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1. Strengthening for flexure using EB-FRP

2. RC beam strengthened for flexure - Application

3. Shear strengthening using EB-FRP

4. RC beam strengthened for shear - Application

5. Confinement

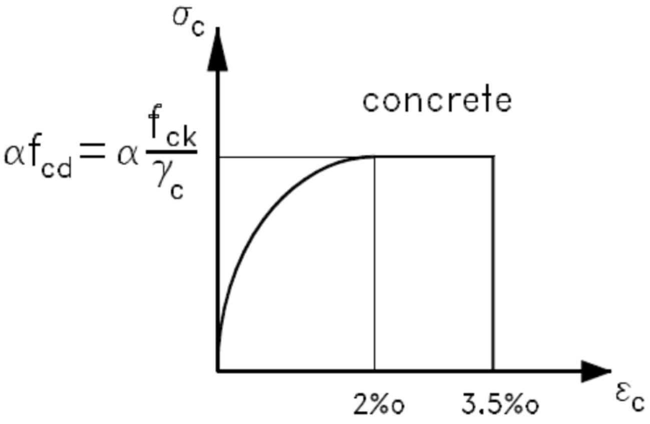
Initial situation

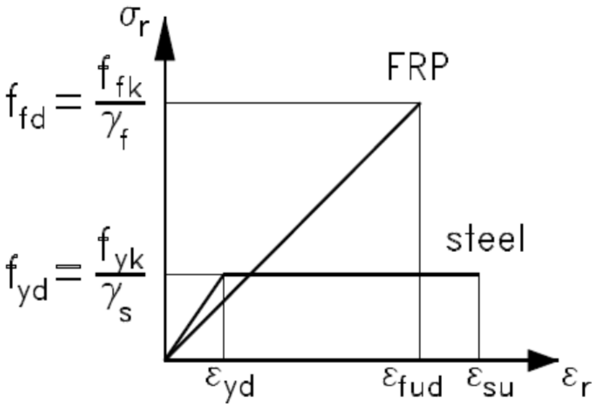
Initial load $\Rightarrow$ M_o = service moment acting during strengthening

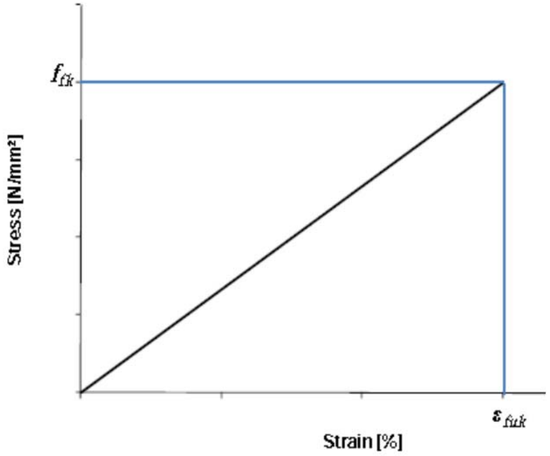
M_o is typically larger than the cracking moment M_{cr}

$\Rightarrow$ the calculation is based on a cracked section

Constitutive material models







$\gamma_c = 1.5$ - $\gamma_s = 1.15$ - $\gamma_f = 1.2$

For FRP

Serviceability Limit State (SLS)

$G + \psi_2 Q_k$ - reversible, long term effect

$$\sigma_f = E_f \varepsilon_f$$

Ultimate Limit State (ULS)

$1.35G + 1.5Q_{dominant} + 1.5\psi_{0,i} Q_{k,i}$

$$f_{fk} = E_f \varepsilon_{fuk}$$

(Stijn Matthys, Ghent University)

Failure modes – Ultimate Limit States

1. **Full composite action** of concrete and FRP is maintained until the concrete reaches crushing in compression or the FRP fails in tension (such failure modes may also be characterized as “ideal”)

2. **Composite action is lost** prior to class 1 failure, e.g. due to peeling-off or by debonding of the FRP

Failure modes – Full composite action

- Steel yielding followed by concrete crushing
- Steel yielding followed by FRP fracture

Desired

- Concrete crushing or FRP failure without steel yielding

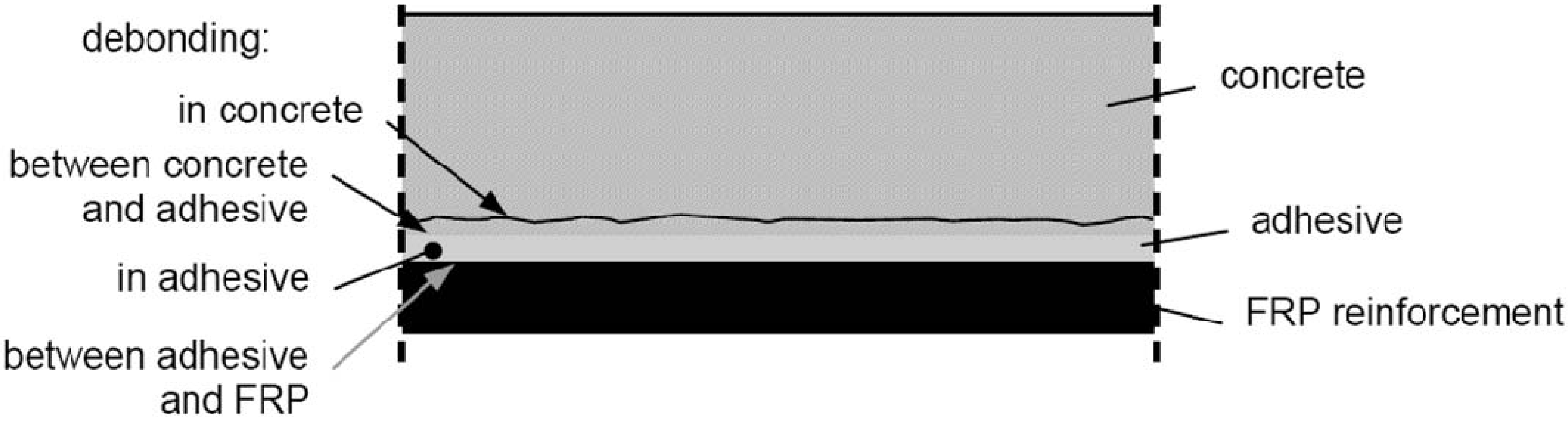
Allowed

- Rupture of steel, before concrete crushing or FRP failure

To be avoided

Failure modes – Loss of composite action

- **Debonding and bond failure modes**



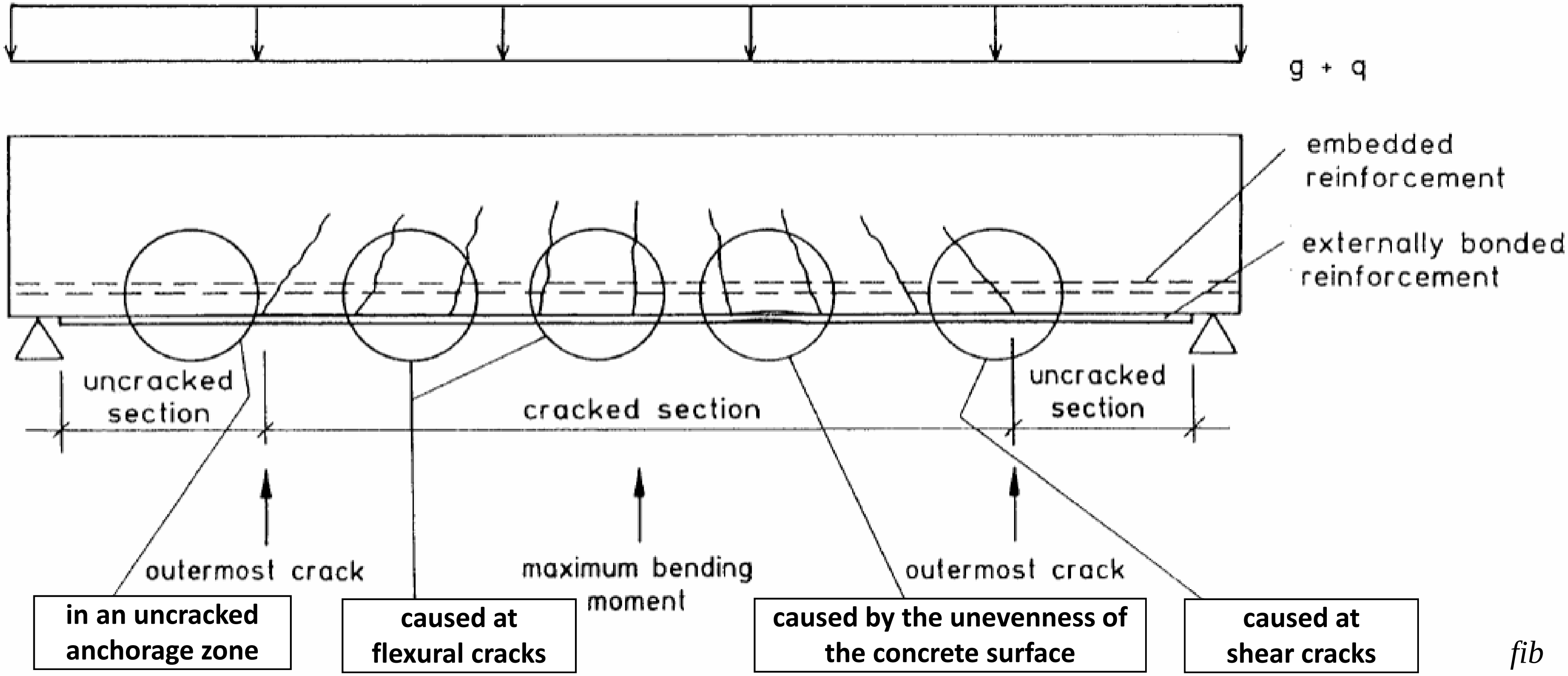
fib

Failure modes – Loss of composite action

Bond behaviour of RC members strengthened with FRP

Most failures observed → caused by **peeling-off** of the EBR element.

These depends on the starting point:



in an uncracked anchorage zone

caused at flexural cracks

caused by the unevenness of the concrete surface

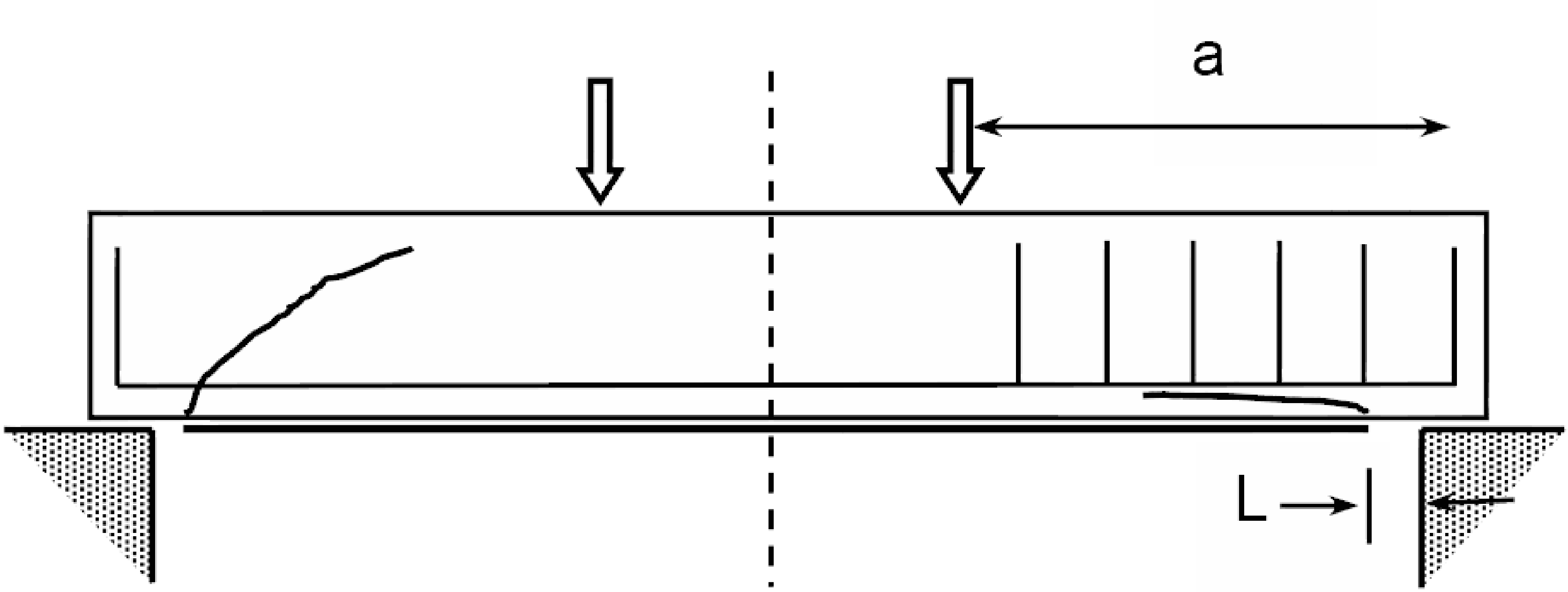
caused at shear cracks

fib

Failure modes – Loss of composite action

Bond behaviour of RC members strengthened with FRP

Also was observed → **FRP end shear failure** (or concrete rip-off)

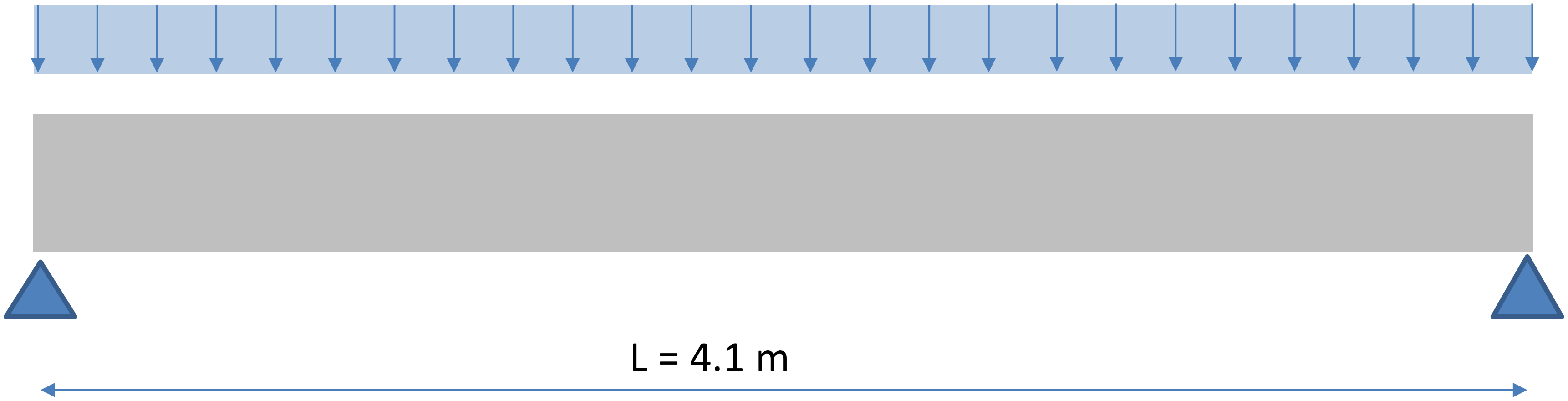


fib

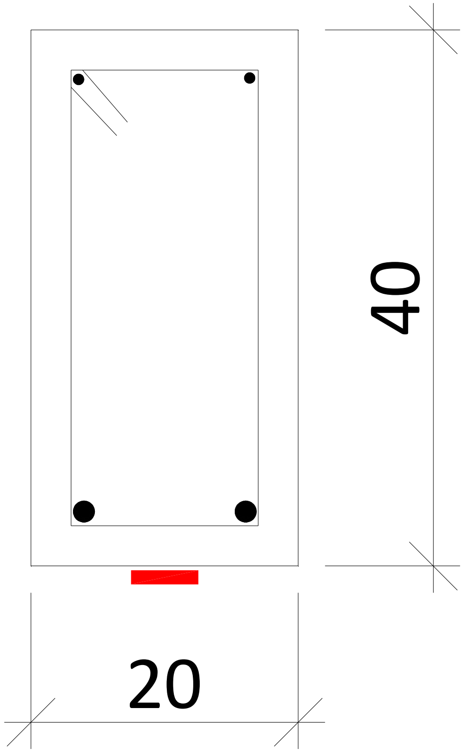
1. Strengthening for flexure using EB-FRP
2. **RC beam strengthened for flexure - Application**
3. Shear strengthening using EB-FRP
4. RC beam strengthened for shear - Application
5. Confinement

RC beam strengthened with CFRP composite for bending

1. SYSTEM



2. CROSS SECTION AND MATERIALS



RC beam (indoor)

$h = 40$ cm

$b = 20$ cm

$d = 36.7$ cm

$A_{s1} = 2\phi16 = 4.02\ cm^2$

Concrete:

C30/37

$f_{ck} = 30\ N/mm^2$

$E_c = 33000\ N/mm^2$

$f_{ctm} = 2.9\ N/mm^2$

Steel:

$f_{yk} = 500\ N/mm^2$

$E_s = 200000\ N/mm^2$

CFRP composite

$b_f = 80$ mm

$t_f = 1.2$ mm

$E_{fk} = 165000\ N/mm^2$

$\varepsilon_{fk} = 17$ ‰

3. LOADS AND DESIGN VALUES

1. Self-weight $G =$ _____ kN/m

2. Live load before strengthening $q_1 = 8.0$ kN/m

3. Additional live load $q_2 = 18.0$ kN/m

4. Live load after strengthening $q_1 + q_2 = 26.0$ kN/m

3. LOADS AND DESIGN VALUES

Fundamental load combination $1.35\sum_{j=1}^{n} G_{k,j} + 1.5Q_{k,1}$

Total load before strengthening $= \_\_\_\_\_\_ kN/m$

Bending moment before strengthening $M_o = \_\_\_\_ \mathrm{kNm}$

Total design load $= \_\_\_\_\_\_ kN/m$

Total bending moment $M_{Ed} = \_\_\_\_\_\_ \mathrm{kNm}$

3. LOADS AND DESIGN VALUES

$$f_{cd} = \frac{f_{ck}}{\gamma_c} = \_\_\_ \, MPa$$

$$\gamma_c = 1.5$$

$$f_{yd} = \frac{f_{yk}}{\gamma_s} = \_\_\_\_ MPa$$

$$\gamma_s = 1.15$$

3. LOADS AND DESIGN VALUES

Resisting moment of the unstrengthened member

$M_{Rd} = \mu b d^2 f_{cd}$ Where $\mu = \omega(1 - 0{,}5\omega)$

and $\omega = \frac{A_s}{bd} \frac{f_{yd}}{f_{cd}}$

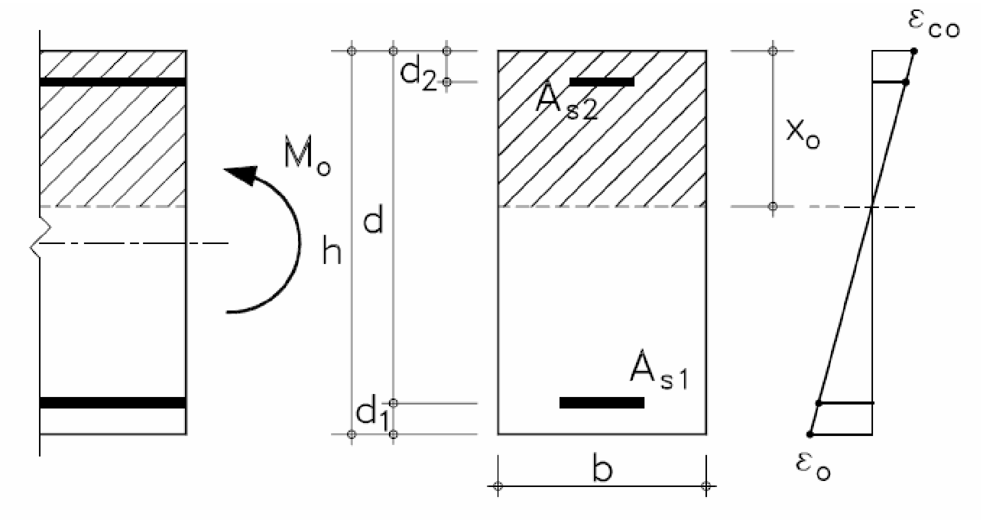
$\omega =$ ____ → $\mu =$ ____ $< \mu_{lim} = 0.8\xi_{lim}(1 - 0.4\xi_{lim}) =$ ____

$\xi_{lim} = \frac{\varepsilon_{cu3}}{\varepsilon_{cu3} + f_{yd}/E_s} =$ _____

→ $M_{Rd} =$ _____ kNm → $\boxed{\frac{M_{Ed}}{M_{Rd}} = \_\_\_\_}$

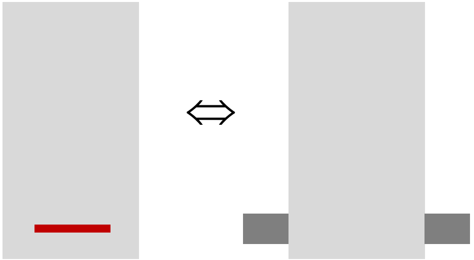
4. INITIAL SITUATION

Service moment M_o → self-weight + q_1



Calculation of the neutral axis depth x_o:

$$\frac{1}{2}bx_o^2 + \cancel{(\alpha_s - 1)A_{s2}(x_o - d_2)} = \alpha_s A_{s1}(d - x_o)$$



Where $\alpha_s = \frac{E_s}{E_c} =$ _____ - coefficient of equivalence

4. INITIAL SITUATION

$$0.5bx_o^2 - \alpha_s A_{s1}(d - x_o) = 0$$

$$0.5 \cdot \_\_\_\_\_ \cdot x_o^2 - \_\_\_\_ \cdot \_\_\_\_\_ \cdot (\_\_\_\_\_ - x_o) = 0$$

$$\rightarrow \qquad x_o = \_\_\_, \_\; mm$$

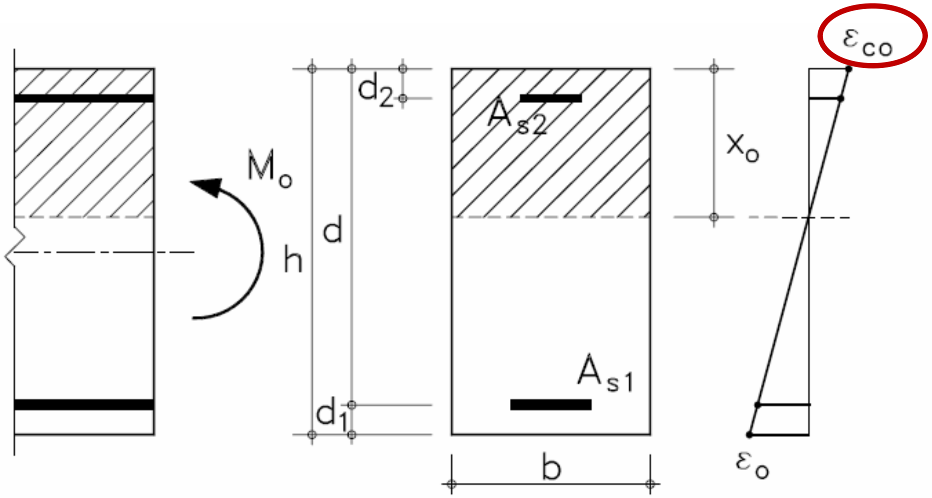
$$ax^2+bx+c=0$$

$$x=\frac{-b\pm\sqrt{b^2-4ac}}{2a}$$

4. INITIAL SITUATION

The concrete strain ε_{co} at the top fibre can be expressed as:

$$\varepsilon_{co} = \frac{M_o x_o}{E_c I_{co}} = 0,\_\_\_\_\_\_\_\_$$



Where

$$I_{co} = \frac{b x_o^3}{3} + \cancel{(\alpha_s - 1)A_{s2}(x_o - d_2)}^2 + \alpha_s A_{s1}(d - x_o)^2$$

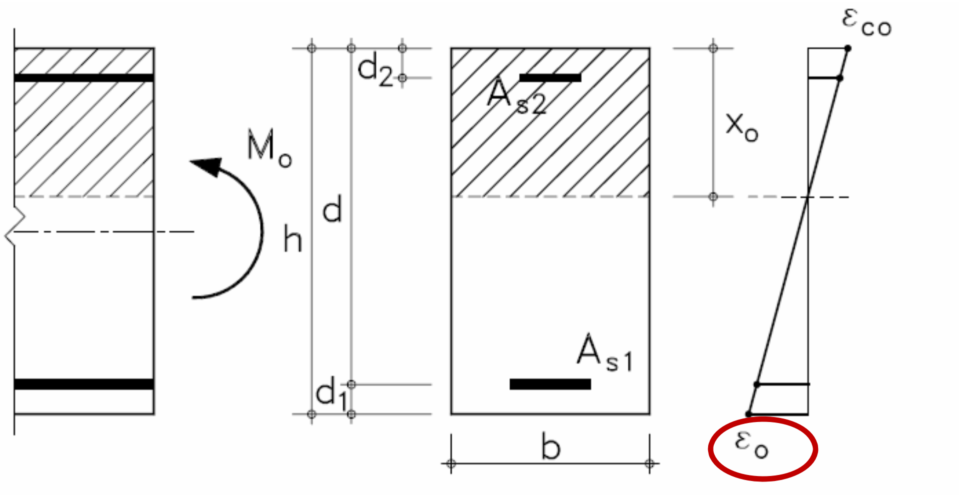
$$I_{co} = \_\_\_\_\_\_\_\_\_\_\_\_ mm^4$$

4. INITIAL SITUATION

Based on the strain compatibility, the strain ε_o at the extreme tension fiber can be derived as

→

$$\varepsilon_o = \varepsilon_{co}\frac{h - x_o}{x_o} = 0.\_\_\_\_\_\_\_\_$$



5. ANALYSIS IN ULS

General condition $M_{Ed} \leq M_{Rd}$

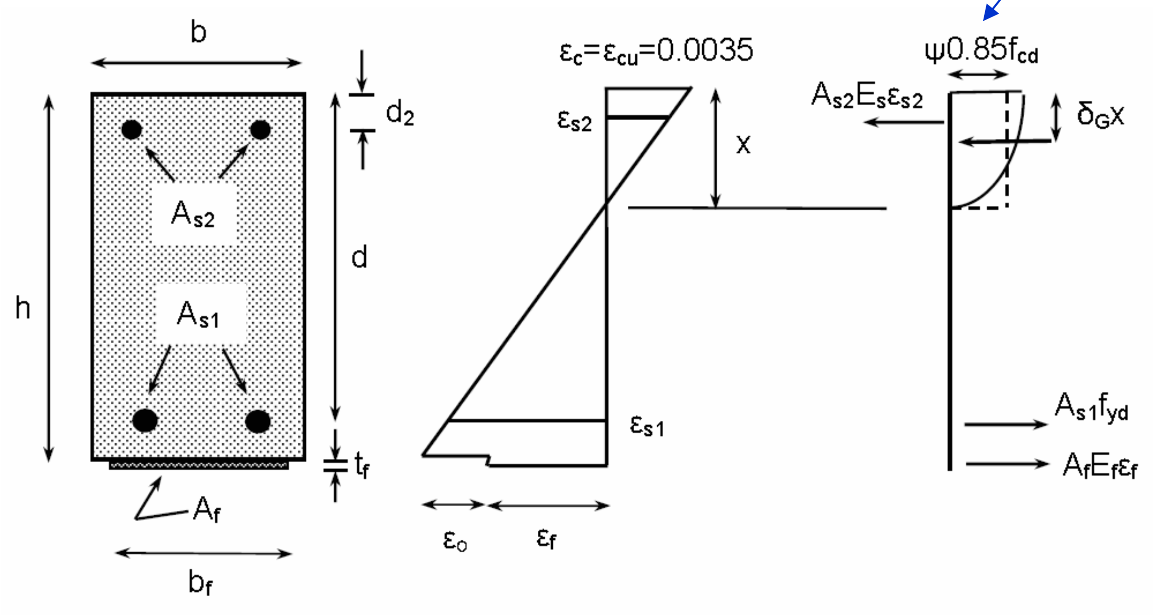
It is assumed that flexural failure takes place when one of the following conditions is met:

- The maximum concrete compressive strain (ε_{cu}) is reached.

- The maximum FRP tensile strain (ε_{fd}) is reached.

5. ANALYSIS IN ULS

Additional safety factor



$$\psi = 0.8$$

$$\delta_G = 0.4$$

$$\sum N = 0 \quad \rightarrow \qquad 0.85\psi f_{cd} bx + \cancel{A_{s2}E_s\varepsilon_{s2}} = A_{s1}f_{yd} + A_f E_f \varepsilon_f$$

Where

$$\varepsilon_f = \varepsilon_{cu}\frac{h-x}{x} - \varepsilon_o$$

5. ANALYSIS IN ULS

$\sum N = 0 \quad \rightarrow \quad 0.85\psi f_{cd} b x = A_{s1} f_{yd} + A_f E_f \varepsilon_f$ → only iterative solving is possible

1st proposal $x = 102\ mm$

$$\varepsilon_f = \varepsilon_{cu} \frac{h-x}{x} - \varepsilon_o = \_\_\_\_\_$$

$$0.85\psi f_{cd} b x = A_{s1} f_{yd} + A_f E_f \varepsilon_f$$

dif~? %

$\_\_\_\_\_ \qquad \_\_\_\_\_$

2nd proposal $x = \_\_\_\_\_\ mm$

$$\varepsilon_f = \_\_\_\_\_$$

$\_\_\_\_\_ \qquad \_\_\_\_\_$

dif ~? %

5. ANALYSIS IN ULS

3rd proposal $\boldsymbol{x = 110\,mm}$

$$\varepsilon_f = \varepsilon_{cu}\frac{h-x}{x} - \varepsilon_o = \_\_\_\_\_$$

____________ ≈ ____________[N]

difference ~ ______%

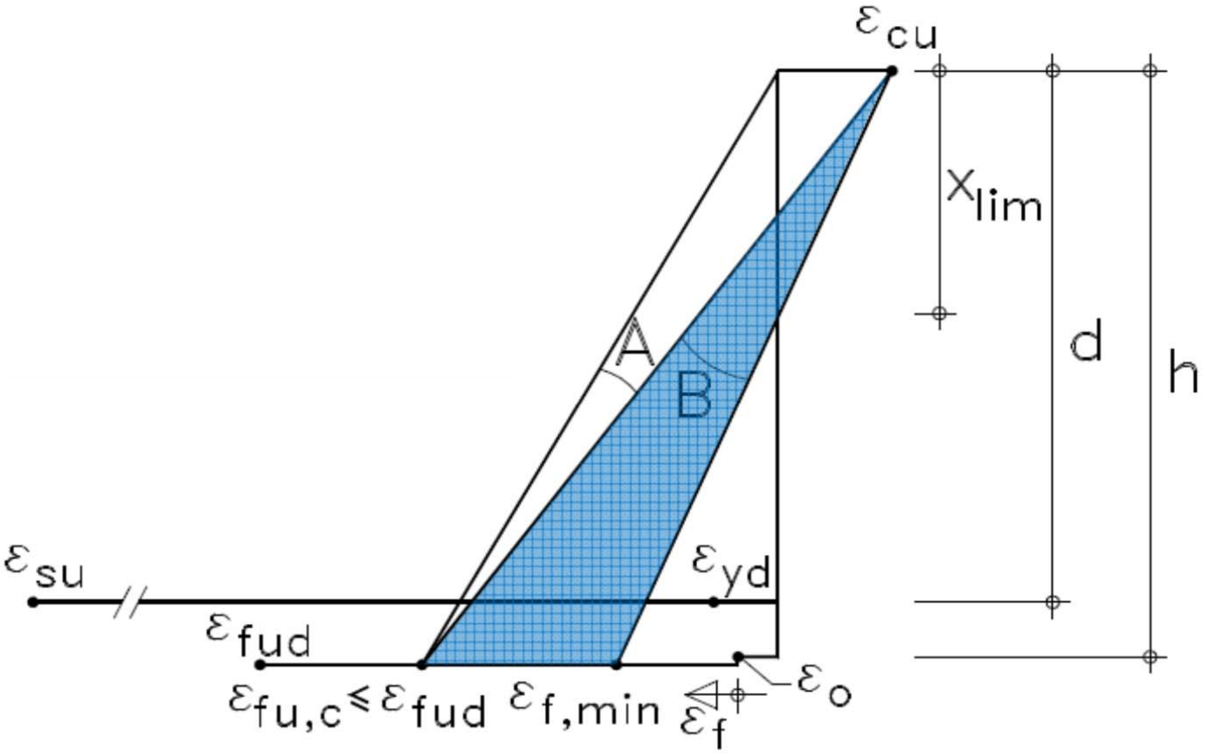
→

$$\varepsilon_f = \varepsilon_{cu}\frac{h-x}{x} - \varepsilon_o = \_\_\_\_\_$$

5. ANALYSIS IN ULS

It must be verified if

$$\varepsilon_{f,min} \le \varepsilon_f \le \varepsilon_{fd}$$



(Stijn Matthys, Ghent University)

5. ANALYSIS IN ULS

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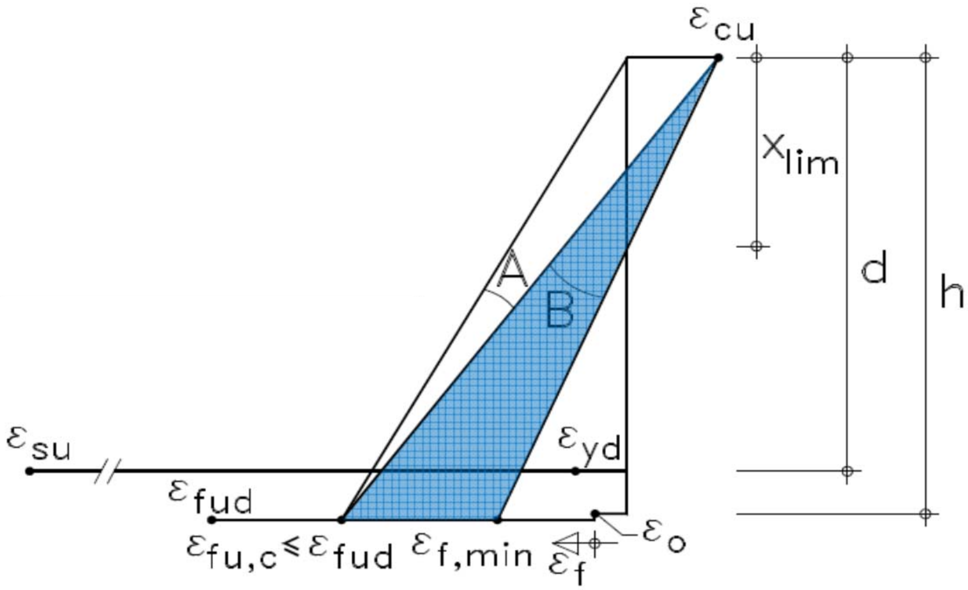
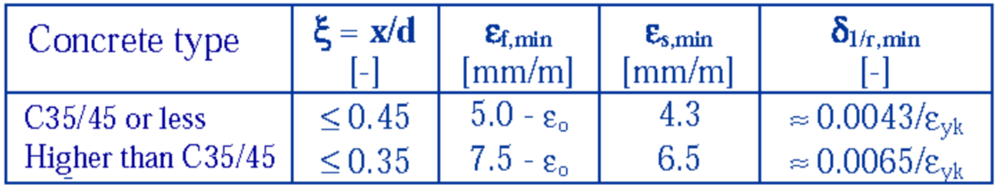


Deformability condition



Concrete type	$\xi = x/d$ [-]	$\varepsilon_{f,min}$ [mm/m]	$\varepsilon_{s,min}$ [mm/m]	$\delta_{1/r,min}$ [-]
C35/45 or less	≤ 0.45	$5.0 - \varepsilon_o$	4.3	$\approx 0.0043/\varepsilon_{yk}$
Higher than C35/45	≤ 0.35	$7.5 - \varepsilon_o$	6.5	$\approx 0.0065/\varepsilon_{yk}$

Based on CEB-FIP Model Code 1990

(Stijn Matthys, Ghent University)

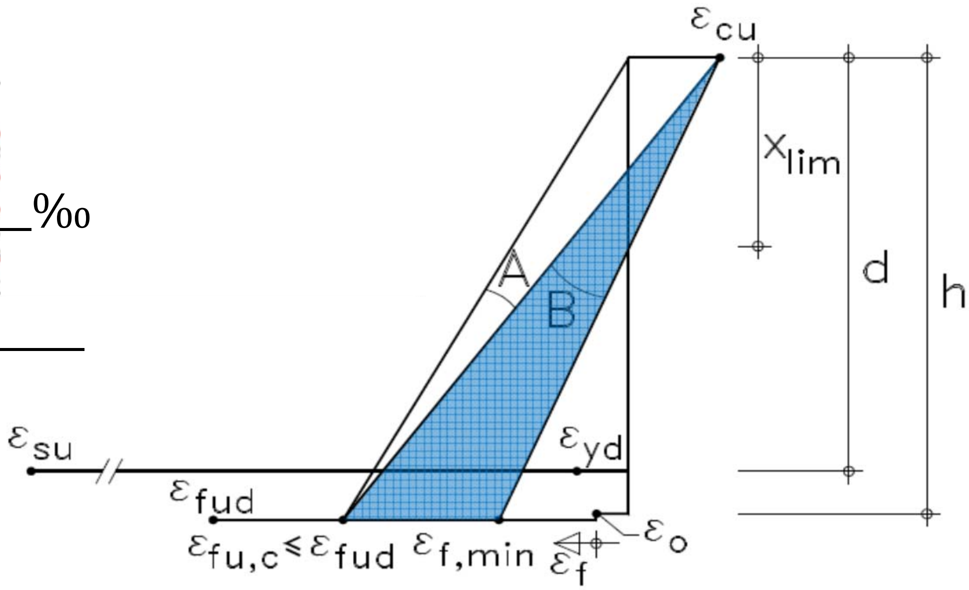
5. ANALYSIS IN ULS

It must be verified if

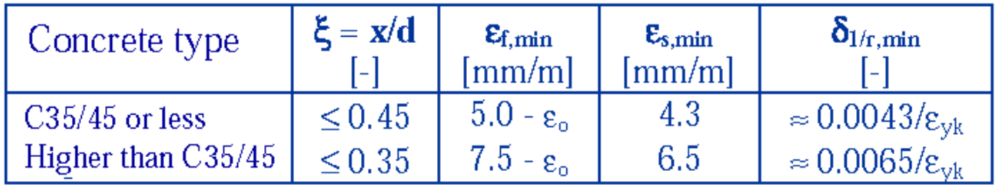
$$\varepsilon_{f,min} \leq \varepsilon_f \leq \varepsilon_{fd}$$

$$\varepsilon_{f,min} = 5.0 - \varepsilon_o = 5.0 - \_\_\_\_\_ = \_\_\_\_\_‰$$

$$\varepsilon_{f,min} = \_\_\_\_\_‰ \leq \varepsilon_f = \_\_\_\_\_‰ \quad \_\_\_\_\_$$



Deformability condition **in ‰ !!!**



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5. ANALYSIS IN ULS

It must be verified if

$$\varepsilon_{f,min} \leq \varepsilon_f \leq \varepsilon_{fd}$$

FRP bond failure

$$\varepsilon_{fd} = \min\left(\underbrace{\eta_a \frac{\varepsilon_{fk}}{\gamma_f}}_{\_\_\_\_\_\text{‰}} ; \varepsilon_{fdd}\right)$$

$\eta_a = 0.75$
$\varepsilon_{fk} = 17\ \text{‰}$
$\gamma_f = 1.1$

In conformity of CNR-DT 200/2004

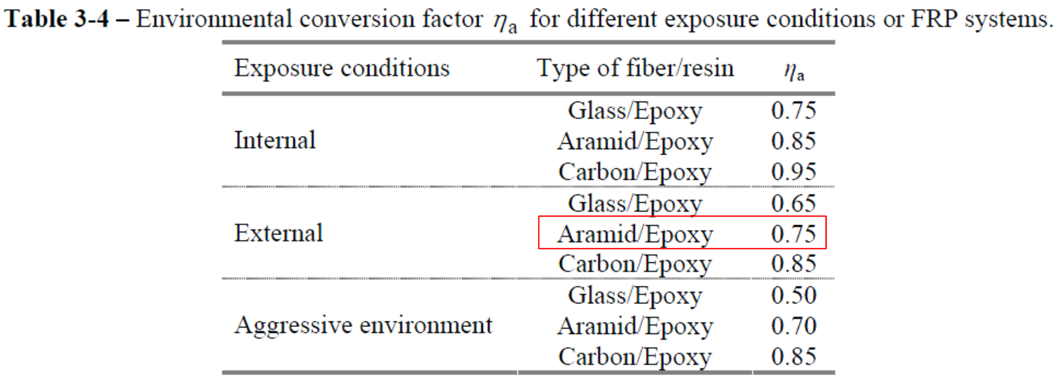


Table 3-4 – Environmental conversion factor η_a for different exposure conditions or FRP systems.

Exposure conditions	Type of fiber/resin	η_a
Internal	Glass/Epoxy	0.75
	Aramid/Epoxy	0.85
	Carbon/Epoxy	0.95
External	Glass/Epoxy	0.65
	Aramid/Epoxy	0.75
	Carbon/Epoxy	0.85
Aggressive environment	Glass/Epoxy	0.50
	Aramid/Epoxy	0.70
	Carbon/Epoxy	0.85

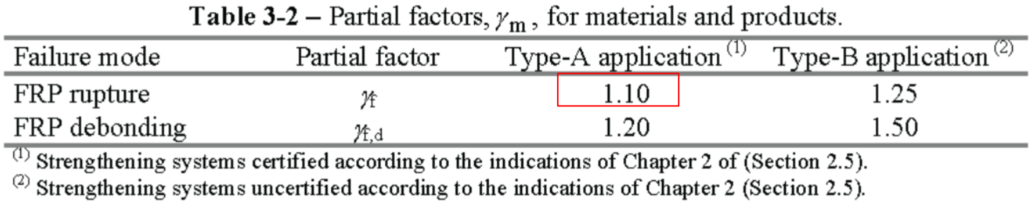
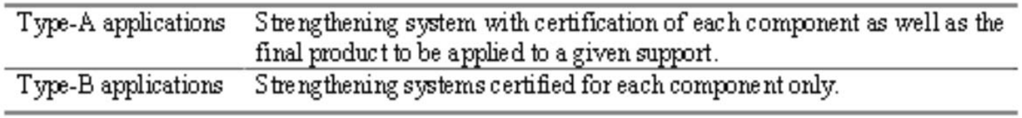


Table 3-2 – Partial factors, γ_m, for materials and products.

Failure mode	Partial factor	Type-A application (1)	Type-B application (2)
FRP rupture	γ_f	1.10	1.25
FRP debonding	$\gamma_{f,d}$	1.20	1.50

(1) Strengthening systems certified according to the indications of Chapter 2 of (Section 2.5).
(2) Strengthening systems uncertified according to the indications of Chapter 2 (Section 2.5).



Type-A applications	Strengthening system with certification of each component as well as the final product to be applied to a given support.
Type-B applications	Strengthening systems certified for each component only.

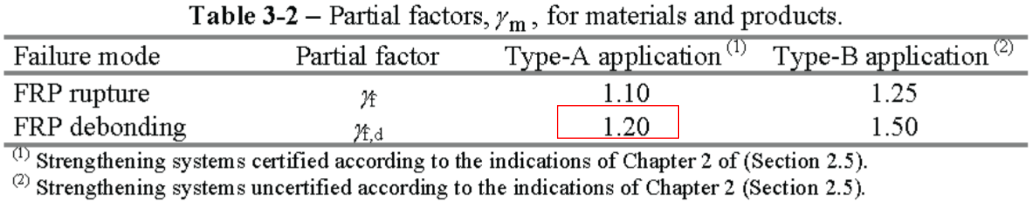
5. ANALYSIS IN ULS

It must be verified if

$$\varepsilon_{f,min} \leq \varepsilon_f \leq \varepsilon_{fd}$$

FRP bond failure

$$\varepsilon_{fd} = \min\left(\eta_a \frac{\varepsilon_{fk}}{\gamma_f}; \varepsilon_{fdd}\right)$$



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(1) Strengthening systems certified according to the indications of Chapter 2 of (Section 2.5).

(2) Strengthening systems uncertified according to the indications of Chapter 2 (Section 2.5).

$$\varepsilon_{fdd} = k_{cr} \frac{1}{\gamma_{fd} \cdot \sqrt{\gamma_c}} \sqrt{\frac{2 \cdot \Gamma_{Fk}}{E_f \cdot t_f}}$$

$k_{cr} = 3.0$ - coefficient

$\Gamma_{Fk} = 0.03 k_b \cdot \sqrt{f_{ck} \cdot f_{ctm}}$ - the specific fracture energy of the FRP - concrete interface

$$k_b = \sqrt{\frac{2 - b_f/b}{1 + b_f/400}} \geq 1$$

is a geometric coefficient depending on both width b of the strengthened beam and width b_f of the FRP system. If $b_f/b < 0.33$, the value for k_b corresponding to $b_f/b = 0.33$ is adopted.

5. ANALYSIS IN ULS

It must be verified if

$$\varepsilon_{f,min} \leq \varepsilon_f \leq \varepsilon_{fd}$$

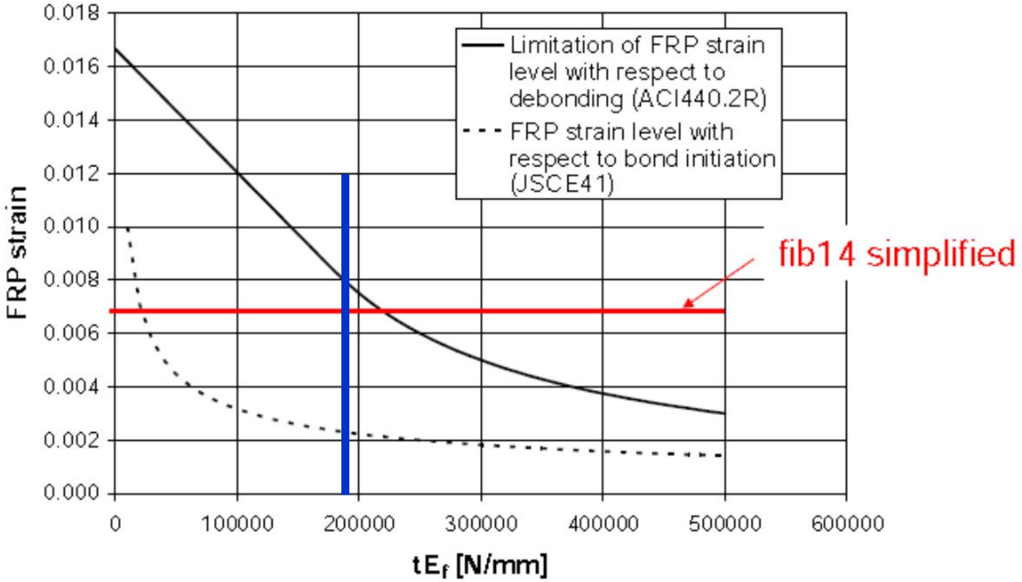
$$\varepsilon_{fd} = \min\left(\eta_a \frac{\varepsilon_{fk}}{\gamma_f}; \varepsilon_{fdd}\right) = \_\_\_\_\_\_$$

$$\varepsilon_{fdd} = k_{cr} \frac{1}{\gamma_{fd} \cdot \sqrt{\gamma_c}} \sqrt{\frac{2 \cdot \Gamma_{Fk}}{E_f \cdot t_f}} = \_\_\_\_\_\_$$

$$k_{cr} = 3.0$$

$$\Gamma_{Fk} = 0.03 k_b \cdot \sqrt{f_{ck} \cdot f_{ctm}} = \_\_\_\_\_ MPa$$

$$k_b = \sqrt{\frac{2 - \frac{b_f}{b}}{1 + \frac{b_f}{400}}} = \_\_\_\_\_$$



$$b_f / b = \_\_\_\_\_$$

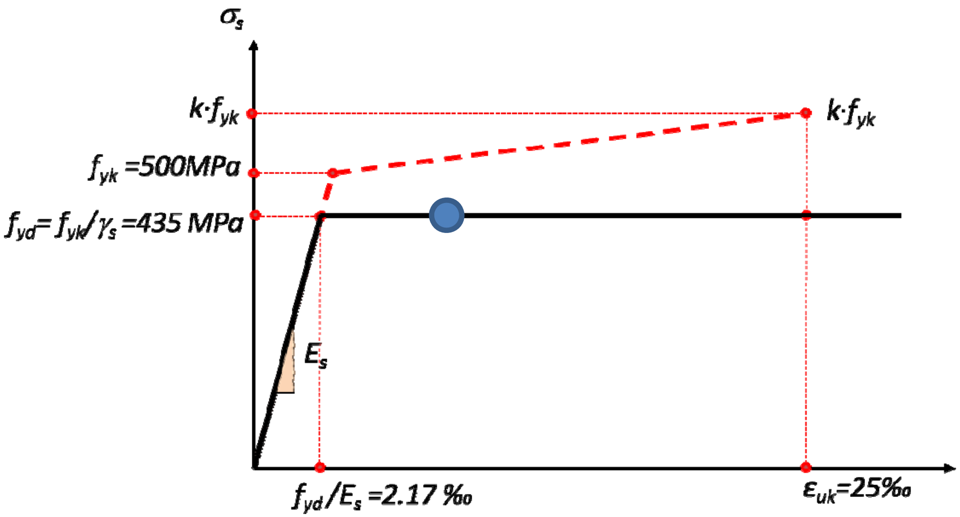
If $b_f / b < 0.33$, the value for k_b corresponding to $b_f / b = 0.33$ is adopted

5. ANALYSIS IN ULS

Verification of the strain in reinforcement

$$\varepsilon_{s1} = \varepsilon_{cu}\frac{d-x}{x} = 0.\_\_\_\_\_\_ \qquad \geq \frac{f_{yd}}{E_s} = 0.\_\_\_\_\_$$

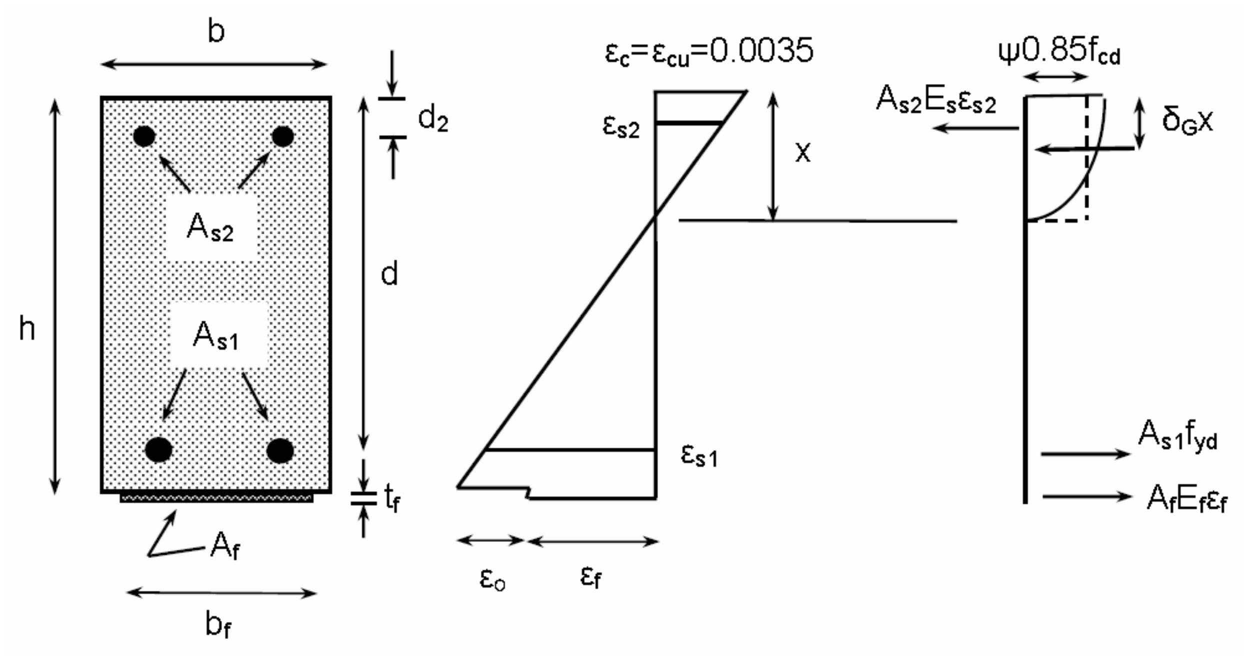
$$\varepsilon_{uk} <$$



5. ANALYSIS IN ULS

The flexural capacity of the strengthened member:

$$M_{Rd} = \frac{1}{\gamma_{Rd}} \psi b x f_{cd} (d - \delta_G x) + A_f E_f \varepsilon_f (h - d)$$



5. ANALYSIS IN ULS

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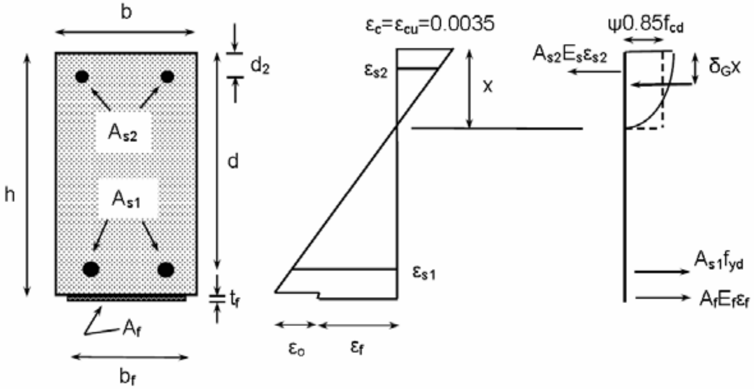


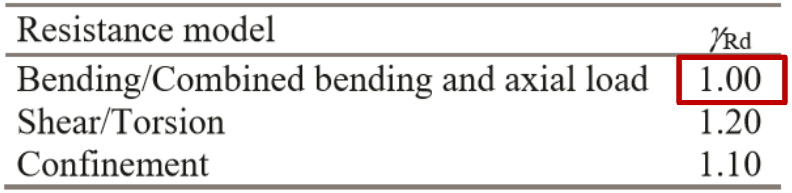
$$\lambda = \frac{0.002}{\varepsilon_{fu,c} + \varepsilon_o} \frac{h - x}{x} = \_\_\_\_\_\_\_$$

$$\lambda \geq 1: \quad \psi = \frac{3\lambda - 1}{3\lambda^2} \qquad \delta_G = \frac{4\lambda - 1}{4(3\lambda - 1)}$$

$$\lambda \leq 1: \quad \psi = 1 - \frac{\lambda}{3} \qquad \delta_G = \frac{\lambda^2 - 4\lambda + 6}{4(3 - \lambda)}$$

$$= \_\_\_\_\_ \qquad = \_\_\_\_\_$$

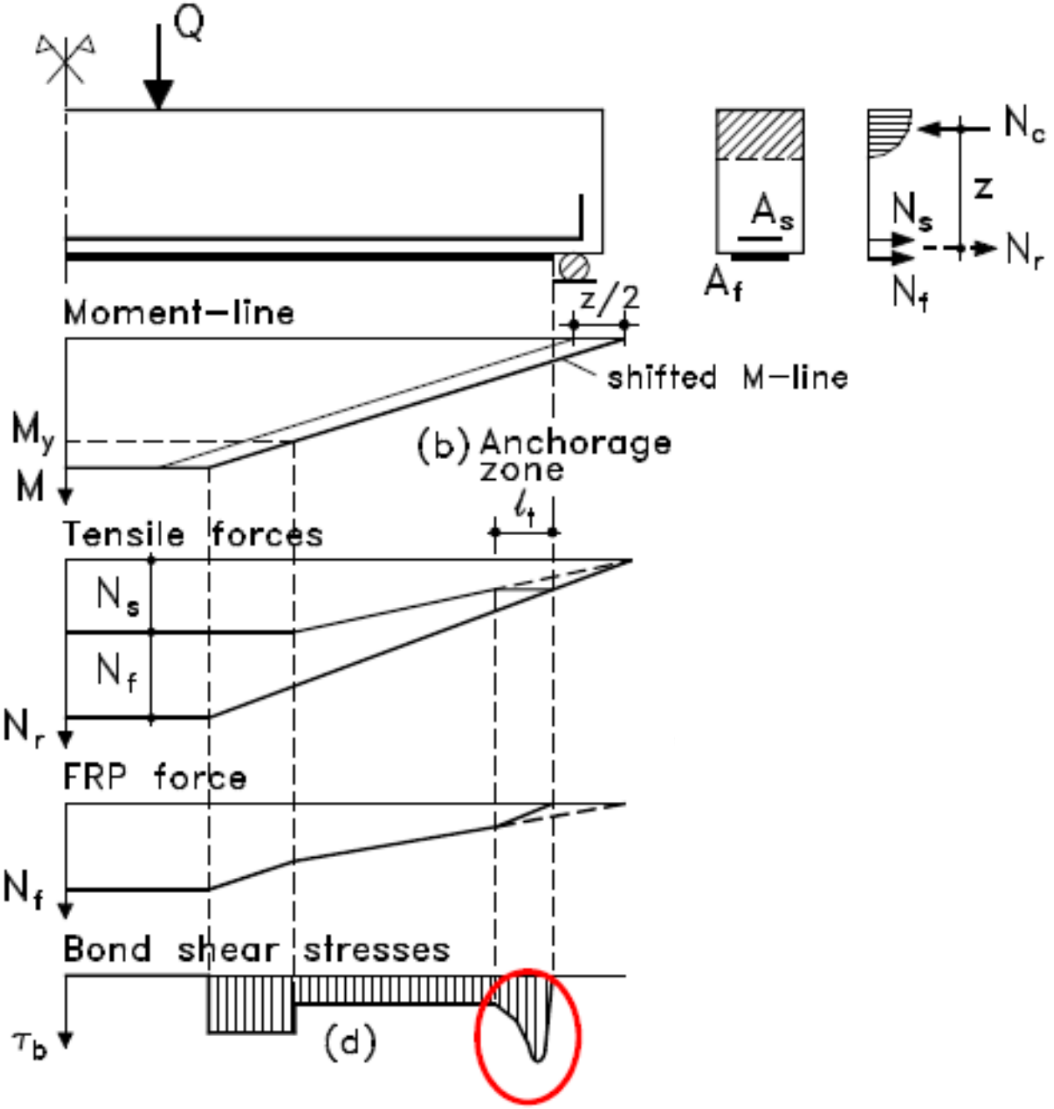
Table 3-3 – Partial factors γ_{Rd}.

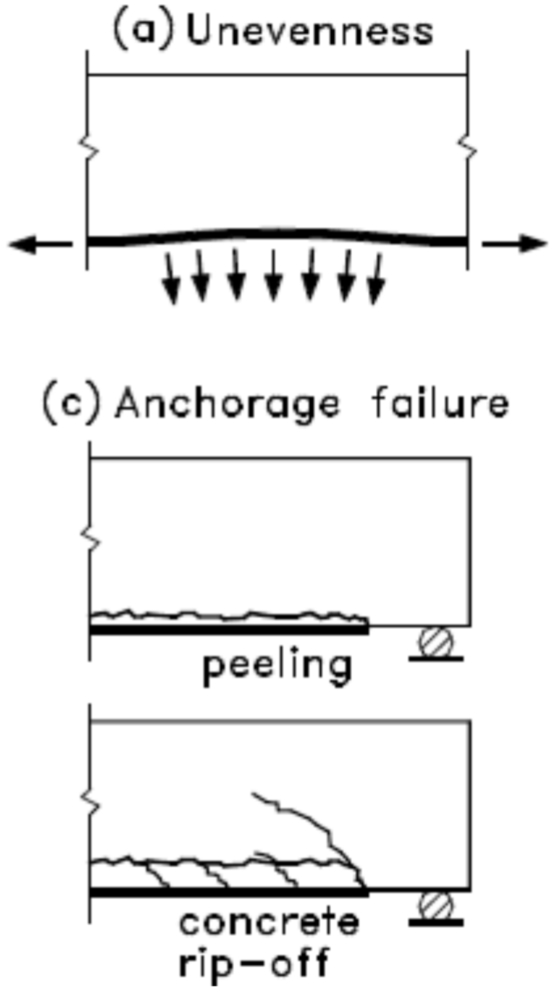


Resistance model	γ_{Rd}
Bending/Combined bending and axial load	1.00
Shear/Torsion	1.20
Confinement	1.10

$$\boldsymbol{M_{Rd} = \_\_\_\_\_\_ kNm \quad > M_{Ed} = \_\_\_\_\_\_ kNm}$$

6. CHECKING FOR ANCHORAGE FAILURE





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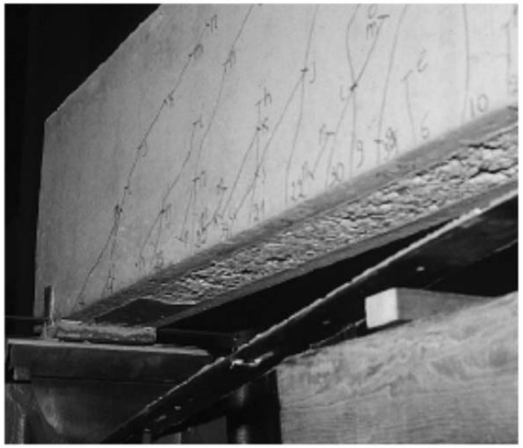
6. CHECKING FOR ANCHORAGE FAILURE

ANCHORAGE FAILURE MODES



Type 1: at interface

Type 2: at internal steel reinforcement level

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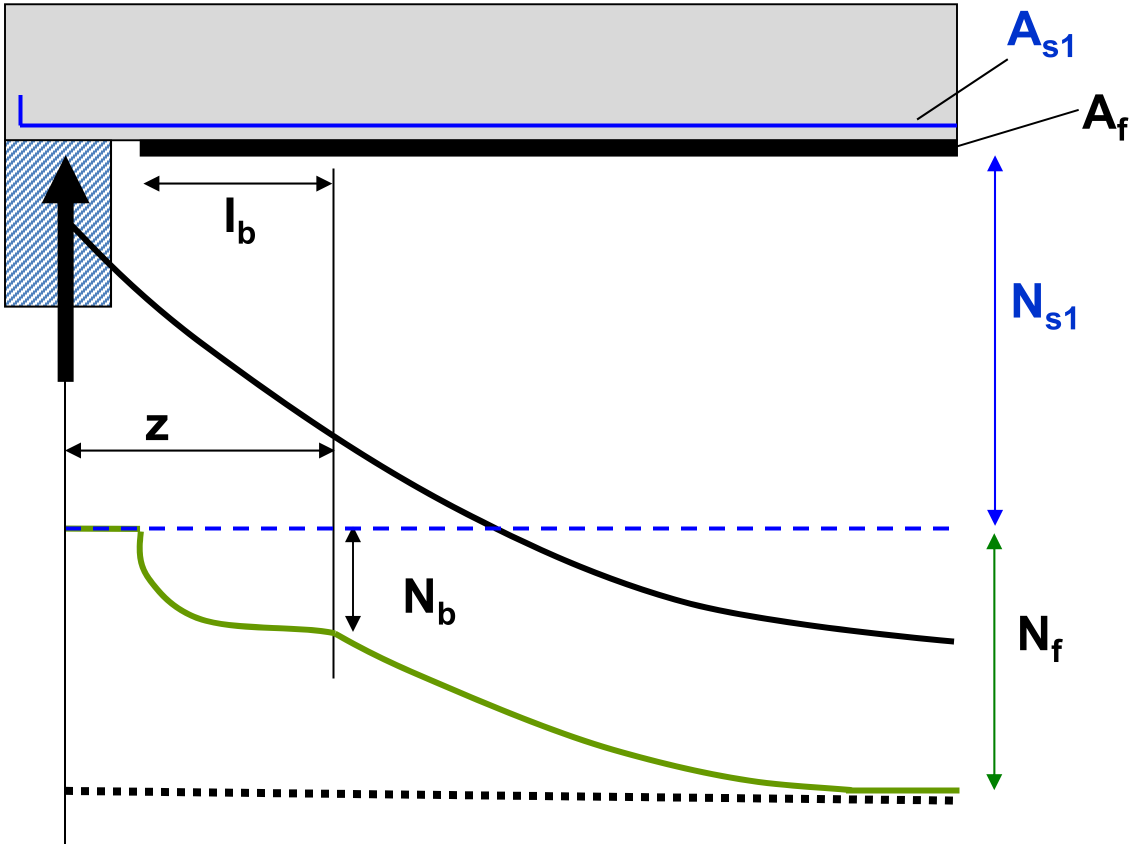
6. CHECKING FOR ANCHORAGE FAILURE



Capacity of the unstrengthened section

Capacity of the strengthened section

6. CHECKING FOR ANCHORAGE FAILURE

The maximum FRP force which can be anchored:

$$N_{fa,max} = \alpha k_c k_b b_f \sqrt{2 c_f f_{ctm} E_f t_f}$$

$\alpha = 1.0 \;\; or \;\; 0.9$	influence of inclined cracks on bond strength
$k_c = 1.0$	influence of the concrete faces with low compaction
$k_b = \sqrt{\frac{2 - b_f / b}{1 + b_f / 400}} \geq 1$	geometric coefficient, in function of b_f / b
$c_f = 0.205$	for CFRP laminate

The optimal bond length:

$$l_e = \sqrt{\frac{E_f t_f}{2 \cdot f_{ctm}}} \leq l_b$$

6. CHECKING FOR ANCHORAGE FAILURE - DEBONDING

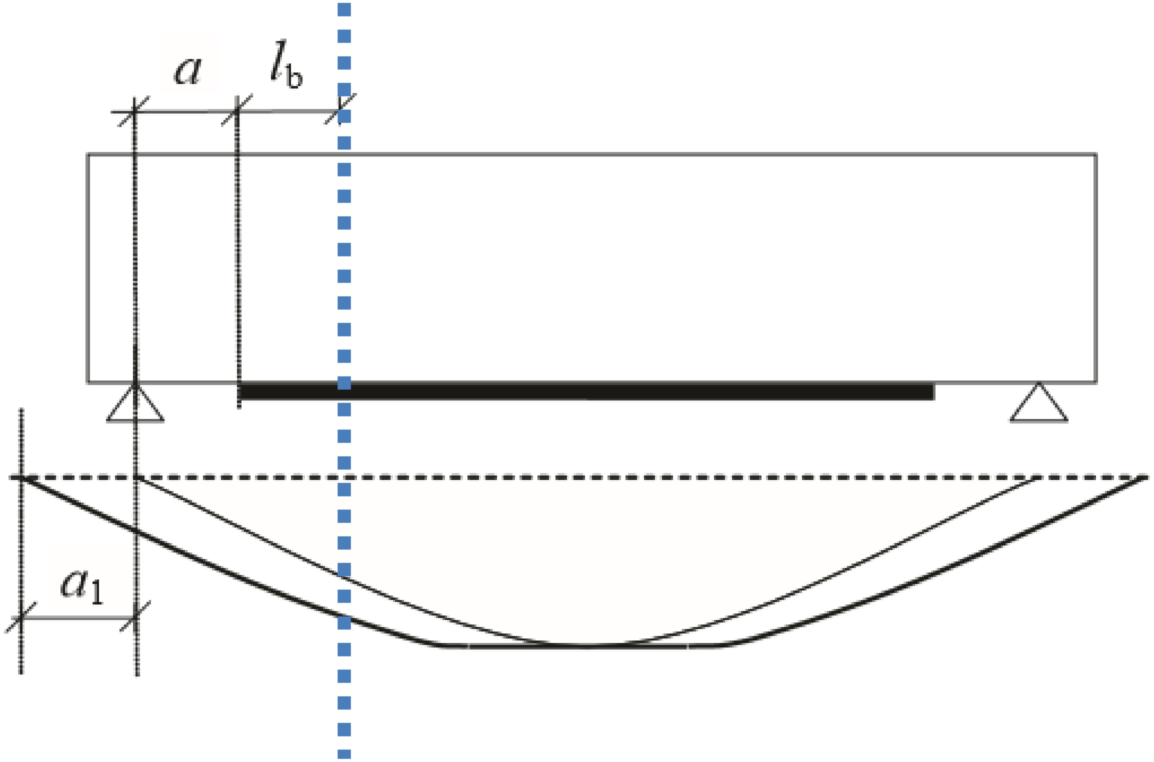
The maximum FRP force which can be anchored:

$$N_{fa,max} = \alpha k_c k_b b_f \sqrt{2 c_f f_{ctm} E_f t_f} = \_\_\_\_\_ \, kN$$

The optimal bond length:

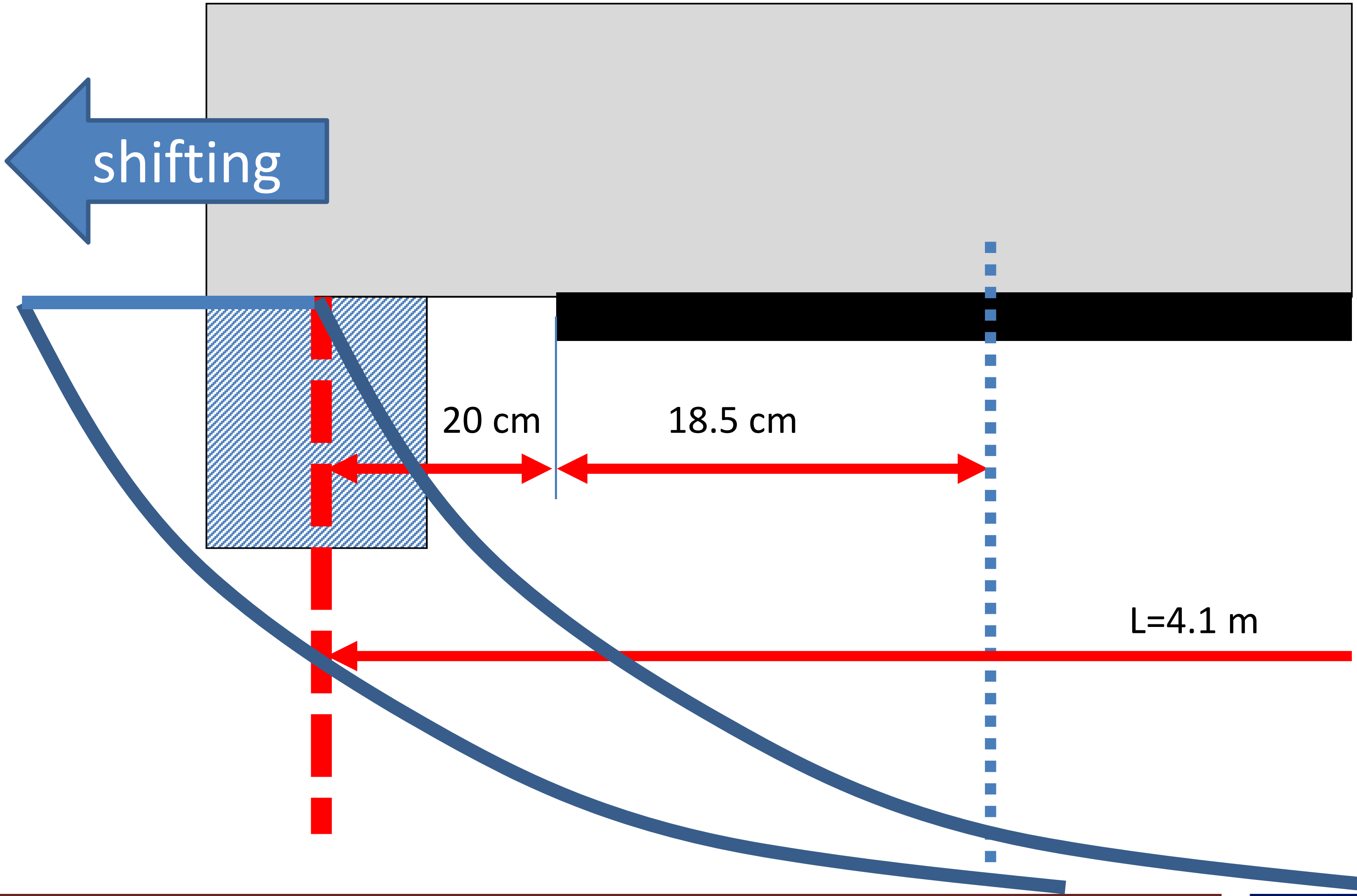
$$l_e = \sqrt{\frac{E_f t_f}{2 \cdot f_{ctm}}} = \_\_\_\_\_\_ \, mm$$

6. CHECKING FOR ANCHORAGE FAILURE - DEBONDING



$$\left.\begin{aligned} a_1 &= 0.9d = 330mm \\ a &= 200\ mm \\ l_b &= 190\ mm > l_e = 185\ mm \end{aligned}\right\} \quad z = a_1 + a + l_b = 720\ mm$$

6. CHECKING FOR ANCHORAGE FAILURE - DEBONDING



6. CHECKING FOR ANCHORAGE FAILURE - DEBONDING

CHECKING THE ANCHORAGE FORCE AT THE DISTANCE OF z :

1. Computation of $\varepsilon_{co} = \frac{M_o(z)\,x_o}{E_c I_{co}}$ and $\varepsilon_o = \varepsilon_{co}\frac{h-x_o}{x_o}$

2. Computation of $\varepsilon_f = \varepsilon_c\frac{h-x}{x} - \varepsilon_o$

from $\sum N = 0 \quad \rightarrow \quad 0.85\psi f_{cd} b x = A_{s1} f_{yd} + A_f E_f \varepsilon_f$

by several iteration the values for x, ε_c and ψ will be obtained

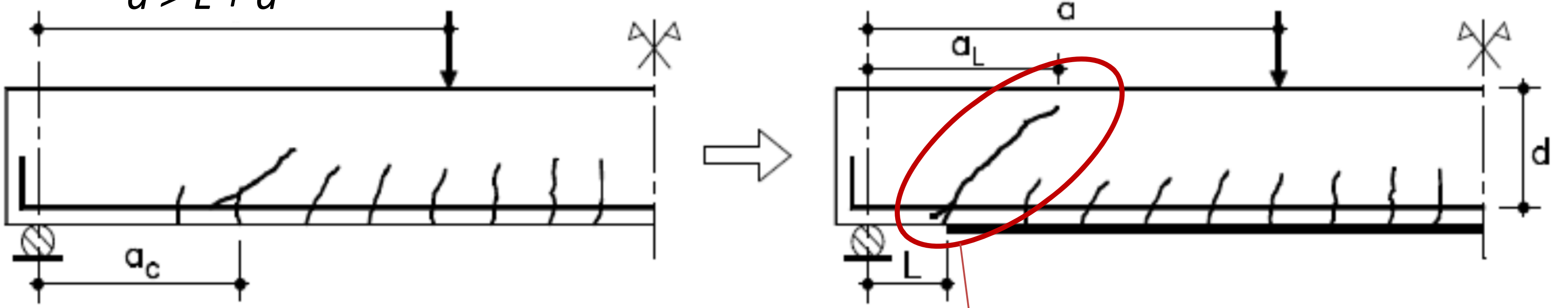
3. Whith ε_f obtained, computation of the effective force in the composite N_{eff} and compare

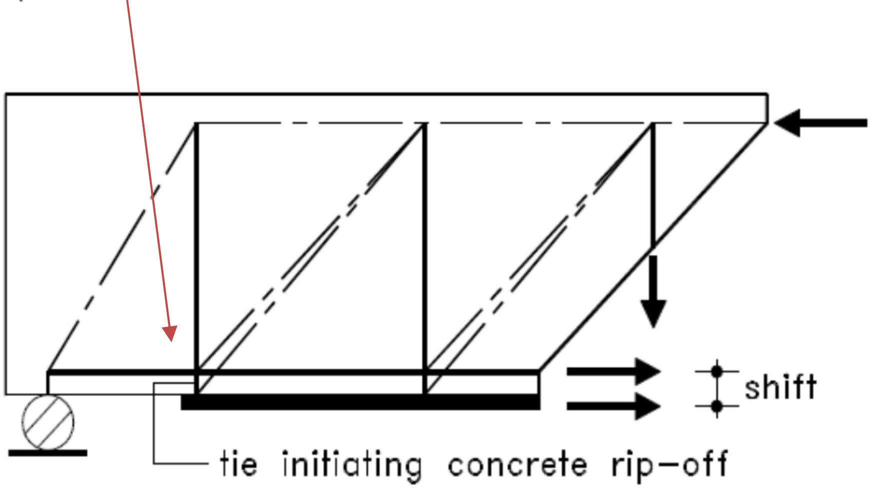
$$N_{eff} <> N_{fa,max}$$

6. CHECKING ANCHORAGE FAILURE – CONCRETE RIP-OFF

(end shear failure)

a > L + d





$$V_{Ed} \leq V_{Rd} = \tau_{Rd} bd$$

6. CHECKING ANCHORAGE FAILURE – CONCRETE RIP-OFF

(end shear failure)

$$V_{Ed} \leq V_{Rd} = \tau_{Rd} bd = \_\_\_\_\_\_ kN$$

where

$$\tau_{Rd} = 0.15 \cdot \sqrt[3]{3\frac{d}{a_L}}\left(1 + \sqrt{\frac{200}{d}}\right)\sqrt[3]{100\rho_s f_{ck}}$$ *design value of resisting shear strength of concrete*

$$a_L = \sqrt[4]{\frac{\left(1-\sqrt{\rho_s}\right)^2}{\rho_s} dL^3}$$

$$\rho_s = \frac{A_{s1}}{bd}$$

1. Strengthening for flexure using EB-FRP

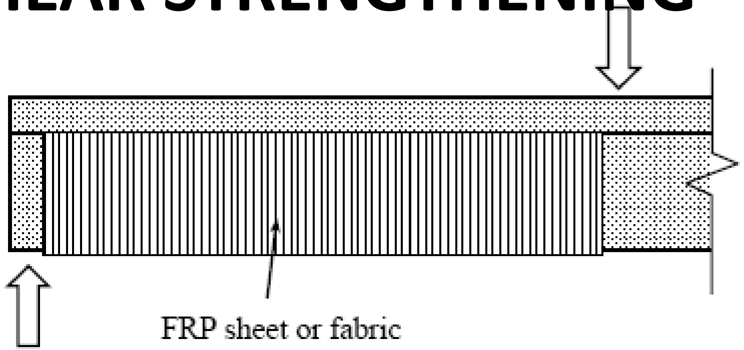
2. RC beam strengthened for flexure - Application

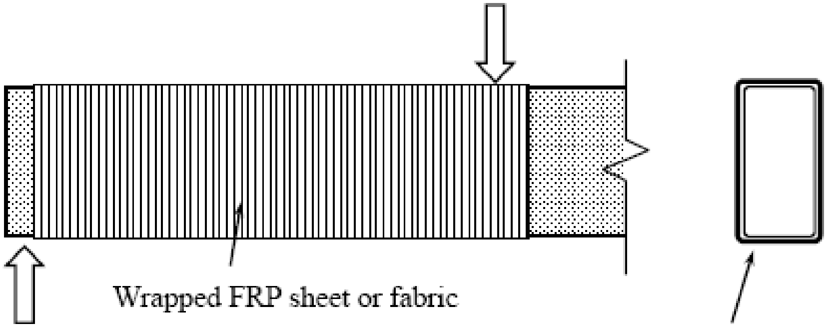
3. **Shear strengthening using EB-FRP**

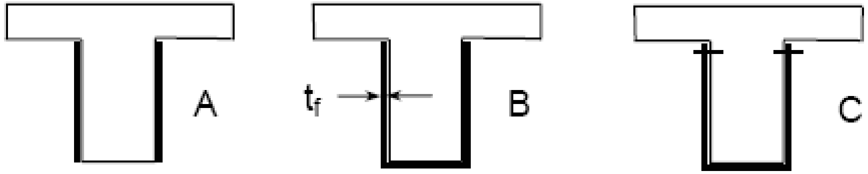
4. RC beam strengthened for shear - Application

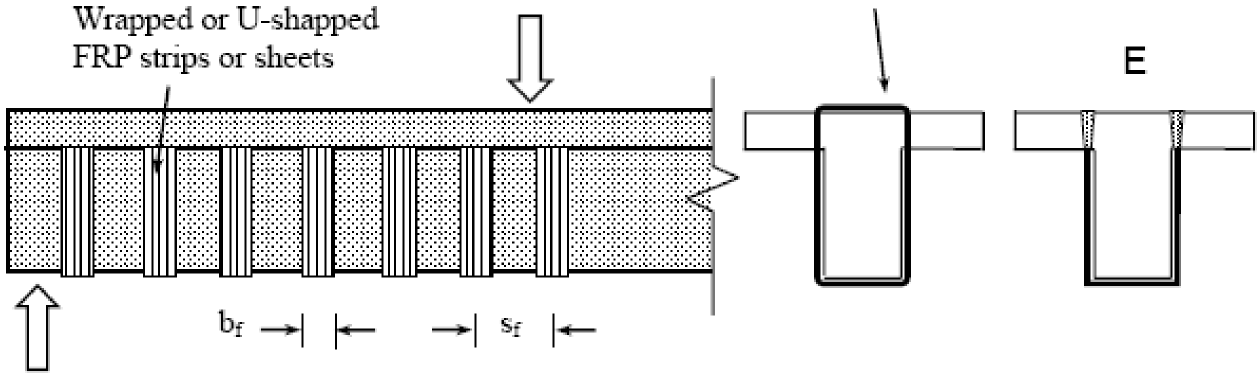
5. Confinement

SHEAR STRENGTHENING



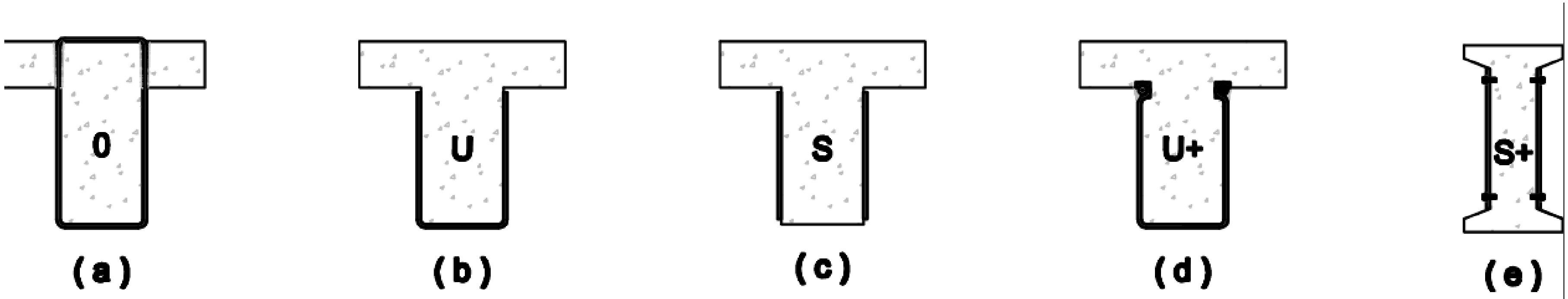




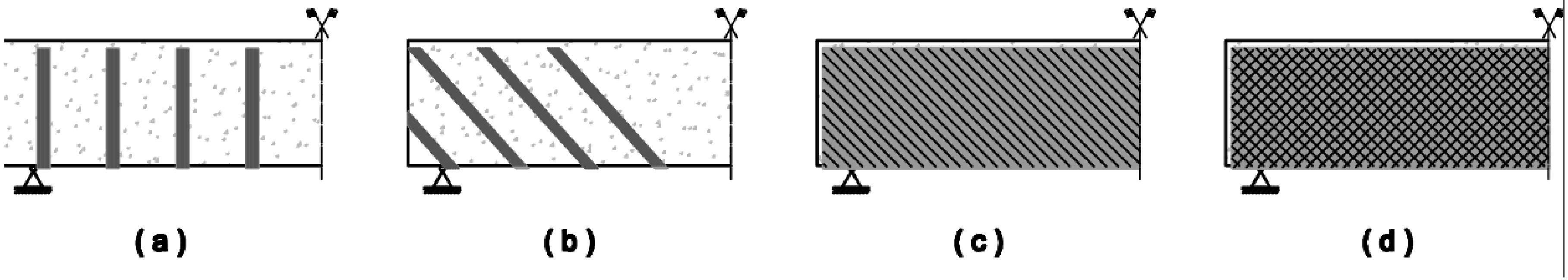


fib

SHEAR STRENGTHENING



Possible arrangements for EBR FRP strengthening



(Barros Joaquim , University of Minho)

SHEAR CAPACITY OF THE STRENGTHENED MEMBERS

$$\boldsymbol{V_{Rd} = min(V_{Rd,c} + V_{Rd,s} + \boxed{V_{Rd,f}}\,; V_{Rd,max})}$$

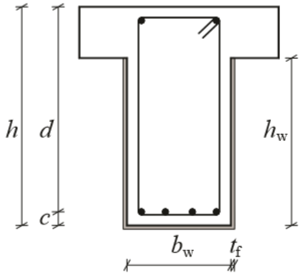
$V_{Rd,c}$	concrete contribution to the shear capacity	EC2 or ACI318
$V_{Rd,s}$	steel contribution to the shear capacity	
$V_{Rd,f}$	**FRP contribution to the shear capacity**	fib CNR-DT200 ACI4408
$V_{Rd,max}$	the ultimate strength of the concretet strut	

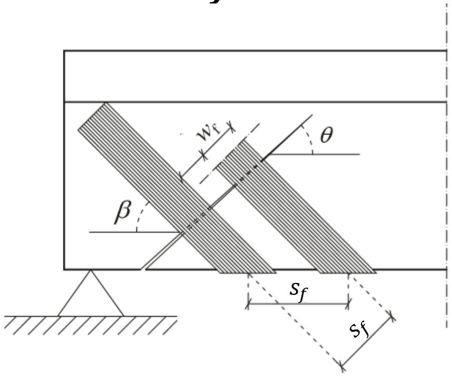
SHEAR CAPACITY OF THE STRENGTHENED MEMBERS

For RC member with rectangular cross-section with U-wrapped or completely wrapped configurations, the FRP contribution to the shear capacity shall be calculated as:

fib → $$V_{Rd,f} = 0.9\varepsilon_{fed}E_f\rho_f b_w d(\cot\theta + \cot\beta)\sin\beta$$

CNR → $$V_{Rd,f} = \frac{1}{\gamma_{Rd}}0.9df_{ed}2t_f(\cot\theta + \cot\beta)\frac{w_f}{s_f}$$

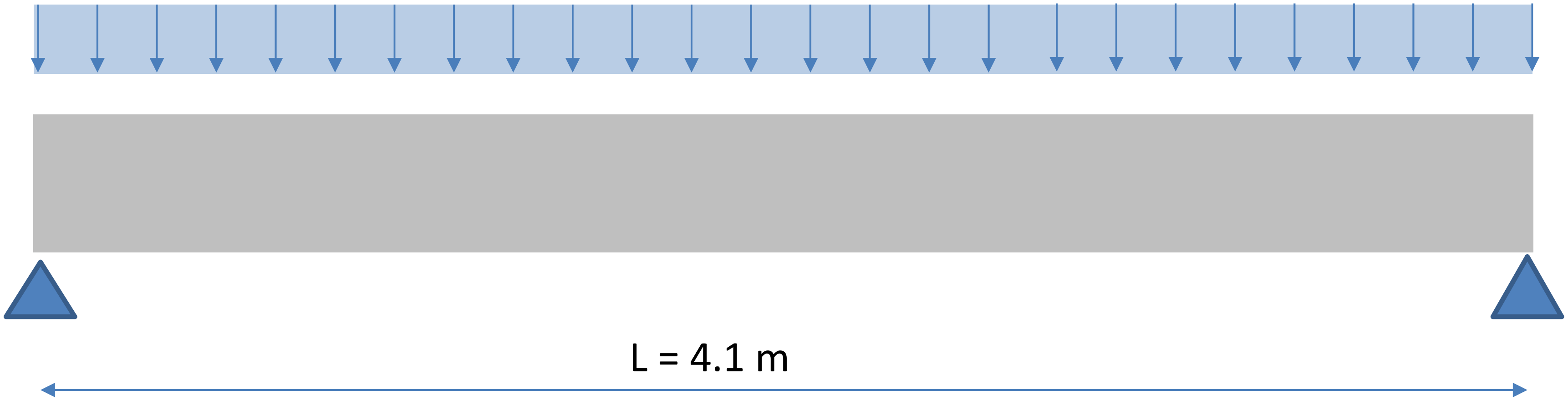




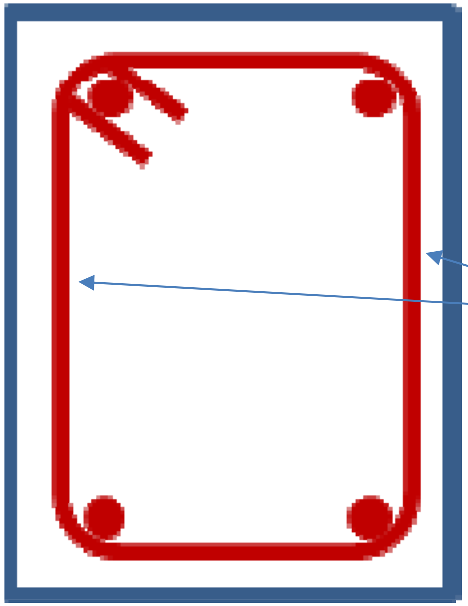
1. Strengthening for flexure using EB-FRP
2. RC beam strengthened for flexure - Application
3. Shear strengthening using EB-FRP
4. **RC beam strengthened for shear - Application**
5. Confinement

RC beam strengthened with CFRP composite for bending

1. SYSTEM



2. CROSS SECTION AND MATERIALS



RC beam (indoor)

$h = 40$ cm

$b = 20$ cm

$d = 36.7$ cm

$A_{s1} = 2\phi16 = 4.02\ \text{cm}^2$

$\phi_w = \phi6$

$s_w = 150$ mm

CFRP composite

$w_f = 200$ mm

$s_f = 200$ mm

$t_f = 0.131$ mm

$E_{fk} = 238000\ \text{N/mm}^2$

$\varepsilon_{fk} = 18$ ‰

Concrete:

C30/37

$f_{ck} = 30\ \text{N/mm}^2$

$E_c = 33000\ \text{N/mm}^2$

$f_{ctm} = 2.9\ \text{N/mm}^2$

Steel:

$f_{ywk} = 500\ \text{N/mm}^2$

$E_s = 200000\ \text{N/mm}^2$

3. LOADS AND DESIGN VALUES

1. Self-weight	$G = 2.0$ kN/m
2. Live load before strengthening	$q_1 = 8.0$ kN/m
3. Additional live load	$q_2 = 18.0$ kN/m
4. Live load after strengthening	$q_1 + q_2 = 26.0$ kN/m

3. LOADS AND DESIGN VALUES

1. Self-weight	G = 2.0 kN/m
2. Live load before strengthening	$q_1 = 8.0$ kN/m
3. Additional live load	$q_2 = 18.0$ kN/m
4. Live load after strengthening	$q_1 + q_2 = 26.0$ kN/m

Fundamental load combination

$$1.35 \sum_{j=1}^{n} G_{k,j} + 1.5 Q_{k,1} \quad = 41.7\ kN/m$$

$$\rightarrow\ V_{Ed} = P_{tot} \cdot \frac{L}{2} = \underline{\hspace{2cm}}\ \mathrm{kN}$$

3. LOADS AND DESIGN VALUES

$$f_{cd} = \frac{f_{ck}}{\gamma_c} = 20\ MPa$$

$$\gamma_c = 1.5$$

$$f_{ywd} = \frac{f_{ywk}}{\gamma_s} = 435\ MPa$$

$$\gamma_s = 1.15$$

3. LOADS AND DESIGN VALUES

Resisting shear force of the unstrengthened member

$$V_{Rd} = \min\left(V_{Rd,s}, V_{Rd,max}\right)$$

Where

$$V_{Rd,s} = \frac{A_{sw}}{s} \cdot z \cdot f_{ywd} \cdot ctg\theta$$

$$V_{Rd,max} = \alpha_{cw} b_w \cdot z \cdot \nu_1 \cdot f_{cd} sin\theta cos\theta$$

$$\nu_1 = 0{,}6\left(1 - \frac{f_{ck}}{250}\right)$$

strength reduction factor for concrete cracked in shear

3. LOADS AND DESIGN VALUES

Resisting shear force of the unstrengthened member

$$V_{Rd} = \min\left(V_{Rd,s}, V_{Rd,max}\right) = \underline{\hspace{3cm}}\ kN$$

Where

$$V_{Rd,s} = \frac{A_{sw}}{s} \cdot z \cdot f_{ywd} \cdot ctg\theta$$

$$V_{Rd,s} = \underline{\hspace{2cm}} kN$$

$$V_{Rd,max} = \alpha_{cw} b_w \cdot z \cdot \nu_1 \cdot f_{cd} sin\theta cos\theta$$

$$V_{Rd,max} = \underline{\hspace{2.5cm}}\ kN$$

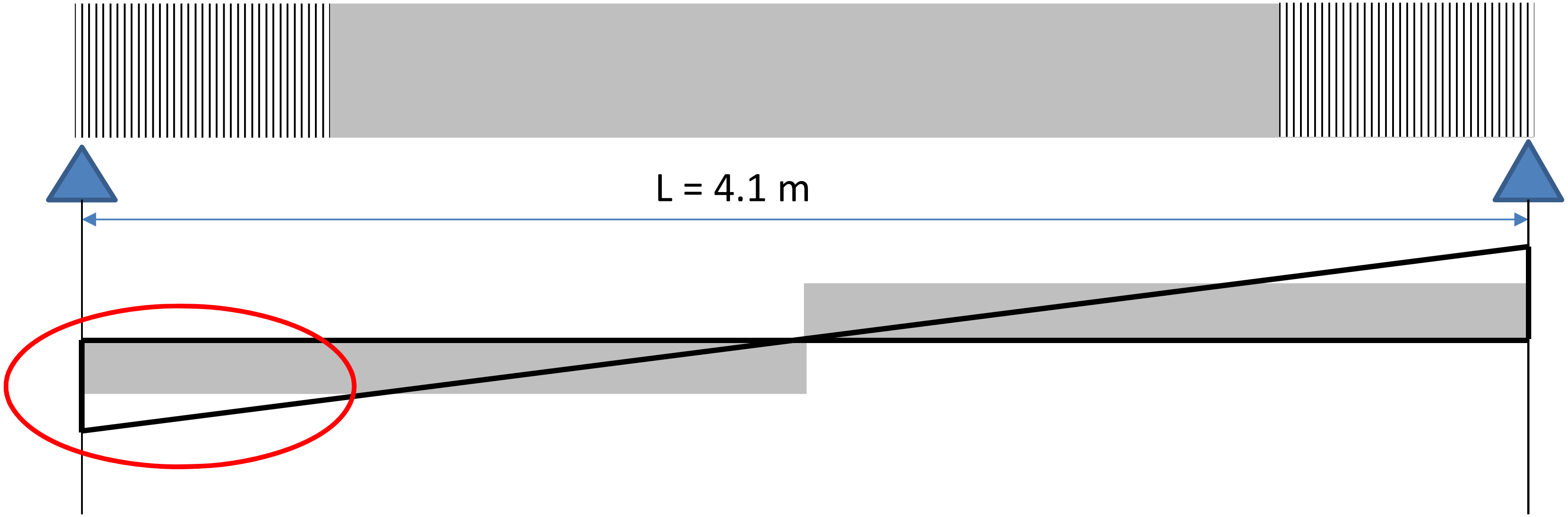
$$\nu_1 = 0{,}6\left(1 - \frac{f_{ck}}{250}\right) = \underline{\hspace{1cm}}$$

strength reduction factor for concrete cracked in shear

3. LOADS AND DESIGN VALUES

Shear force difference:

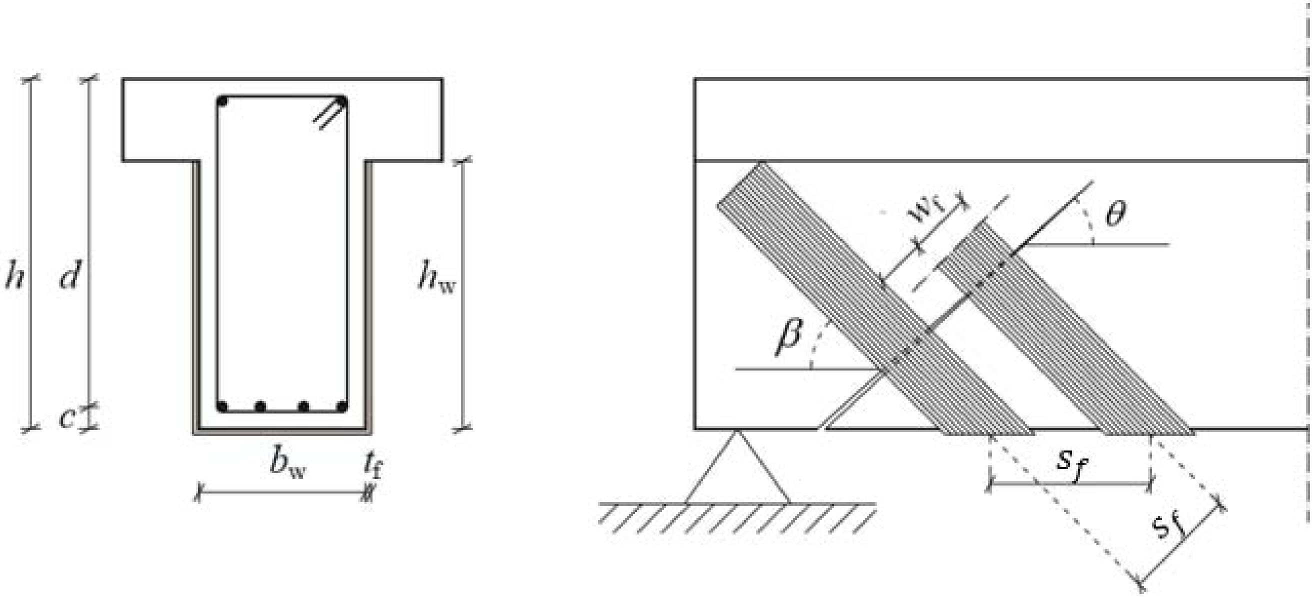
$$V_{Rd,fnec} = V_{Ed} - V_{Rd} = \_\_\_\_\_\ kN$$



4. FRP CONTRIBUTION TO THE SHEAR CAPACITY

$$V_{Rd,f} = \frac{1}{\gamma_{Rd}} 0.9d\, f_{fed} \cdot 2 \cdot t_f (cos\theta + cos\beta) \cdot \frac{w_f}{s_f}$$

(formula for U-wrapped configurations – CNR DT200)



4. FRP CONTRIBUTION TO THE SHEAR CAPACITY

$$V_{Rd,f} = \frac{1}{\gamma_{Rd}} 0.9d f_{fed} \cdot 2 \cdot t_f (cos\theta + cos\beta) \cdot \frac{w_f}{s_f}$$

Where, for a U-wrappwed configuration

$$f_{fed} = f_{fdd} \left(1 - \frac{1}{3} \cdot \frac{l_e \cdot sin\beta}{\min(0.9d, h_w)}\right)$$

$$l_e = \sqrt{\frac{E_f t_f}{2 \cdot f_{ctm}}}$$

the optimal bond length

$$f_{fdd} = \frac{1}{\gamma_{fd} \cdot \sqrt{\gamma_c}} \sqrt{\frac{2 \cdot E_f \cdot \Gamma_{Fk}}{t_f}}$$

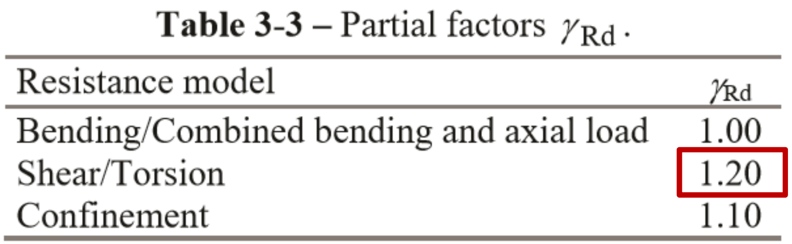


Table 3-3 – Partial factors γ_{Rd}.

Resistance model	γ_{Rd}
Bending/Combined bending and axial load	1.00
Shear/Torsion	1.20
Confinement	1.10

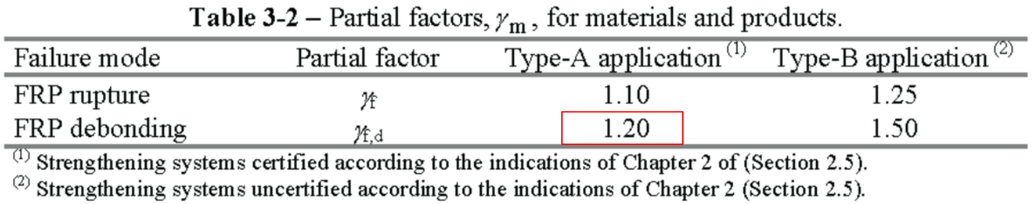


Table 3-2 – Partial factors, γ_m, for materials and products.

Failure mode	Partial factor	Type-A application (1)	Type-B application (2)
FRP rupture	γ_f	1.10	1.25
FRP debonding	$\gamma_{f,d}$	1.20	1.50

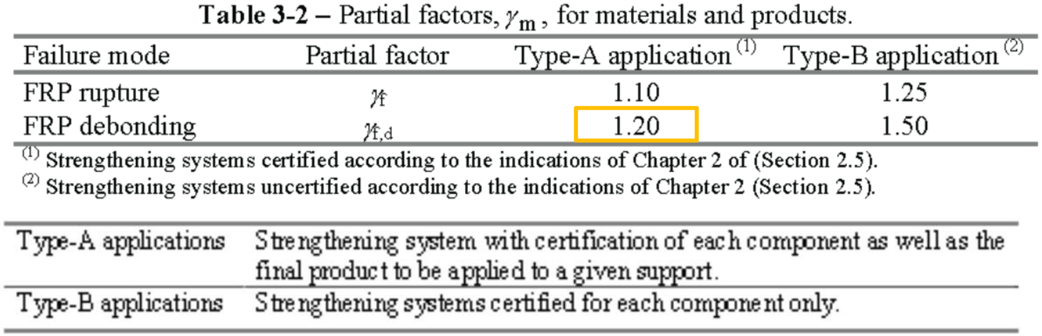
(1) Strengthening systems certified according to the indications of Chapter 2 of (Section 2.5).
(2) Strengthening systems uncertified according to the indications of Chapter 2 (Section 2.5).

4. FRP CONTRIBUTION TO THE SHEAR CAPACITY

$$V_{Rd,f} = \frac{1}{\gamma_{Rd}} 0.9d\, f_{fed} \cdot 2 \cdot t_f (cos\theta + cos\beta) \cdot \frac{w_f}{s_f}$$

Where, for a U-wrapped configuration

$$f_{fdd} = \frac{1}{\gamma_{fd} \cdot \sqrt{\gamma_c}} \sqrt{\frac{2 \cdot E_f \cdot \Gamma_{Fk}}{t_f}}$$



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(1) Strengthening systems certified according to the indications of Chapter 2 of (Section 2.5).
(2) Strengthening systems uncertified according to the indications of Chapter 2 (Section 2.5).

Type-A applications	Strengthening system with certification of each component as well as the final product to be applied to a given support.
Type-B applications	Strengthening systems certified for each component only.

$\Gamma_{Fk} = 0.03 k_b \cdot \sqrt{f_{ck} \cdot f_{ctm}}$ - the specific fracture energy of the FRP - concrete interface

$$k_b = \sqrt{\frac{2 - b_f/b}{1 + b_f/400}} \geq 1$$

When calculating f_{fdd}, the k_b coefficient shall be considered as follows: for discrete FRP strips application, $b_f = w_f$ and $b = s_f$; for FRP systems installed continuously along the span length of the member it shall be permitted to consider $b_f = b = \min(0.9d, h_w) \cdot \sin(\theta + \beta)/\sin\theta$

4. FRP CONTRIBUTION TO THE SHEAR CAPACITY

$$V_{Rd,f} = \frac{1}{\gamma_{Rd}} 0.9d\, f_{fed} \cdot 2 \cdot t_f (cos\theta + cos\beta) \cdot \boxed{\frac{w_f}{s_f}}$$

Where, for a U-wrappwed configuration

$\frac{w_f}{s_f} = 1$ *for a continues fiber application*

4. FRP CONTRIBUTION TO THE SHEAR CAPACITY

$$k_b = \sqrt{\frac{2-b_f/b}{1+b_f/400}} = \_\_\_\_\_\_\_$$

$$b_f = b = \min(0.9d, h_w) \cdot \frac{\sin(\theta+\beta)}{\sin\theta} = \_\_\_\_\_ mm$$

$$\Gamma_{Fk} = 0.03k_b \cdot \sqrt{f_{ck} \cdot f_{ctm}} = \_\_\_\_\_ MPa$$

$$f_{fdd} = \frac{1}{\gamma_{fd} \cdot \sqrt{\gamma_c}} \sqrt{\frac{2 \cdot E_f \cdot \Gamma_{Fk}}{t_f}} = 686.09\ MPa$$

$$l_e = \sqrt{\frac{E_f t_f}{2 \cdot f_{ctm}}} = \_\_\_ mm$$

4. FRP CONTRIBUTION TO THE SHEAR CAPACITY

$$f_{fed} = f_{fdd}\left(1 - \frac{1}{3}\cdot\frac{l_e \cdot sin\beta}{\min(0.9d, h_w)}\right) = \_\_\_\_\_\_ MPa$$

$$V_{Rd,f} = \frac{1}{\gamma_{Rd}} 0.9d\, f_{fed} \cdot 2 \cdot t_f (cos\theta + cos\beta) \cdot \frac{w_f}{s_f} =$$

$$V_{Rd,f} = \_\_\_\_\_\_\_ kN$$

$$\boldsymbol{V_{Rd,f} = \_\_\_\_\_ kN > V_{Rd,nec} = 31.35\ kN}$$

1. Strengthening for flexure using EB-FRP

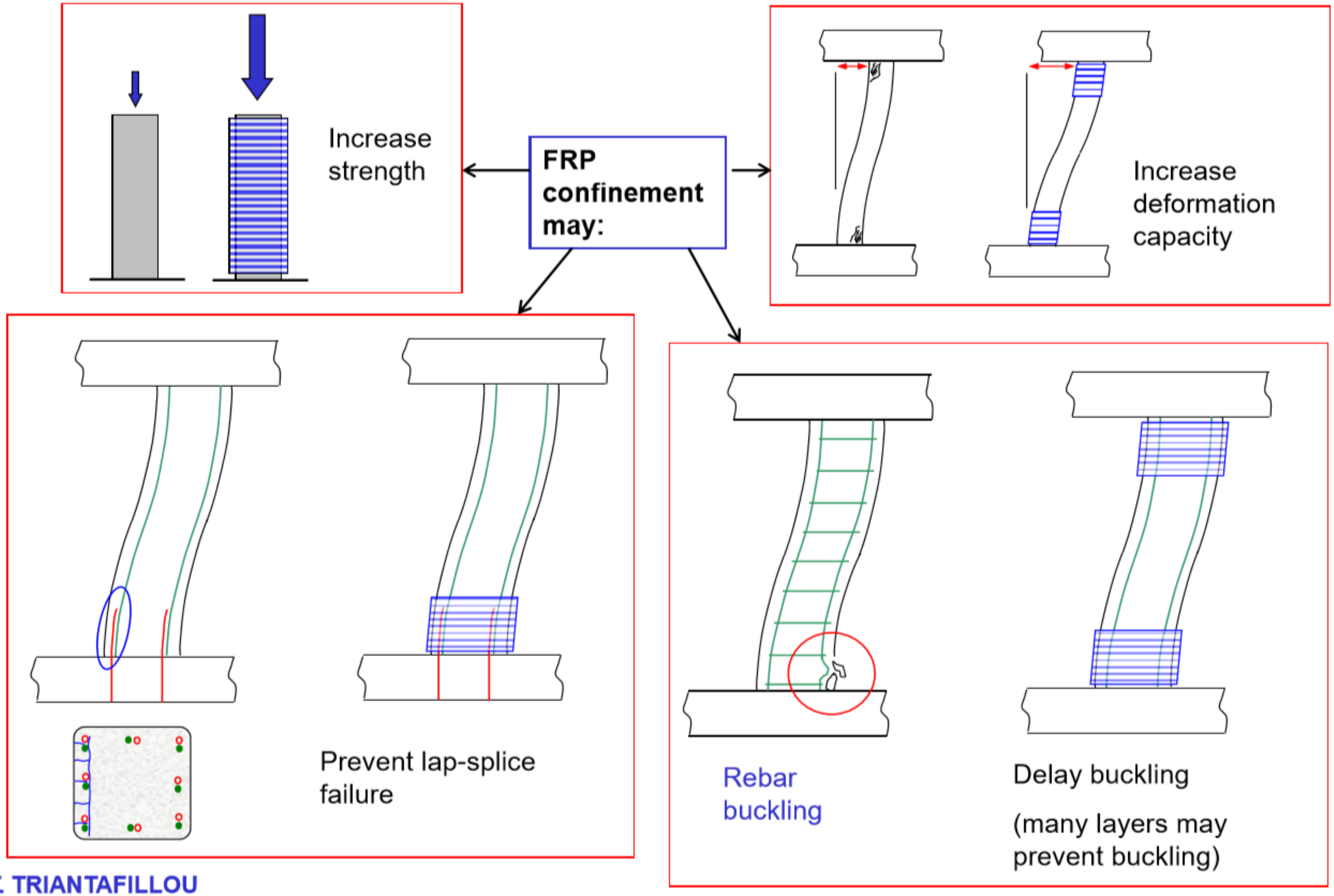
2. RC beam strengthened for flexure - Application

3. Shear strengthening using EB-FRP

4. RC beam strengthened for shear - Application

5. Confinement

CONFINEMENT EFFECTS



FRP confinement may:

Increase strength

Increase deformation capacity

Prevent lap-splice failure

Rebar buckling

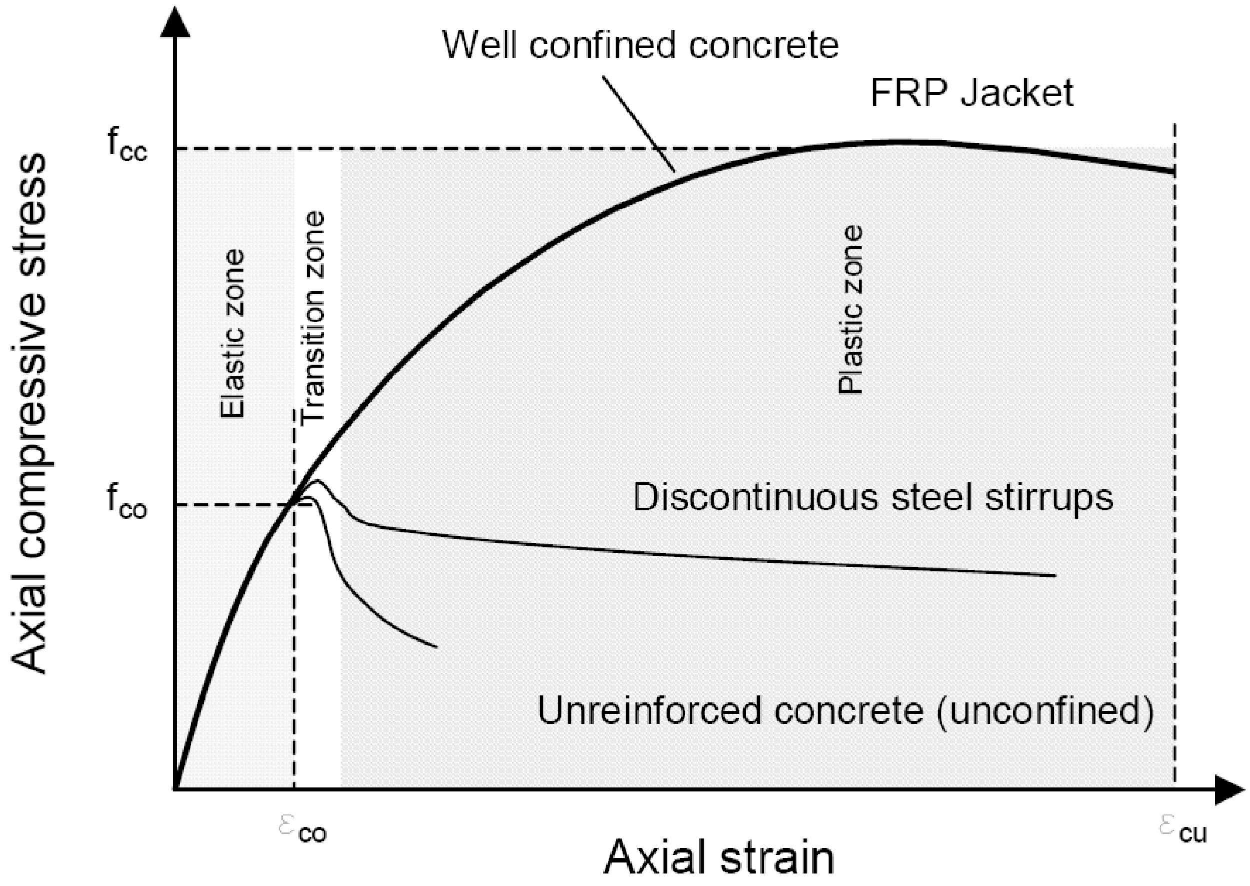
Delay buckling

(many layers may prevent buckling)

T. TRIANTAFILLOU

(Thanasis Triantafillou, University of Patras)

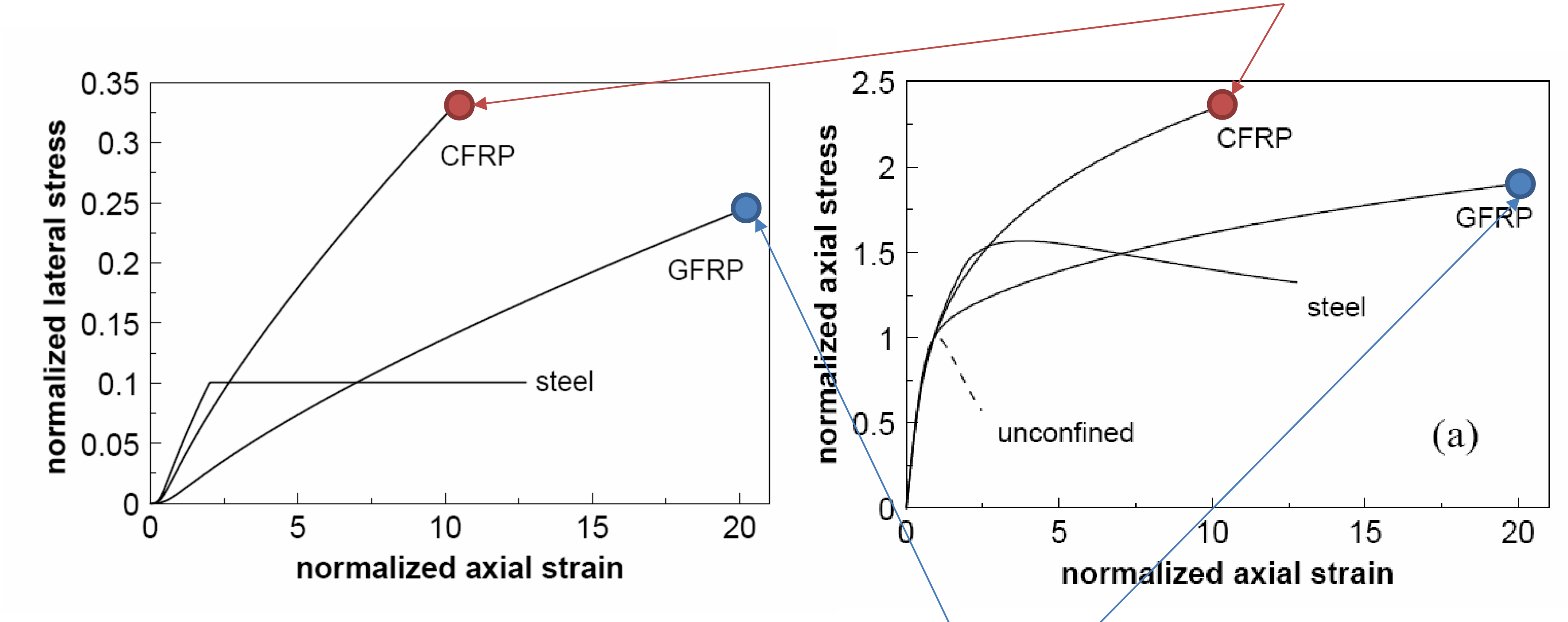
CONFINEMENT EFFECTS



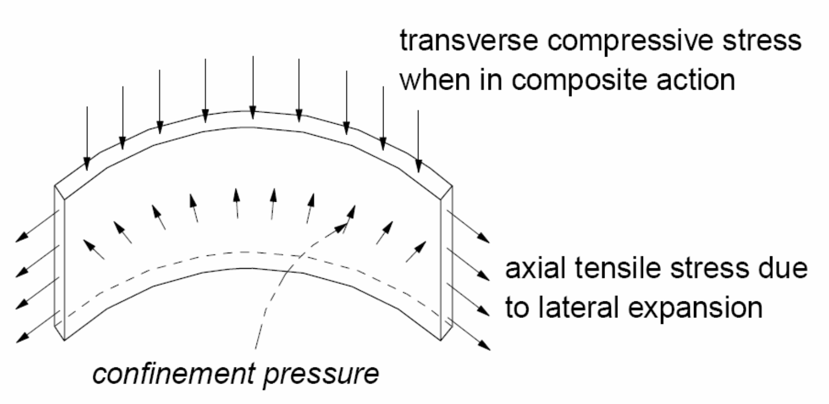
Comparison of the axial compressive stress as a function of the axial strain for an unreinforced, reinforced with steel stirrups and FRP-wrapped column (Holloway and Head, 2001).

CONFINEMENT EFFECTS

higher strength



higher deformation



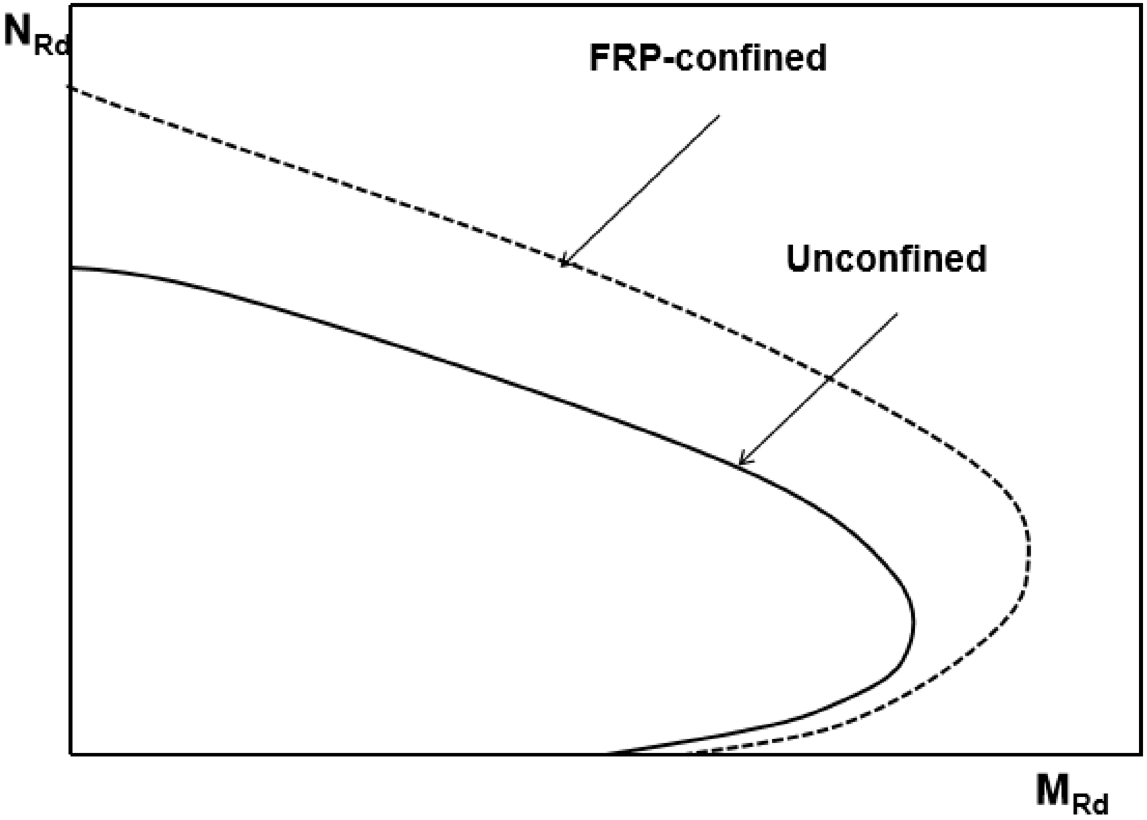
(fib)

CONFINEMENT JACKETS SHOULD BE DESIGNED

→ **To increase deformation capacity** (chord rotation or ductility factor)

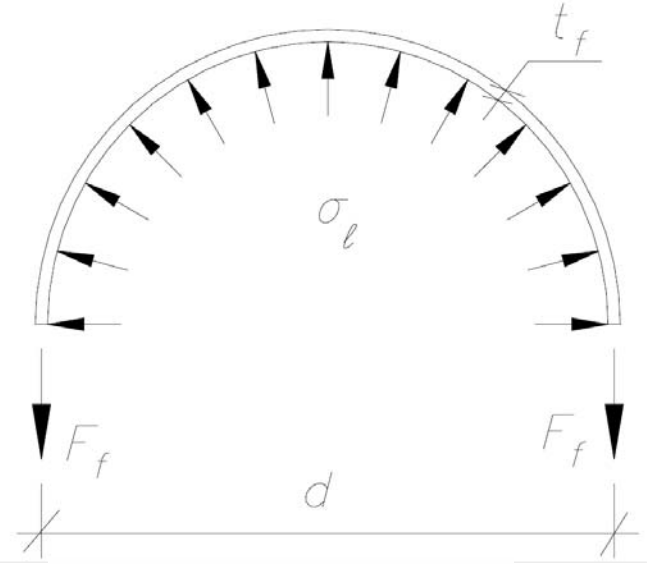
→ **To increase shear resistance** in such way, that flexural failure precedes shear failure.

CONFINEMENT JACKETS SHOULDN'T BE USED TO INCREASE FLEXURAL RESISTANCE



CONFINEMENT DESIGN

Circular column



$$\sigma_\ell = \frac{1}{2}\rho_f \varepsilon_f E_f$$

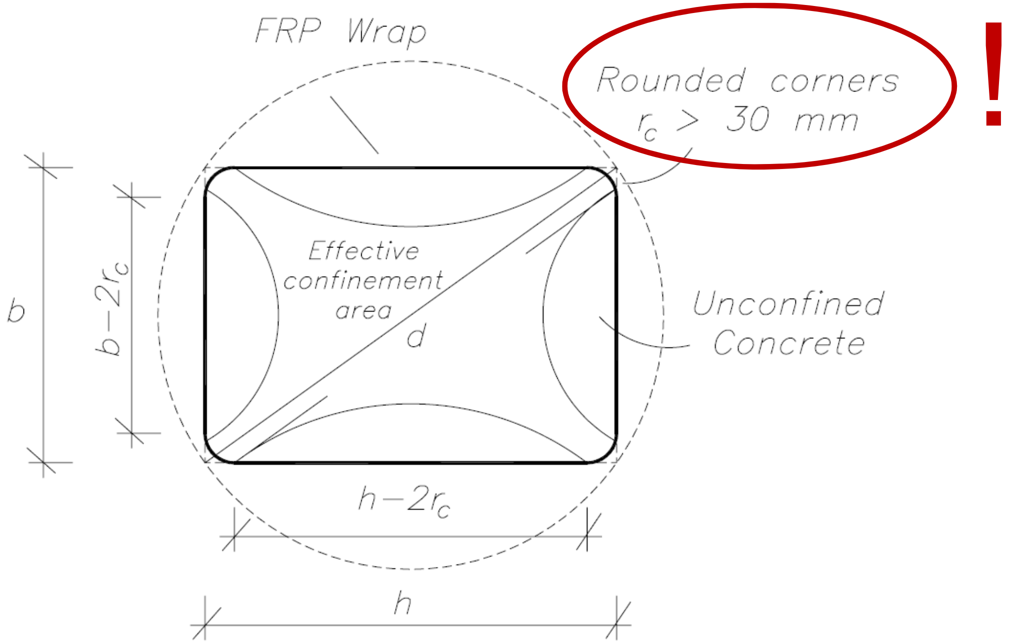
$$\rho_f \approx \frac{4t_f}{d}$$

$$\varepsilon_f = \varepsilon_{fu}$$

!

fib

Rectangular column



$$\sigma_\ell = \frac{2\varepsilon_f E_f t_f}{\sqrt{h^2 + b^2}}$$

Teng et. al.

THANK YOU FOR YOUR ATTENTION!

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