failure

- When $\rho_{frp} < \rho_{frpb}$ → Tension failure

Design for Flexure

Compression Failure



Objective: Solve for moment resistance of section (M_r)

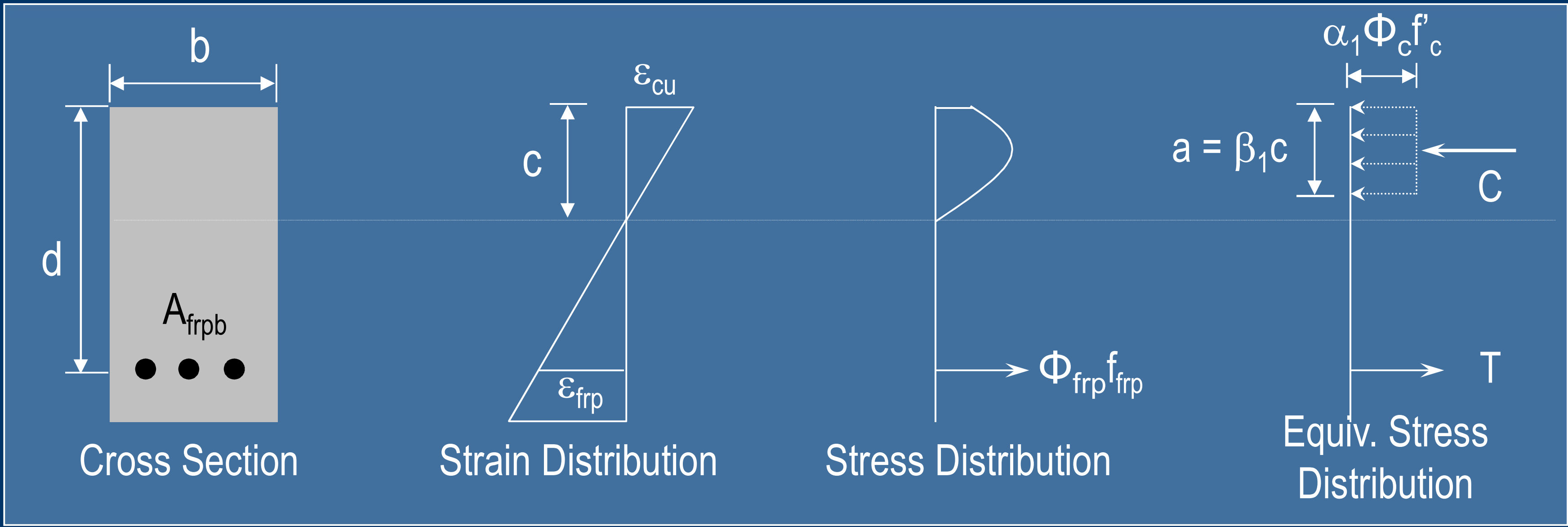
Step 1: Strains

Concrete: $\varepsilon_c = \varepsilon_{cu} = 0.0035$

FRP: $\varepsilon_{frp} < \varepsilon_{frpu}$

Design for Flexure

Compression Failure



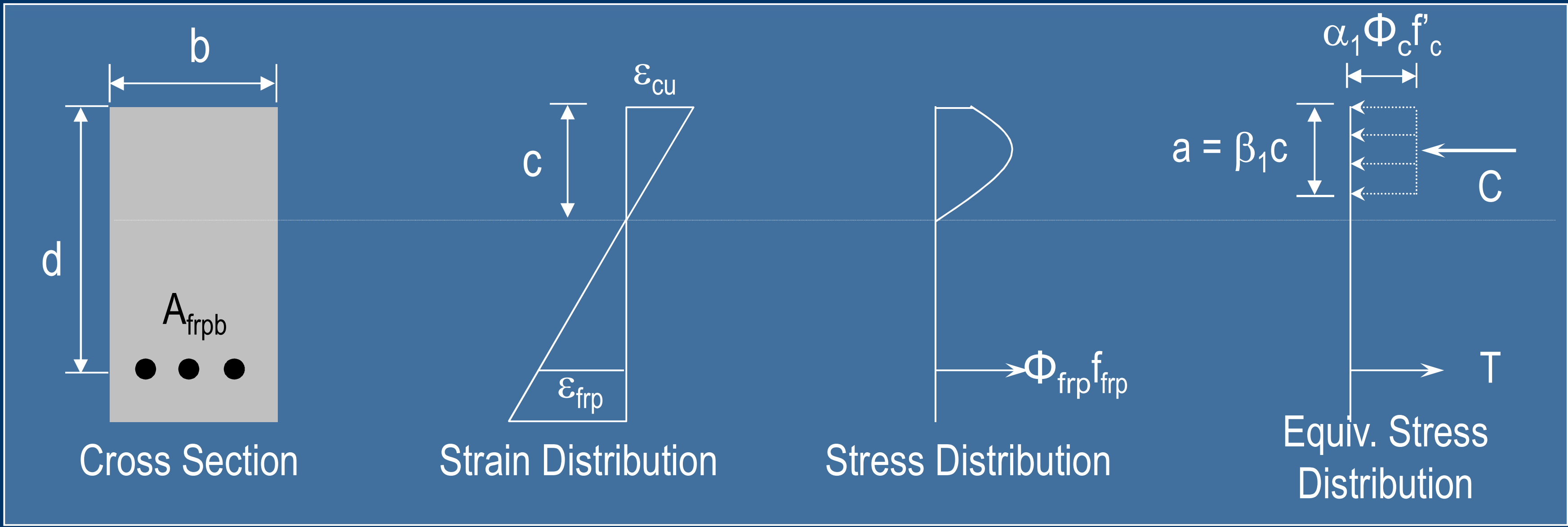
Step 2: Apply equilibrium

$$T = C$$

$$\phi_{frp}A_{frp}f_{frp} = \phi_c\alpha_1 f'_c\beta_1 cb$$

Design for Flexure

Compression Failure



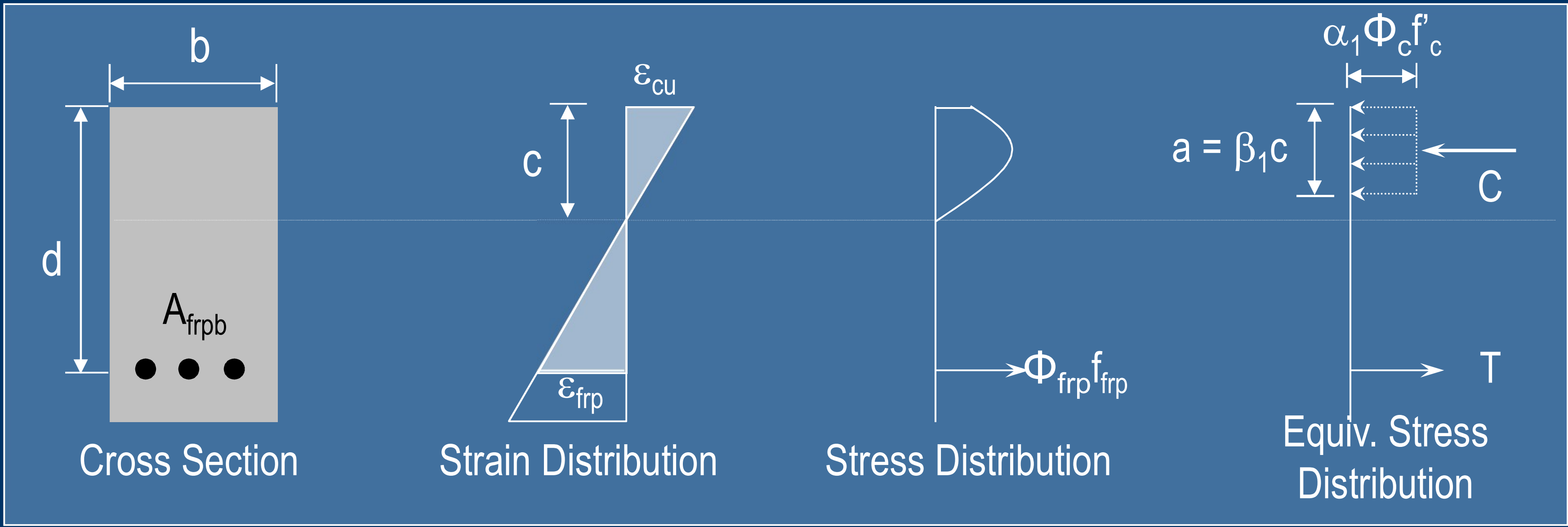
<u>Step 3</u>: Rearrange and solve for $\beta_1 c = a$

unknown $= E_{frp} \bullet \varepsilon_{frp}$

$$(\beta_1 c) = \frac{\phi_{frp} A_{frp} f_{frp}}{\phi_c(\alpha_1 f'_c)\ b}$$

Design for Flexure

Compression Failure



Derivation: Strain compatibility to solve for ε_{frp} and f_{frp}

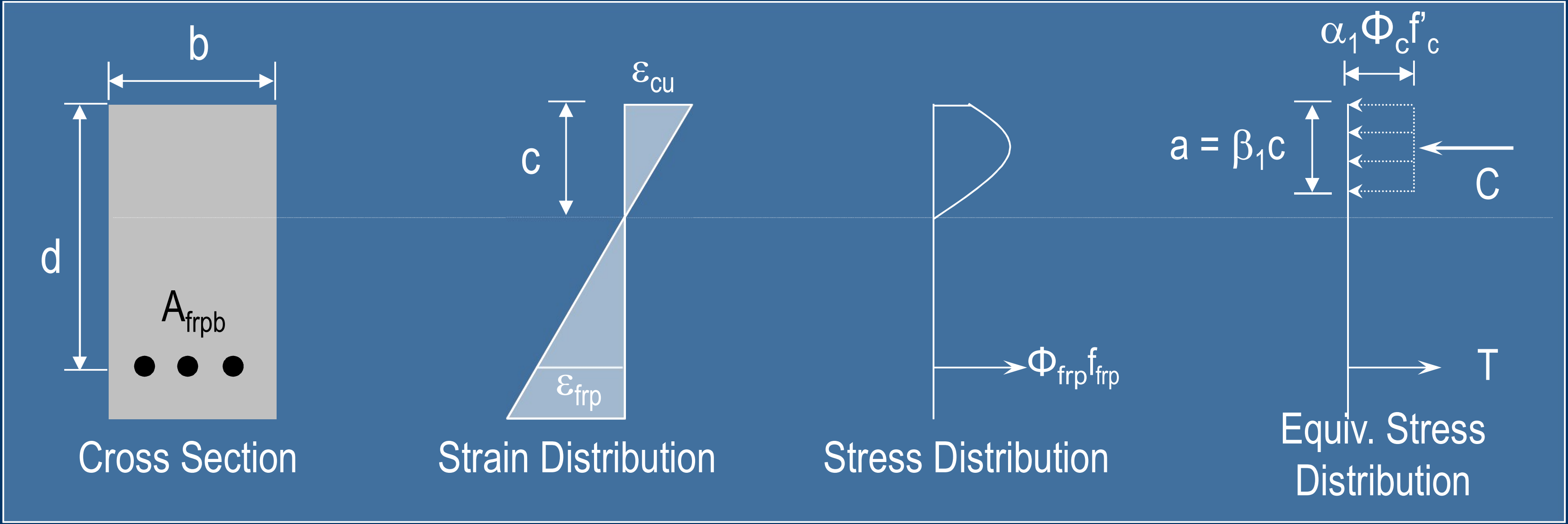
$$\frac{\varepsilon_{frp}}{\varepsilon_{cu}} = \frac{d-c}{c}$$

$$\varepsilon_{frp} = \varepsilon_{cu} \frac{\beta_1 d - \beta_1 c}{\beta_1 c}$$

$$f_{frp} = E_{frp} \varepsilon_{cu} \frac{\beta_1 d - a}{a}$$

Design for Flexure

Compression Failure

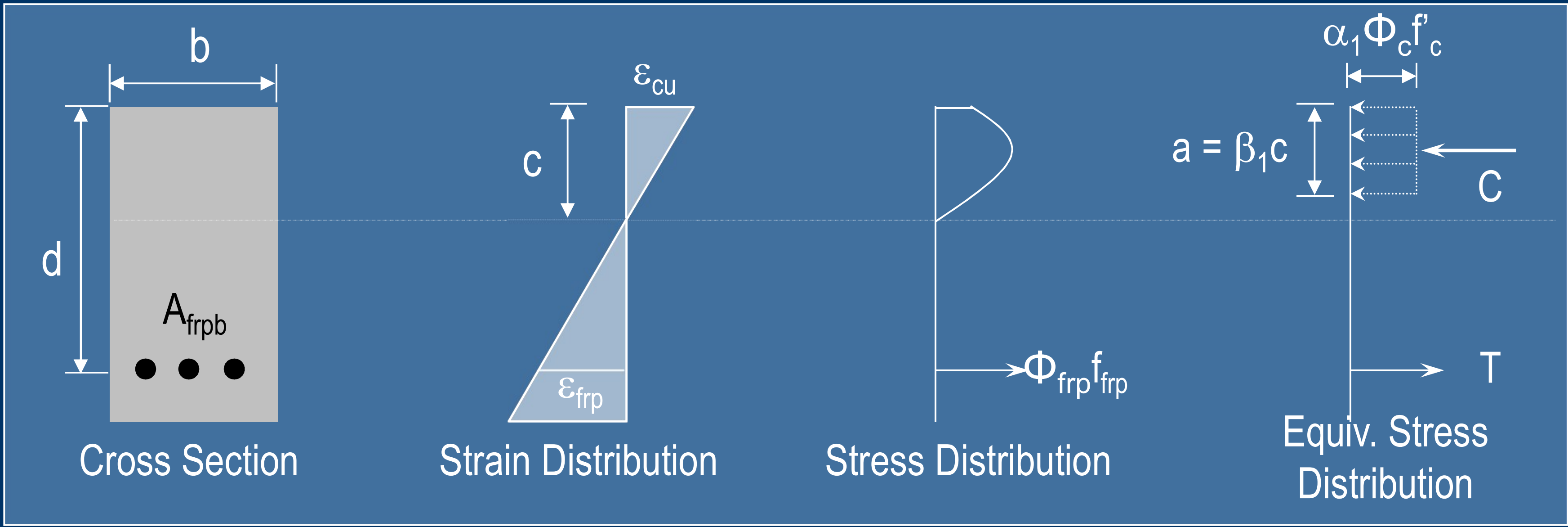


Derivation: Substitution to obtain f_{frp} implicitly

$$f_{frp} = 0.5 E_{frp} \varepsilon_{cu} \left(\left(1 + \frac{4 \alpha_1 \beta_1 \phi_c f'_c}{\rho_{frp} f_{frp} E_{frp} \varepsilon_{cu}} \right)^{1/2} - 1 \right)$$

Design for Flexure

Compression Failure

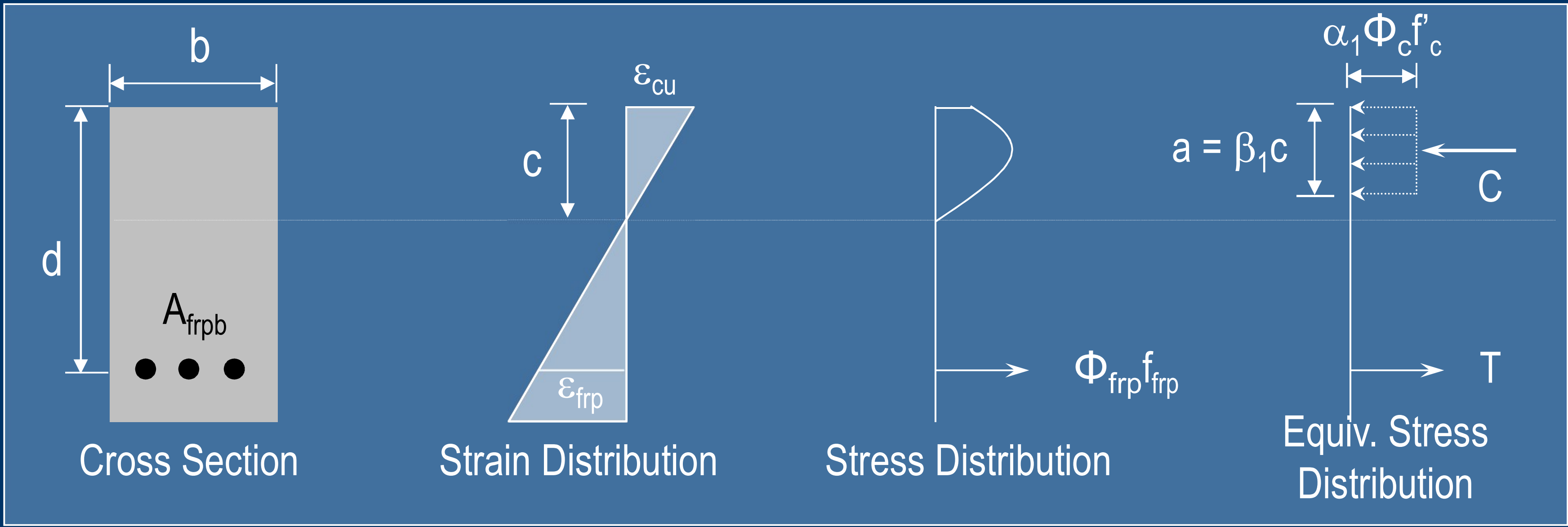


Step 4: Solve for f_{frp} using previous equation

Step 5: Solve for *a* using previous equation

Design for Flexure

Compression Failure

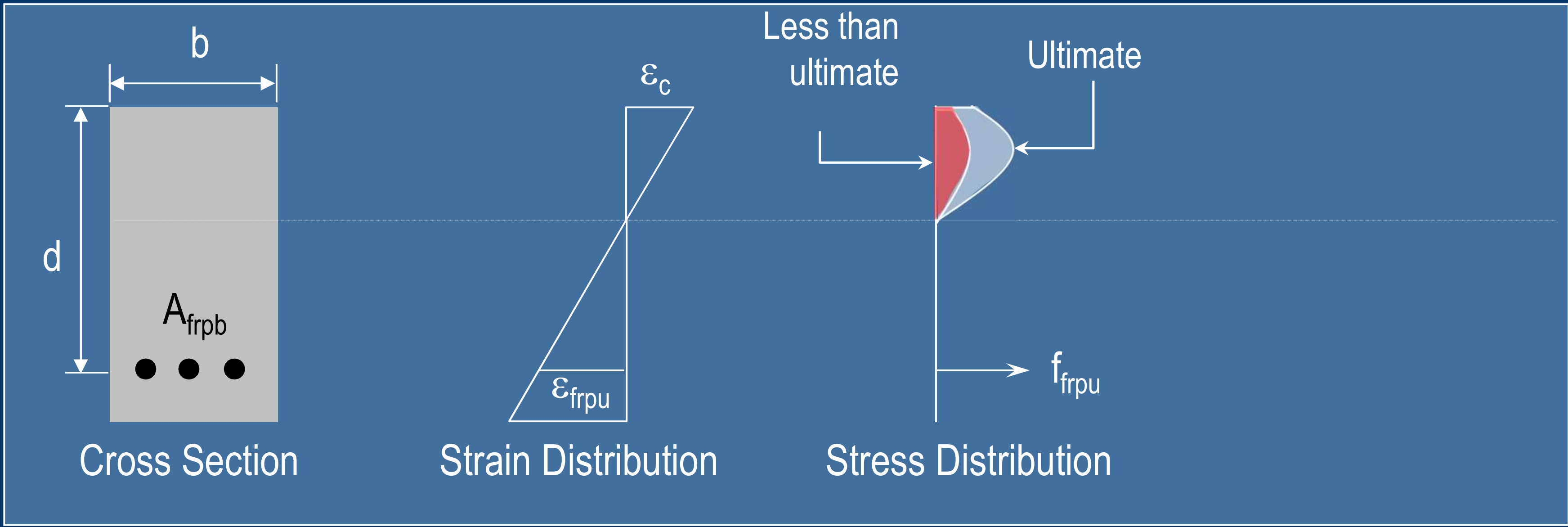


Step 6: Solve M_r

$$M_r = \phi_{frp} A_{frp} f_{frp} \left(d - \frac{a}{2} \right)$$

Design for Flexure

Tension Failure



Objective: Solve for moment resistance of section (M_r)

Step 1: Strains

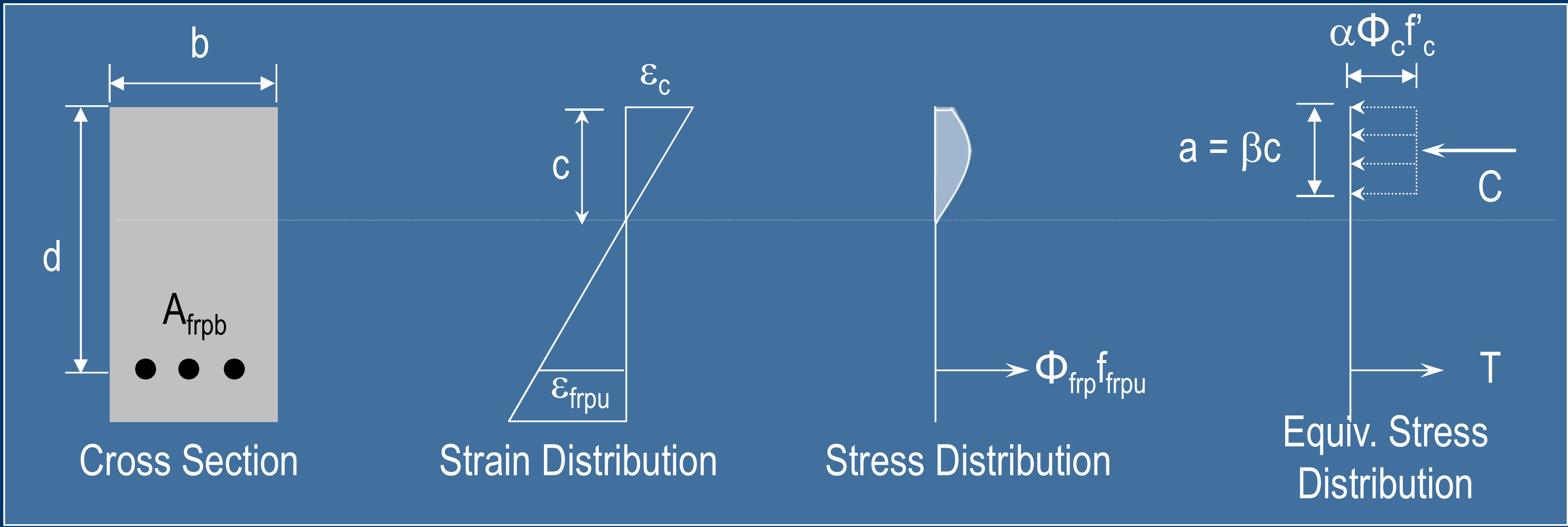
Concrete: $\varepsilon_c < \varepsilon_{cu}$

Stress block parameters don't apply!

FRP: $\varepsilon_{frp} = \varepsilon_{frpu} = f_{frpu}/E_{frp}$

Design for Flexure

Tension Failure



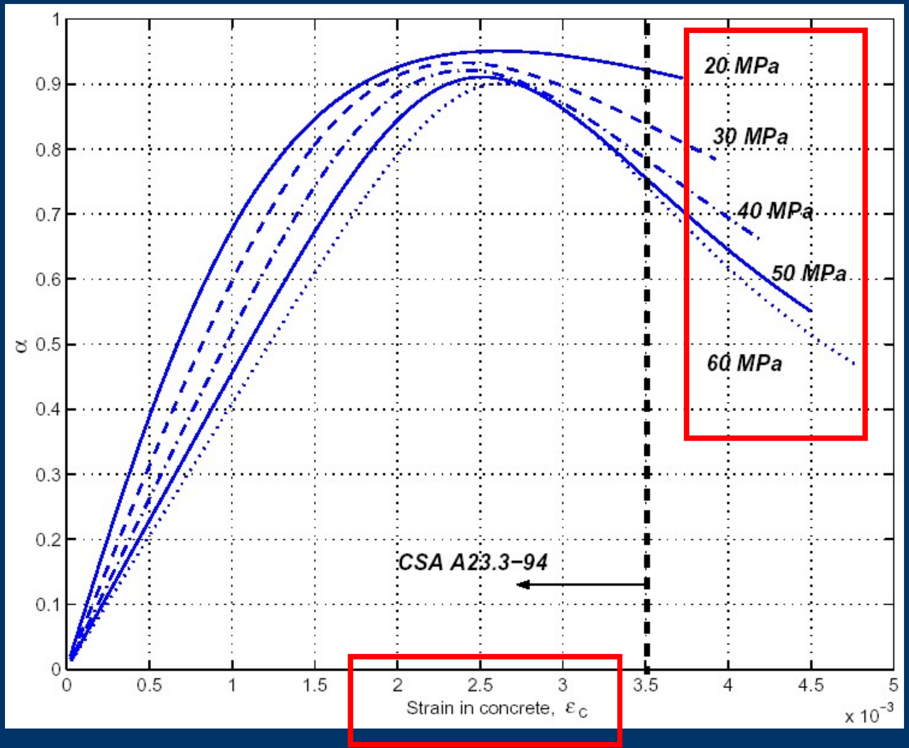
Step 2: Assume neutral axis depth, c

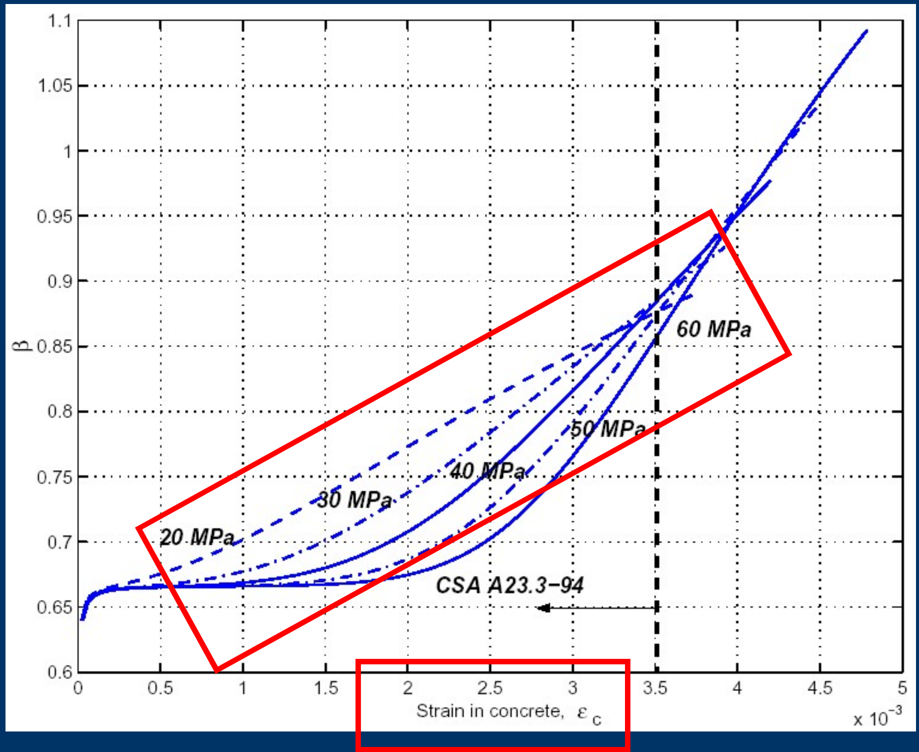
Step 3: Determine modified stress block parameters

α & β → *From tabulated values or figures in ISIS Manual No. 3*

Design for Flexure

Tension Failure

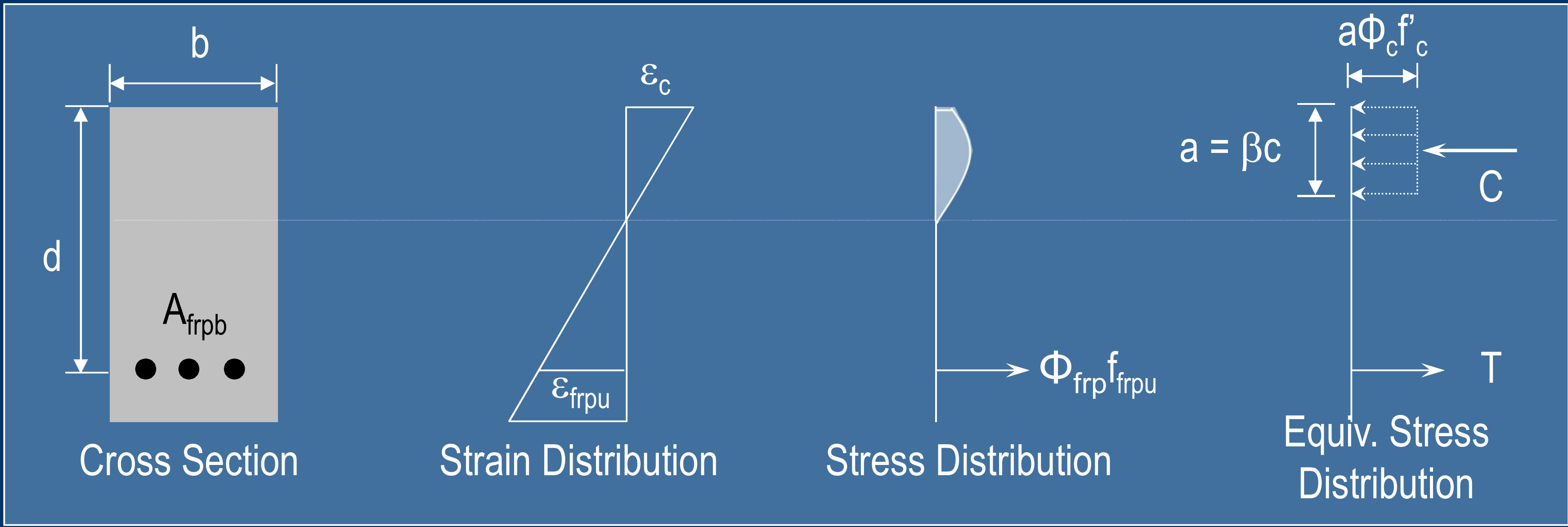




α & β —
- Concrete strain, ε_c
- Concrete strength, f'_c

Design for Flexure

Tension Failure



<u>Step 4</u>: Apply equilibrium

$$T = C$$

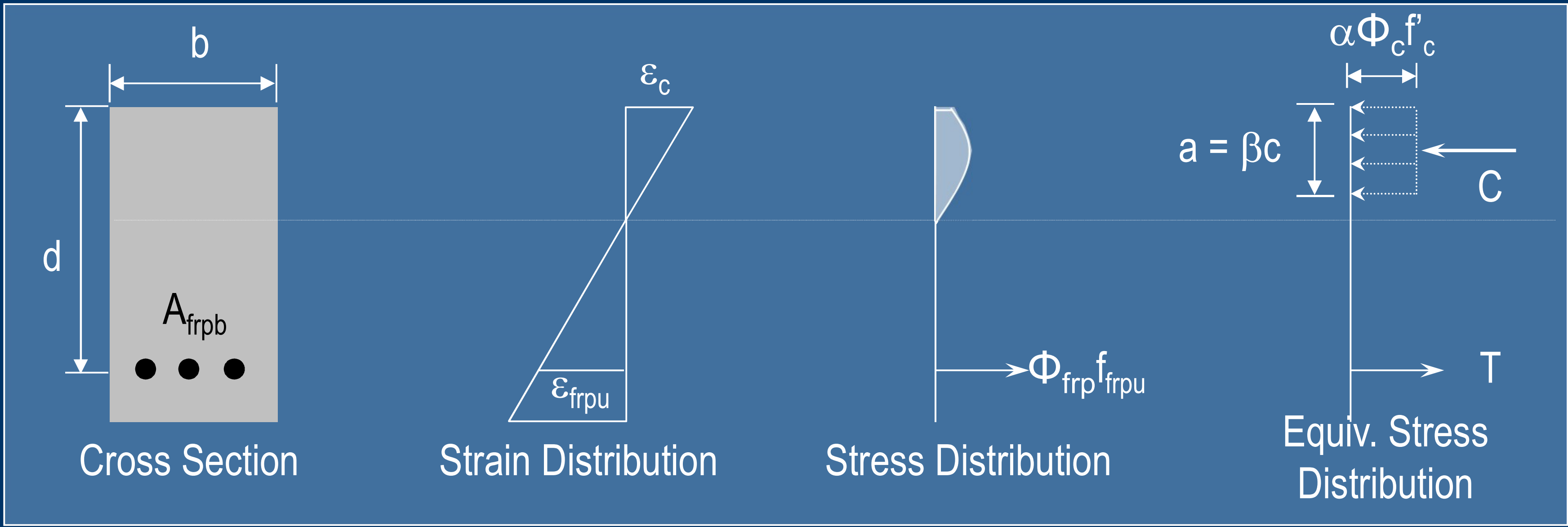
$f_{frp} A_{frp} (\varepsilon_{frpu} E_{frp})$

$f_c\,(\,\alpha\, f'_c)\,(\beta\, c)\,b$

Substitute assumed ***c***

Design for Flexure

Tension Failure



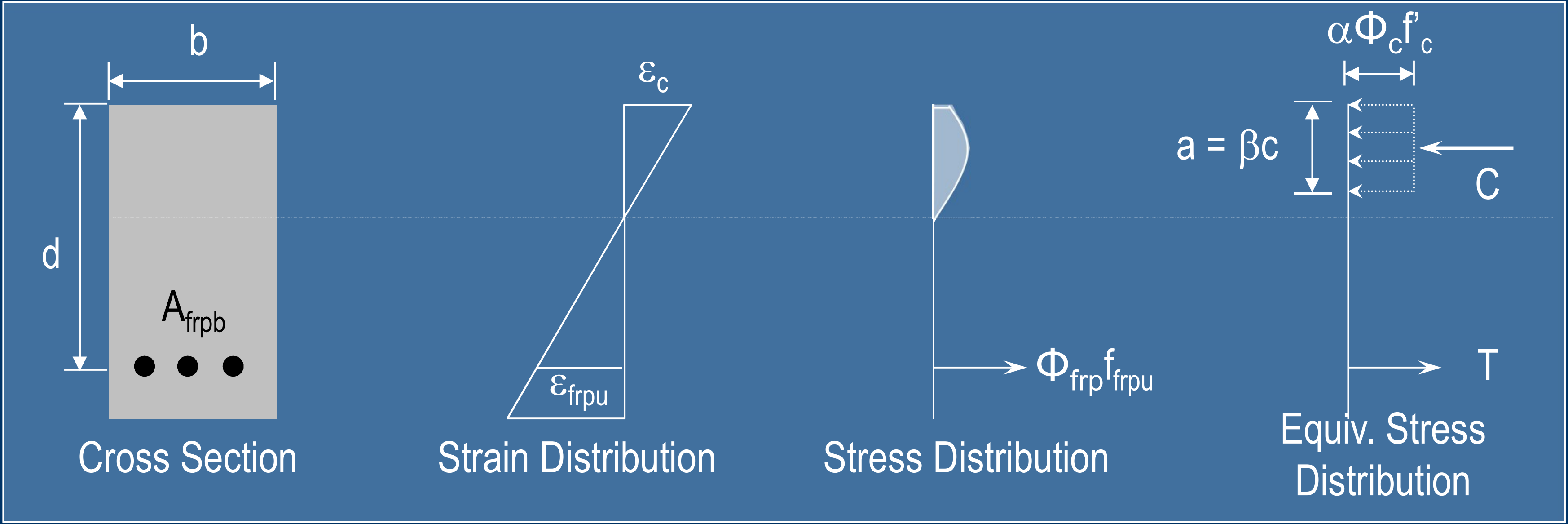
Step 4: Apply equilibrium

$$T = C$$

If this equation is not satisfied, select a new neutral axis depth (c) and iterate

Design for Flexure

Tension Failure



Step 4: Apply equilibrium

Select new *c* from:

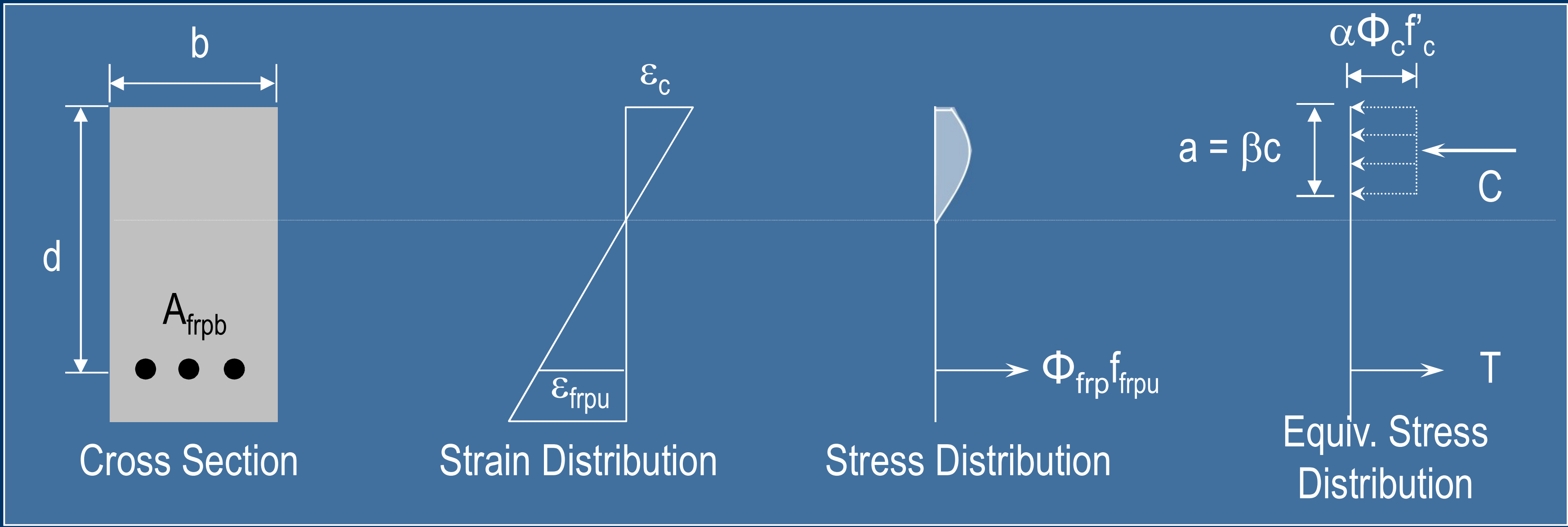
$$c = \frac{\phi_{frp} A_{frp} E_{frp} \varepsilon_{frpu}}{\phi_c (\alpha f'_c)\, \beta\, b}$$

Re-calculate α and β based on new *c*

Check equilibrium

Design for Flexure

Tension Failure

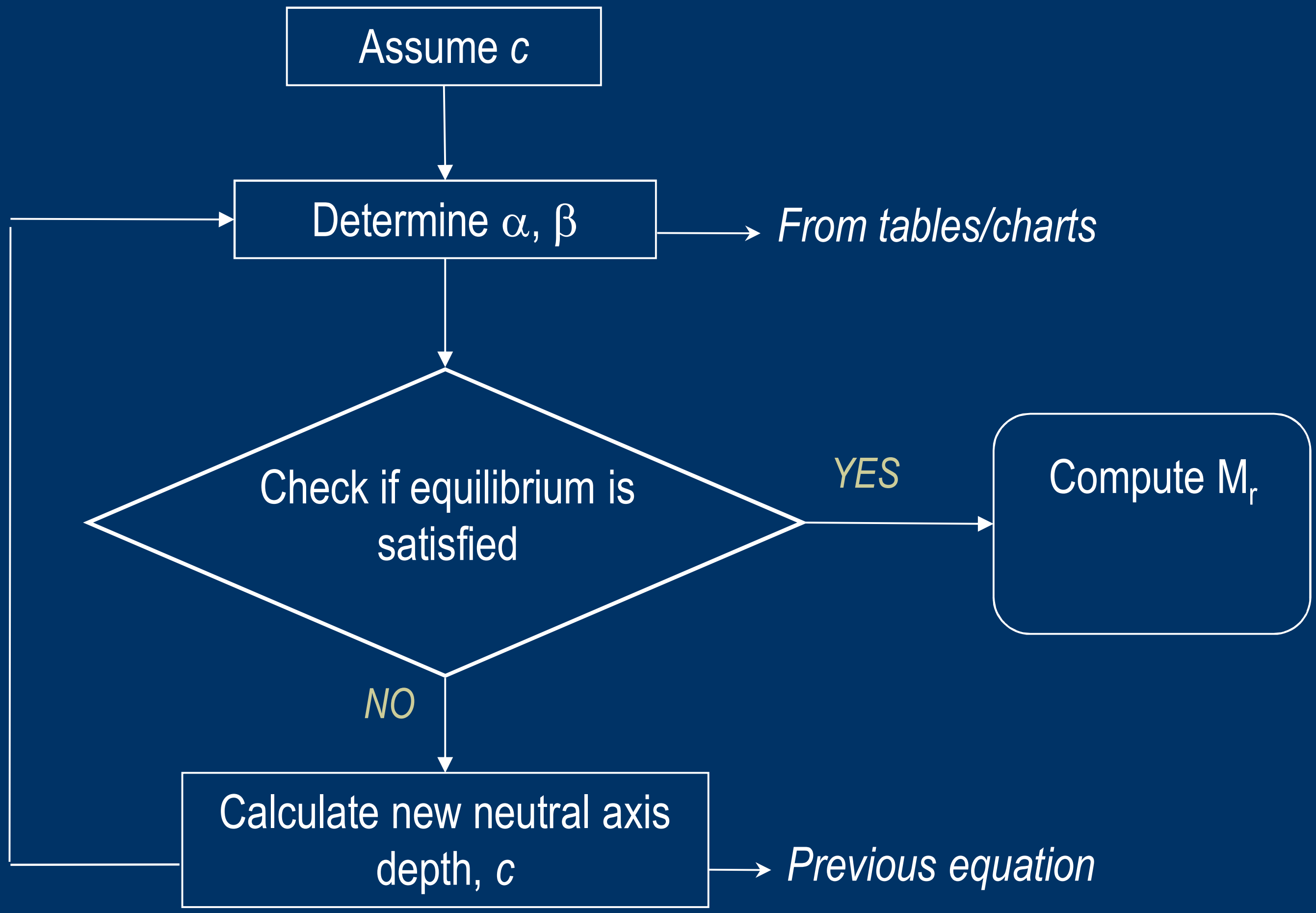


<u>Step 5</u>: Solve M_r

$$M_r = \phi_{frp} A_{frp} f_{frpu} \left(d - \frac{\beta c}{2} \right)$$

Design for Flexure

To summarize:



Design for Flexure

To avoid sudden failure immediately after cracking:

$$M_r > 1.5\, M_{cr} \quad \Rightarrow \quad M_{cr} = \frac{f_r\, I_t}{y_t}$$

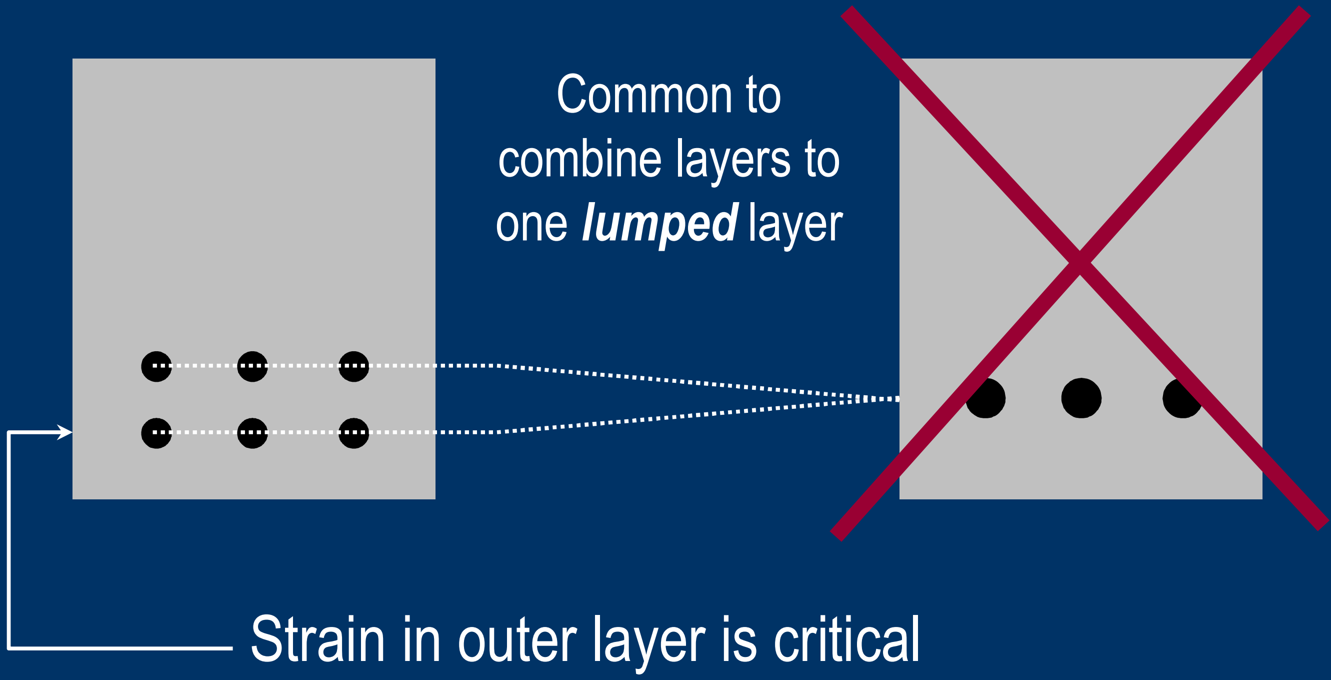
To meet minimum reinforcement requirements:

$$A_{frp\ min} = \frac{5 \sqrt{f'_c}}{12\, f_{frpu}} (bd)$$

Design for Flexure

Addl. Considerations

Beams with FRP reinforcement in multiple layers



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

Design for Flexure

Beams with FRP compression reinforcement

FRPs are generally weak in compression

↓

Neglect their compressive contribution to flexural strength

Serviceability

General

- Flexural design with FRPs is a function of:

Strength

required to resist applied loads

Serviceability

required to minimize cracking & deflection

$E_{frp} < E_{steel}$

Allows for large cracks & deflections

In many cases, controls design of FRP-reinforced members

Serviceability

- Why must cracking be controlled?

Steel RC members

- Aesthetics
- Prevent corrosion

FRP RC members

- Aesthetics
- Control sustained stresses (creep rupture)

Serviceability

- To control cracking, ISIS Canada guidelines currently suggest:

$$\varepsilon_{frps} \leq 0.002$$

FRP strain under sustained load

Serviceability

- To calculate strain at service load levels:

$M_{service} < M_{cr}$:	Use transformed section I
$M_{service} > M_{cr}$:	Use effective I

- Note: if crack width at service is required:

See §7.3.1 of ISIS Design Manual No. 3

Serviceability

- For steel-RC members, CSA A23.3-94 recommends span (l_n) to depth (*h*) ratios

	Minimum thickness (*h*)			
	Simply supported	One end cont.	Both ends cont.	Cantilever
One-way slabs	$l_n/20$	$l_n/24$	$l_n/28$	$l_n/10$
Beams	$l_n/16$	$l_n/18.5$	$l_n/21$	$l_n/8$

Serviceability

- This value (l_n/h) can be modified to be applied to an FRP-RC member

$$\left(\frac{l_n}{h}\right)_{frp} = \left(\frac{l_n}{h}\right)_{Steel} \left(\frac{\varepsilon_s}{\varepsilon_{frp}}\right)^{\alpha_d}$$

l_n = member span

h = member thickness

ε_s = maximum strain allowed in steel at service

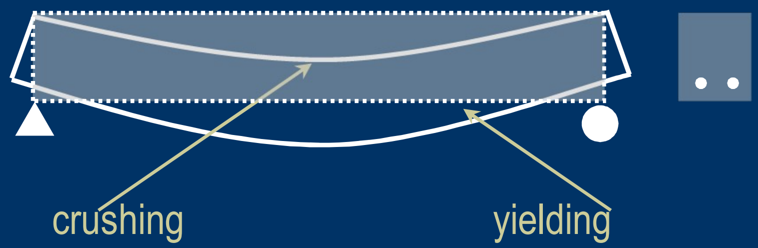
ε_{frp} = maximum strain allowed in FRP at service

α_d = coefficient = 0.5 for rectangular section

Deformability

Steel-RC members

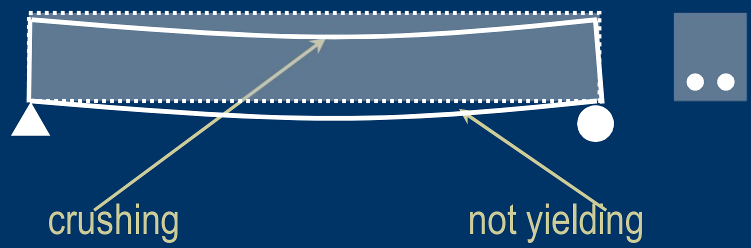
$\rho < \rho_{bal}$



Ductile behaviour

A lot of curvature
before failure

$\rho > \rho_{bal}$

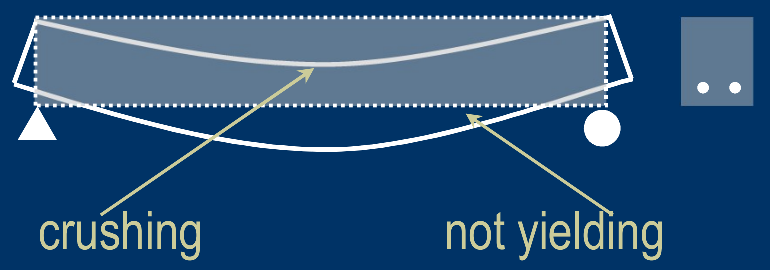


Over reinforced

Less deformation
before failure

Deformability

FRP-RC members



FRPs will not yield

A lot of curvature before failure → Because $E_{frp} < E_{steel}$

Important to check deformability of FRP-RC members

Deformability

FRP-RC members

* ψ = curvature

$$\psi_{service} << \psi_{ultimate}$$

Deformability factor (*DF*):

$$DF = \left(\frac{\psi_u M_u}{\psi_s M_s} \right)$$

Curvature and moment at **ultimate** conditions

Curvature and moment at **service** conditions (ε_{frps} = 0.002)

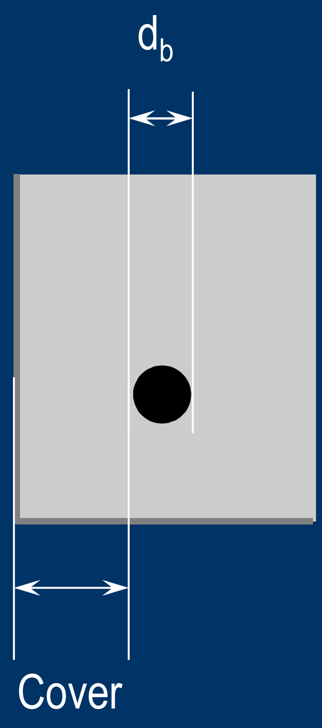
ISIS currently requires:

$DF \geq 4 \longrightarrow$ rectangular and T-beams in flexure

Spacing and Cover

Concrete Cover

- Adequate cover required to:
  - Prevent cracking due to thermal expansion
  - Prevent swelling from moisture ingress
  - Protect reinforcement from fire



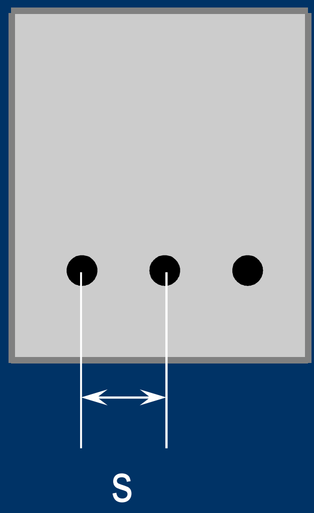
Exposure	Beams	Slabs
Interior	$2.5d_b$ or 40 mm	$2.5d_b$ or 20 mm
Exterior	$2.5d_b$ or 50 mm	$2.5d_b$ or 30 mm

Spacing and Cover

- Adequate bar spacing required to:
  - Allow for easy placement of concrete
  - Prevent temperature cracking

Minimum "s"
1.4 d_b
1.4·max. aggregate size
30 mm
concrete cover

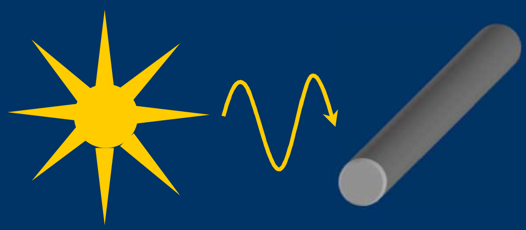
Maximum "s"
$5h_{slab}$
500 mm

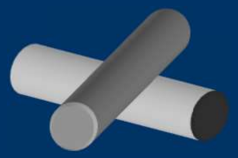


Spacing and Cover

Constructability

- When designing with FRPs:
  - Protect FRPs against UV radiation
  - Store and handle each FRP product carefully
  - Avoid contact between carbon FRPs and steel (galvanic corrosion)
  - Tie FRP bars to formwork (with plastic ties) to prevent floating during concrete pour
  - Avoid damaging FRP bars during concrete vibration by using a plastic protected vibrator





Additional Topics

- Development length of FRP bars depends on:
  - Bar diameter
  - Bar shape
  - Surface condition
  - Embedment length

Differs depending on FRP type

↓

Check manufacturer specifications

Additional Topics

- Flexural design aids are available

What: Series of charts to aid in design of rectangular sections with 1-layer of reinforcement

Where: In Chapter 10 of ISIS Design Manual No. 3

Why: Use of charts will satisfy both serviceability and ultimate limit states requirements

Additional Topics

- FRP as shear reinforcement has successfully been used in field applications

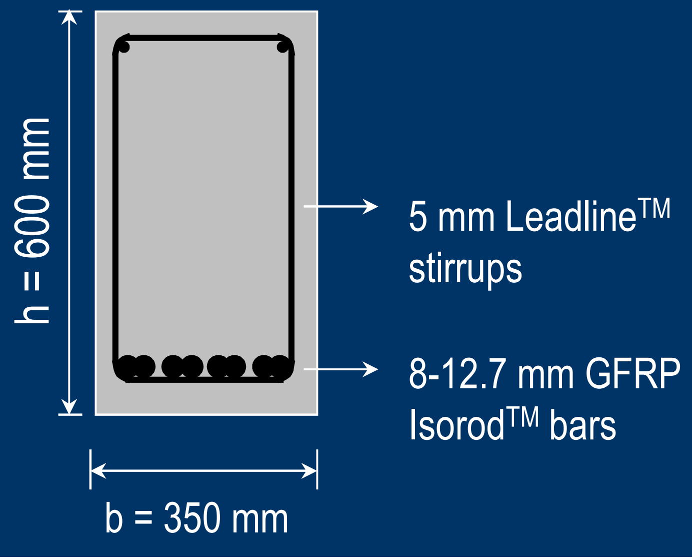
Examples

Example 1

Problem statement

Calculate the moment resistance (M_r) for a precast FRP-reinforced concrete section

Section information



Interior exposure

f'_c = 35 MPa

f_{frpu} = 617 MPa

E_{frp} = 42 GPa

A_{bar} = 129 mm^2

Example 1

Solution

Step 1: Concrete cover and effective depth

Cover to main reinforcement equals the greater of:

- $2.5d_b = 2.5(12.7)$
  $= 32$ mm
- 40 mm

Effective depth, $d = h - \text{cover} - d_b/2$

$= 600 - 40 - 12.7/2$

$= 554$ mm

Solution

Step 2: Calculate FRP reinforcement ratio

$$\rho_{frp} = \frac{A_{frp}}{b\ d}$$

$$\rho_{frp} = \frac{(8 \times 129)}{350\ (554)}$$

$$\rho_{frp} = 0.00532$$

Solution

Step 3: Calculate balanced FRP reinforcement ratio

$$\rho_{frpb} = \frac{A_{frpb}}{b\,d} = \alpha_1\beta_1 \frac{\Phi_c}{\Phi_{frp}} \frac{f'_c}{f_{frpu}} \left(\frac{\varepsilon_{cu}}{\varepsilon_{cu} + \varepsilon_{frpu}} \right)$$

$\alpha_1 = 0.85\text{-}0.0015f'_c \geq 0.67$

$\beta_1 = 0.97\text{-}0.0025f'_c \geq 0.67$

$\varepsilon_{frpu} = f_{frpu}/E_{frp}$

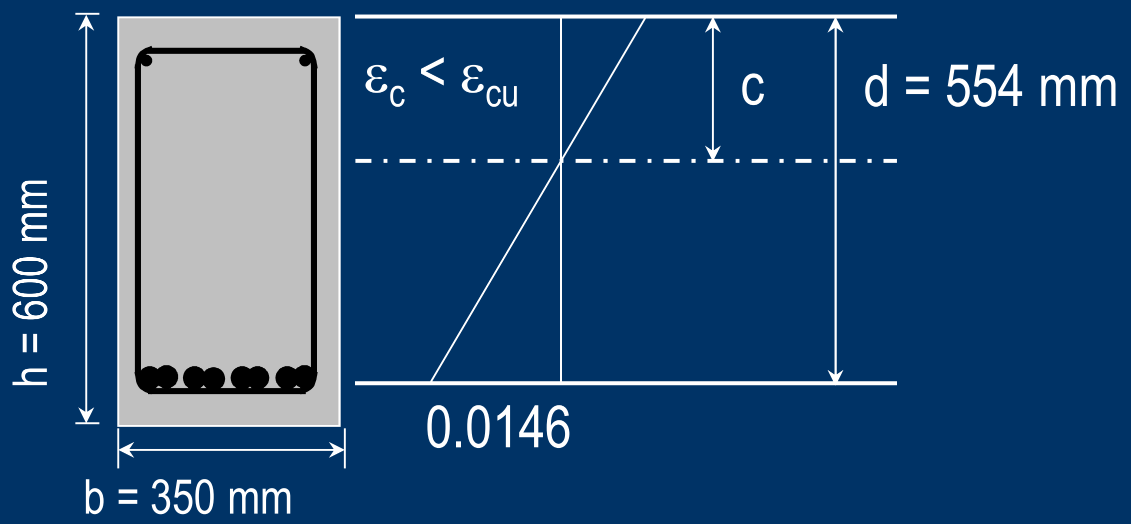
$$\rho_{frpb} = 0.8\,(0.88) \frac{0.65}{0.40} \frac{35}{617} \left(\frac{0.0035}{0.0035 + 0.0146} \right) = 0.0125$$

Solution

Step 4: Determine failure mode

Compression ? Tension

$\rho_{frp} = 0.532\ \% < \rho_{frpb} = 1.250\ \%$



Examples

Example 1

Solution

Step 5: Perform iterative strain-compatibility analysis

Assume c = 50mm

Calculate ε_c:

$$\frac{\varepsilon_c}{c} = \frac{\varepsilon_{frpu}}{d - c} \Rightarrow \frac{\varepsilon_c}{50} = \frac{0.0146}{554 - 50} \Rightarrow \varepsilon_c = 1448 \times 10^{-6}$$

Calculate T:

$$T = \phi_{frp} f_{frpu} A_{frp} \Rightarrow T = 0.4\ (617)\ (8 \times 129) \Rightarrow T = 255000\ N$$

$$= 255\ kN$$

Calculate C: Strains at the extreme compression fibre are less than ultimate, thus equivalent rectangular stress block factors, α and β, must be used

Solution

Step 5: Perform iterative strain-compatibility analysis

Calculate C:

From previous figures

↓

When $\varepsilon_c = 1448 \times 10^{-6}$

And $f'_c = 35$ MPa

↓

Interpolation provides:

$\alpha = 0.75$ $\beta = 0.69$

Solution

Step 5: Perform iterative strain-compatibility analysis

Calculate C: $C = \alpha\ \phi_c f'_c \beta\ c\ b$ → $C = 0.75\ (0.65)\ (35)\ (0.69)\ (50)\ (350)$

→ $C = 206000\ N = 206\ kN$

Check for equilibrium: $C = 206\ kN$ < $T = 255\ kN$

Therefore reiterate

Solution

Step 5: Perform iterative strain-compatibility analysis

Assume c = 57 mm

Calculate ε_c: $\frac{\varepsilon_c}{57} = \frac{0.0146}{554 - 57}$ → $\varepsilon_c = 1674 \times 10^{-6}$

Calculate T: T = 0.4 (617) (8 x 129) → T = 255000 N = 255 kN

Calculate C: Previous figures give: $\alpha = 0.8$ $\beta = 0.69$

C = 0.80 (0.65) (35) (0.69) (72) (350)

C = 251000 N = 251 kN

Solution

Step 5: Perform iterative strain-compatibility analysis

Check for equilibrium: $C = 251\ kN \approx T = 255\ kN$

Examples

Example 1

Solution

Step 6: Calculate moment capacity

$$M_r = \phi_{frp} A_{frp} f_{frpu} \left(d - \frac{\beta c}{2} \right)$$

$$M_r = 0.4\ (8 \text{ x } 129)\ (617) \left(554 - \frac{0.69 \text{ x } 57}{2} \right)$$

$$M_r = 136.1 \times 10^6 \text{ N}\cdot\text{ mm} = 136.1 \text{ kN}\cdot\text{ m}$$

Solution

Step 7: Check minimum flexural capacity requirements

$M_r > 1.5M_{cr}$

$$M_{cr} = \frac{f_r I_t}{y_t}$$

f_r → Modulus of rupture = $0.6\sqrt{f'_c}$

I_t → Transformed section I

y_t → Distance from transformed N.A. to extreme tension fibre in tension = 298 mm

$M_{cr} = 74 \times 10^6$ N· mm = 74.0 kN· m

Solution

Step 7: Check minimum flexural capacity requirements

$$M_r > 1.5M_{cr}$$

$$M_r > 1.5(74.0)$$

$$M_r > 111 \text{ kN}\cdot\text{m} \qquad \textit{OK}$$

***The beam is adequate with respect to strength, but may not satisfy serviceability requirements for cracking and deflection*

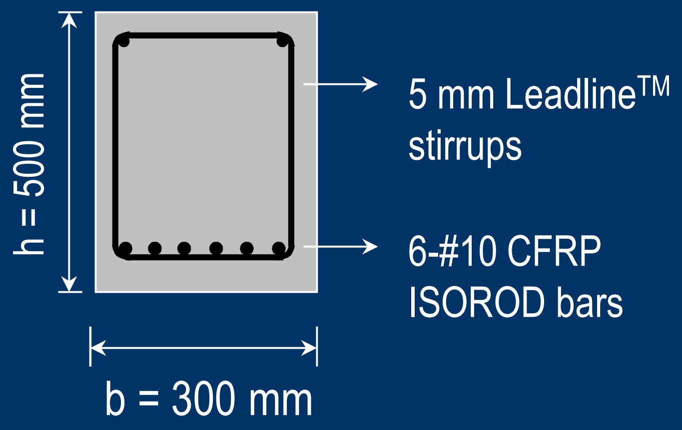
Examples

Example 2

Problem statement

Calculate the moment resistance (M_r) for a precast FRP-reinforced concrete section

Section information



Interior exposure

f_{frpu} = 1596 MPa

f'_c = 35 MPa

E_{frp} = 111 GPa

A_{bar} = 71 mm^2

d_{bar} = 9.3 mm

Solution

Step 1: Concrete cover and effective depth

Cover to the flexural reinforcement equals the greater of:

- $2.5d_b = 2.5\ (9.3) = 23$ mm
- 40 mm

Effective depth, $d = h - \text{cover} - d_b/2$

$= 500 - 40 - 9.3/2$

$= 455$ mm

Solution

Step 2: Calculate FRP reinforcement ratio

$$\rho_{frp} = \frac{A_{frp}}{b\ d}$$

$$\rho_{frp} = \frac{(6 \times 71)}{300 \times 455}$$

$$\rho_{frp} = 0.00312$$

Examples

Example 2

Solution

Step 3: Calculate balanced FRP reinforcement ratio

$$\rho_{frpb} = \frac{A_{frpb}}{b\,d} = \alpha_1 \beta_1 \frac{\Phi_c}{\Phi_{frp}} \frac{f'_c}{f_{frpu}} \left(\frac{\varepsilon_{cu}}{\varepsilon_{cu} + \varepsilon_{frpu}} \right)$$

$$\alpha_1 = 0.85\text{-}0.0015f'_c \geq 0.67$$

$$\beta_1 = 0.97\text{-}0.0025f'_c \geq 0.67$$

$$\varepsilon_{frpu} = f_{frpu}/E_{frp}$$

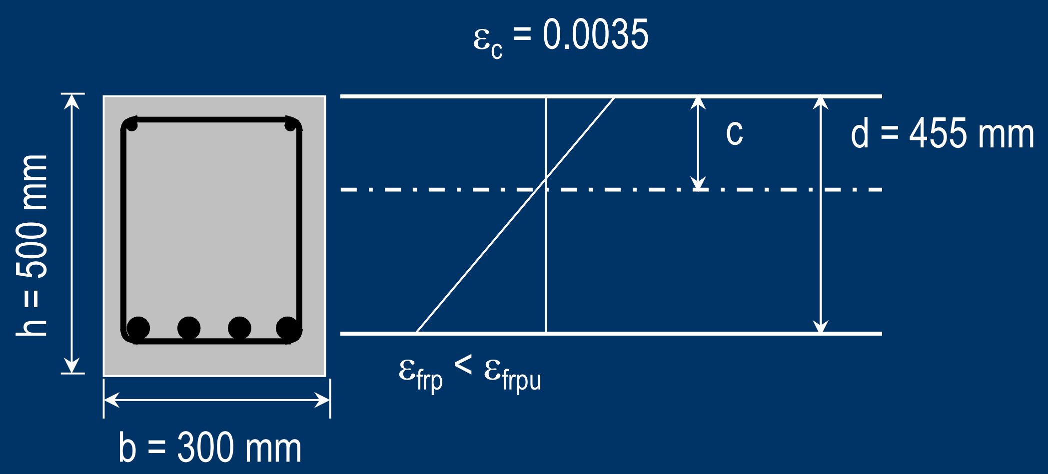
$$\rho_{frpb} = 0.80\,(0.88) \frac{0.65}{0.8} \frac{35}{1596} \left(\frac{0.0035}{0.0035 + 0.0144} \right) = 0.00245$$

Solution

Step 4: Determine failure mode

Compression ? Tension

$$\rho_{frp} = 0.312\% > \rho_{frpb} = 0.245\%$$



Examples

Example 2

Solution

Step 5: Determine the tensile stress in the FRP

$$f_{frp} = 0.5E_{frp}\varepsilon_{cu}\left[\left(1 + \frac{4\alpha_1\beta_1\phi_c f'_c}{\rho_{frp} f_{frp} E_{frp}\varepsilon_{cu}}\right)^{1/2} - 1\right]$$

$$f_{frp} = 0.5\,(111000)\,(0.0035)\left[\left(1 + \frac{4\,(0.80)\,(0.88)\,(0.65)\,(35)}{3.12\times10^{-3}\,(0.8)\,(111000)\,(0.0035)}\right)^{1/2} - 1\right]$$

f_{frp} = 1396 MPa

Solution

Step 6: Determine stress block depth, a

$$a = \frac{\phi_{frp} A_{frp} f_{frp}}{\phi_c (\alpha_1 f'_c)\, b}$$

$$a = \frac{0.8\ (6 \times 71)\ (1396)}{0.79\ (0.65)\ (35)\ (300)}$$

$$a = 87 \text{ mm}$$

Solution

Step 7: Calculate flexural capacity

$$M_r = \phi_{frp} A_{frp} f_{frp} \left(d - \frac{a}{2} \right)$$

$$M_r = 0.8\,(6 \times 71)\,(1396) \left(455 - \frac{87}{2} \right)$$

$$M_r = 196 \times 10^6 \text{ N} \cdot \text{mm} = 196 \text{ kN} \cdot \text{m}$$

Solution

Step 8: Check minimum flexural capacity requirements

$M_r > 1.5M_{cr}$

$$M_{cr} = \frac{f_r I_t}{y_t}$$

f_r → Modulus of rupture = $0.6\sqrt{f'_c}$

I_t → Transformed $I = 3.199 \times 10^9\ mm^4$

y_t → Distance from transformed N.A. to extreme tension fibre in tension = 248 mm

$M_{cr} = 45.8 \times 10^6 = 45.8\ kN \cdot m$

Solution

Step 8: Check minimum flexural capacity requirements

$$M_r > 1.5M_{cr}$$

$$M_r > 1.5\ (45.8)$$

$$M_r > 68.7\ kN \cdot m \quad \textit{OK}$$

***The beam is adequate with respect to strength, but may not satisfy serviceability requirements for cracking and deflection*

Case Studies

Taylor Bridge

Headingley, Manitoba
Opened 1998
165.1 metre span
2-lanes

Case Studies

Taylor Bridge

Flexural reinforcement

*** Taylor Bridge uses PRESTRESSED flexural FRP reinforcement**

Tokyo Rope to **pretension** 2 girders

Leadline™ to **pretension** 2 girders

Case Studies

Taylor Bridge

Shear reinforcement

Epoxy coated steel bar stirrups in 2 girders

Leadline™ carbon FRP stirrups in 2 girders

Case Studies

Bridge during construction

Case Studies

Taylor Bridge

Placement of the deck slab concrete

Case Studies

Taylor Bridge

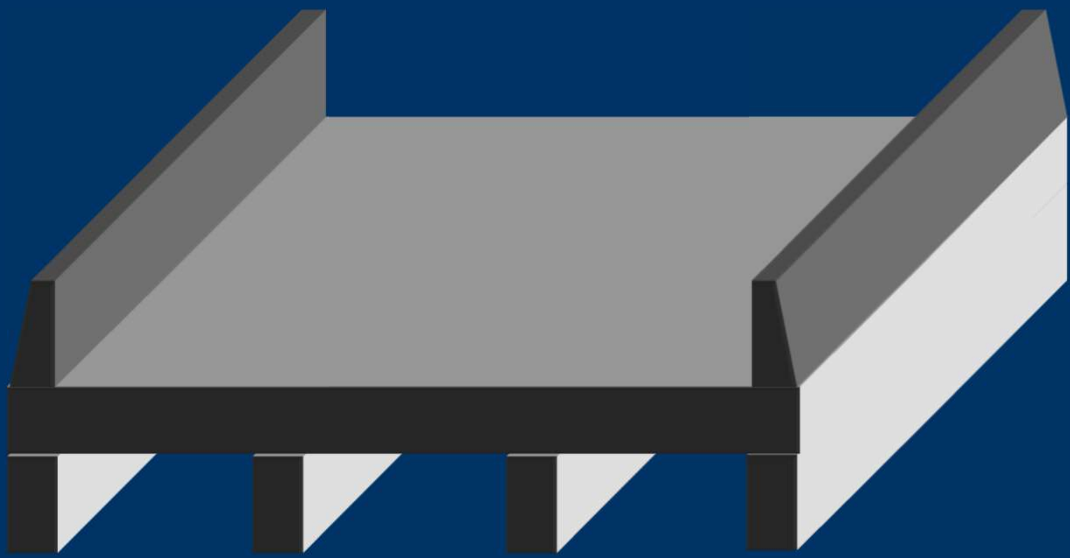
Fibre optic sensors

Strain gauges

Monitor long-term behaviour

Compare FRPs with conventional materials

Sensing system



To view live data go to www.isiscanada.com and click on "Remote Monitoring"

Case Studies

Joffre Bridge

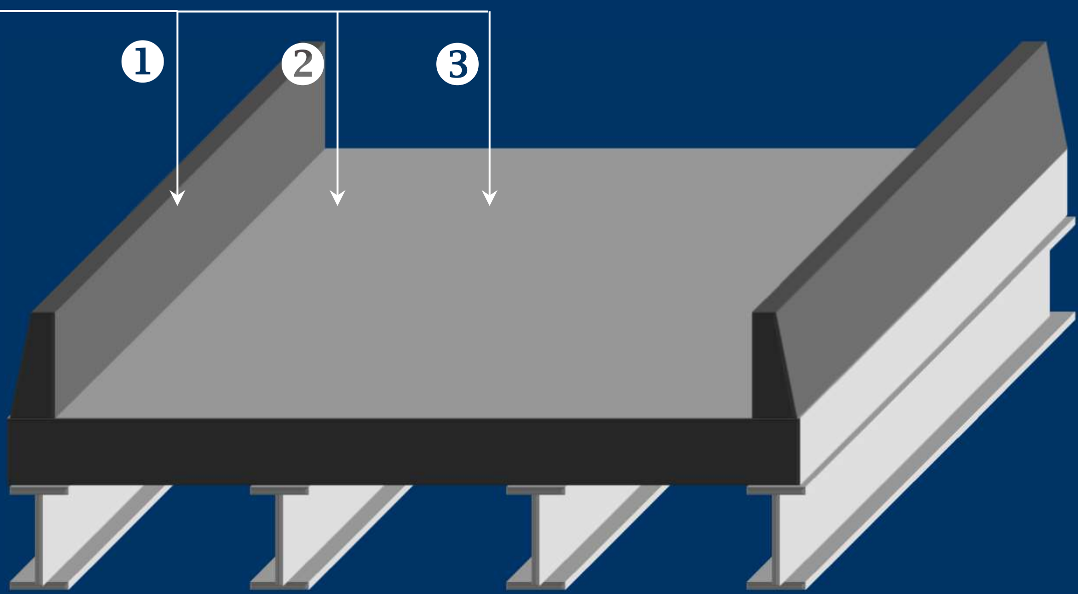
Sherbrooke, Quebec
Re-opened 1997
30.6 metre span
25 000 vehicles daily

Case Studies

Joffre Bridge

Flexural reinforcement

Portions reinforced with carbon FRPs



❶ Barrier Wall

❷ Sidewalk

❸ Deck

Case Studies

Joffre Bridge

Placement of instrumented carbon FRP deck reinforcement grids

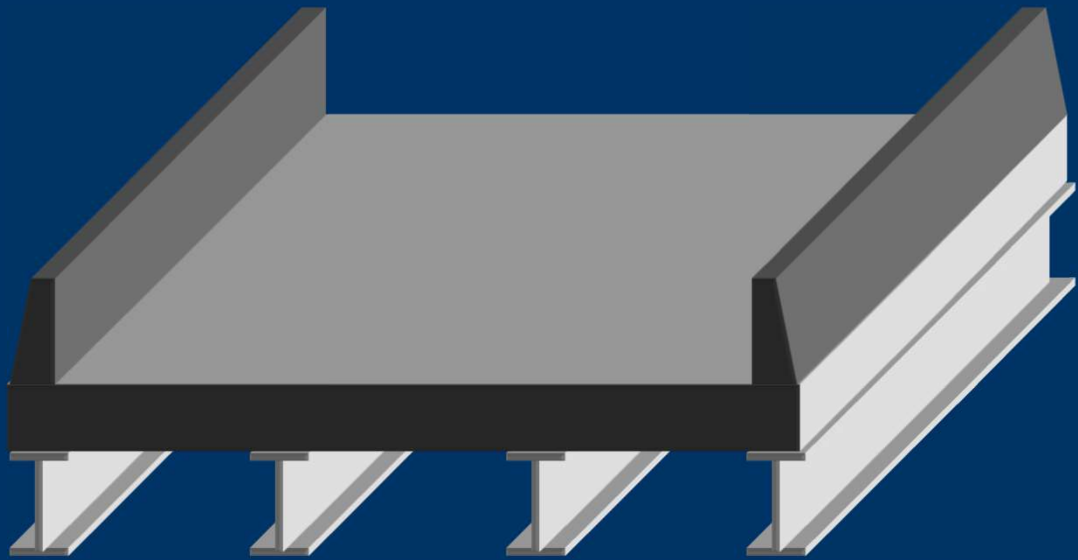
Case Studies

Joffre Bridge

Sensing system

Over 180 monitoring instruments

Measure long-term performance



Case Studies

Wotton bridge

Wotton, Quebec	
Re-opened 2001	
30.6 metre span	
ISOROD GFRP & CFRP in deck slab	

Case Studies

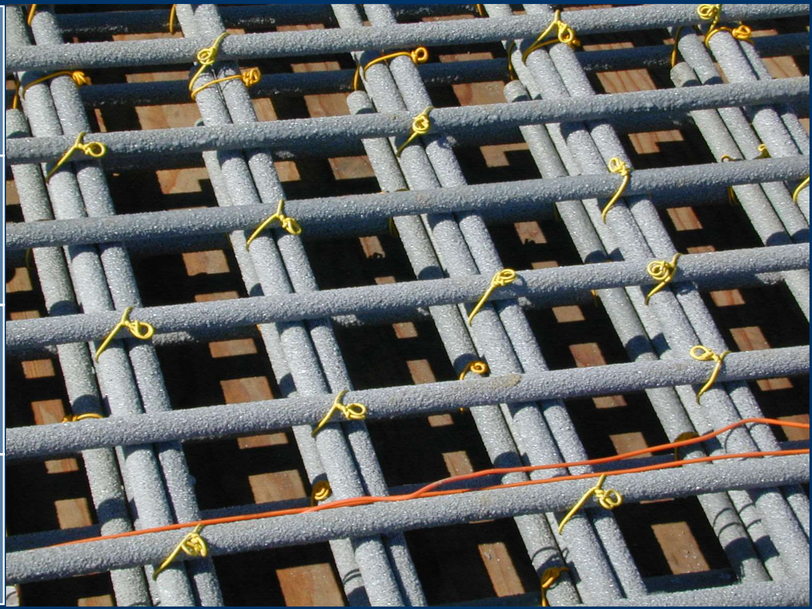
Wotton Bridge

Placement of glass FRP deck reinforcement

Case Studies

Morristown Bridge

Morristown, Vermont
Re-opened 2002
43 metre span
ISOROD GFRP in deck slab



FRP bridge deck reinforcement

Case Studies

Morristown Bridge

GFRP reinforcement for the deck slab just prior to placing the concrete

Design Guidance

Canadian codes exist for the design of FRP-reinforced concrete members

CAN/CSA-S6-00: The Canadian Highway Bridge Design Code (CHBDC)

CAN/CSA-S806-02: Design and Construction of Building Components with Fibre Reinforced Polymers