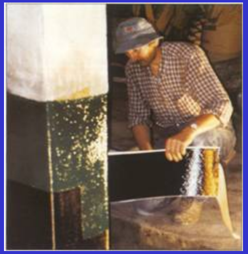
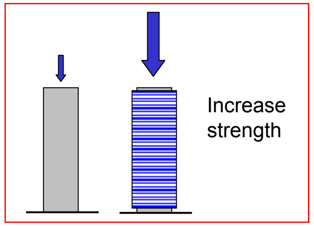
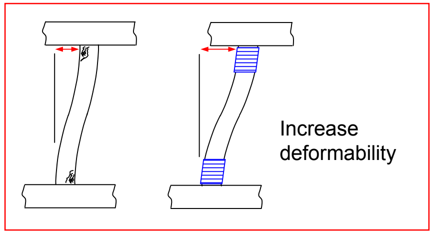
CONFINEMENT OF RC

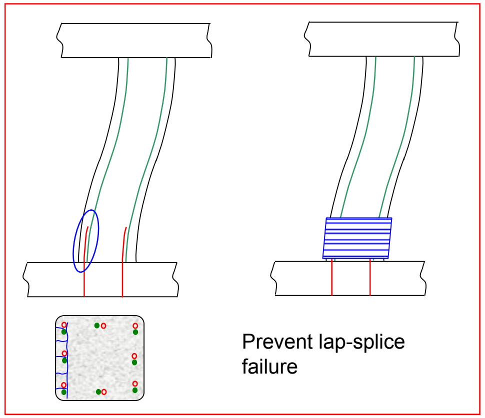




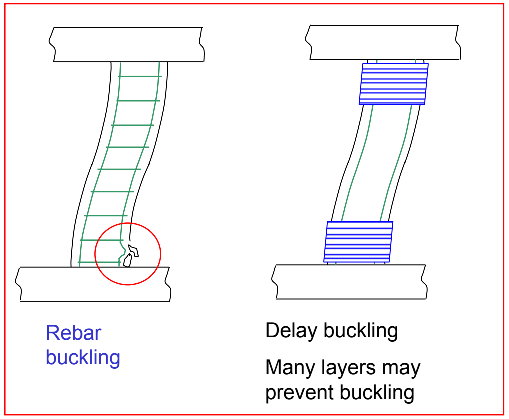
Increase strength



Increase deformability



Prevent lap-splice failure

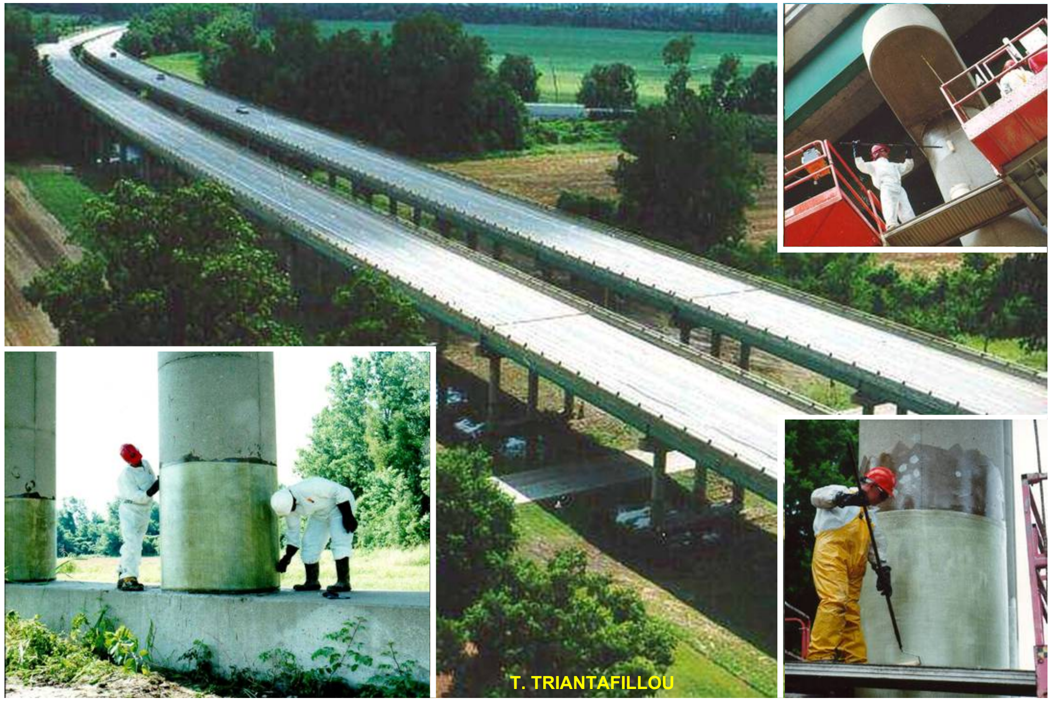


Rebar buckling

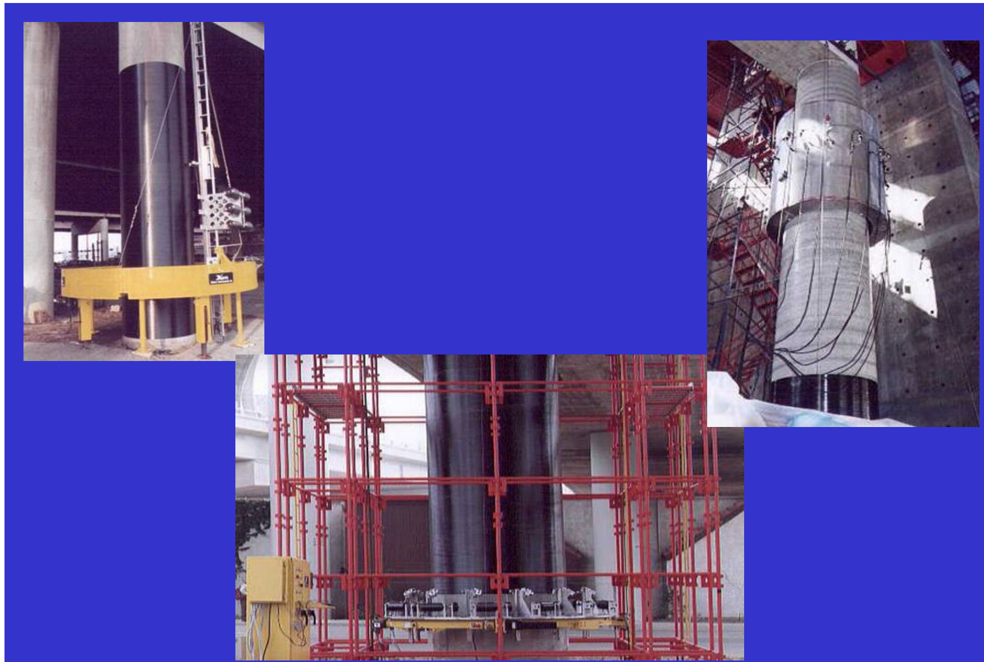
Delay buckling

Many layers may prevent buckling

T. TRIANTAFILLOU



T. TRIANTAFILLOU



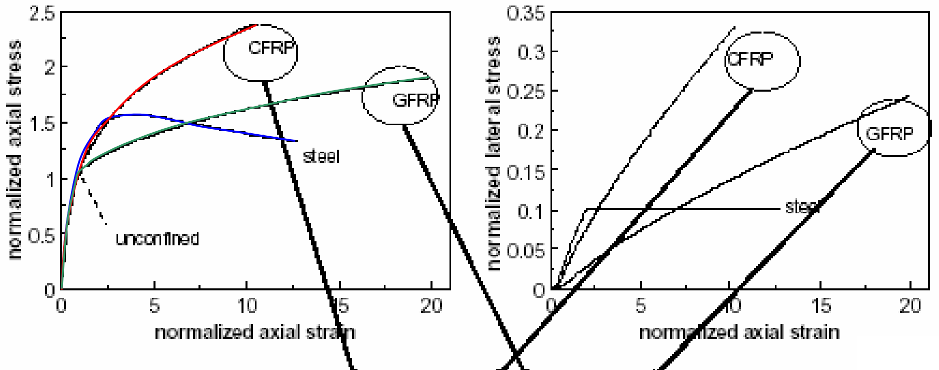
T. TRIANTAFILLOU

T. TRIANTAFILLOU

Impact

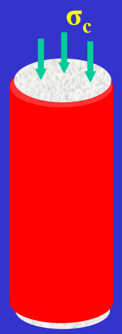
Confinement of leaking water-pipe

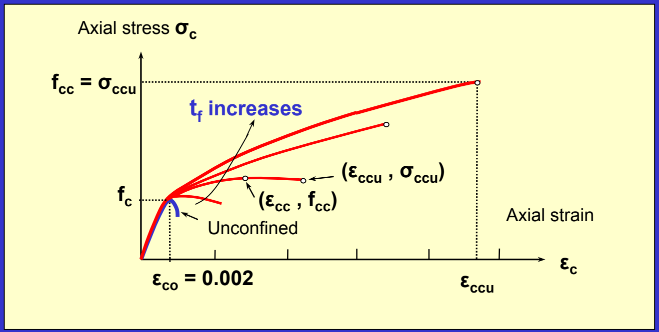
(Thessaloniki, Fyfe Europe s.a.)

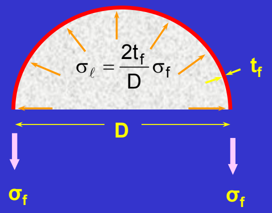


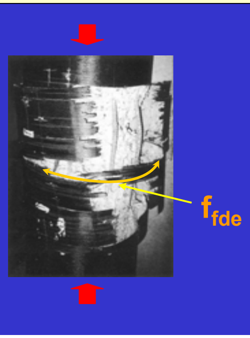
Higher strength

Higher deformability





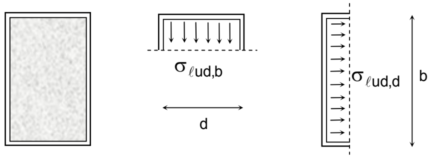




Confinement models

$$\frac{f_{ccd}}{f_{cd}} = 1 + k_1 (\frac{\sigma_{\ell ud}}{f_{cd}})^m$$

$$\frac{\varepsilon_{ccu}}{\varepsilon_{cu}} = 1 + k_2 (\frac{\sigma_{\ell ud}}{f_{cd}})^n$$



Jacket characteristics

$$\sigma_{\ell ud} \approx \frac{1}{2}\left(\sigma_{\ell ud,b} + \sigma_{\ell ud,d}\right) = \frac{1}{2}\alpha_f\left(\frac{2t_f}{d} f_{fde} + \frac{2t_f}{b} f_{fde}\right) = \alpha_f \frac{(b+d)t_f}{bd} f_{fde}$$

Effectiveness coefficient

fib Bulletin 14

$$f_{ccd} = E_{sec,ud}\varepsilon_{ccu} \geq f_{cd}$$

$$\varepsilon_{ccu} = 0.002[1+5(\alpha_{1d}\alpha_{2d}-1)]\left[\frac{E_{sec,Md}(E_c - E_{sec,ud})}{E_{sec,ud}(E_c - E_{sec,Md})}\right]^{1-\frac{E_{sec,Md}}{E_c}}$$

$$E_{sec,ud} = \frac{E_c}{1+2\left(\frac{E_c}{f_{cd}} - \frac{1}{0.002}\right)\frac{f_{fde}}{E_f}} \qquad E_{sec,Md} = \frac{\alpha_{1d}\alpha_{2d}f_{cd}}{0.002[1+5(\alpha_{1d}\alpha_{2d}-1)]}$$

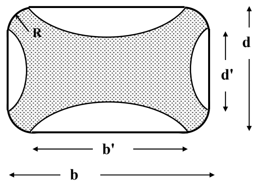
$$\alpha_{1d} = 2.254\sqrt{1+7.94\frac{\sigma_{\ell ud,b}}{f_{cd}}} - 2\frac{\sigma_{\ell ud,b}}{f_{cd}} - 1.254$$

$$\alpha_{2d} = 1 - \left[0.6\left(\frac{d}{b}\right)^2 - 1.4\frac{d}{b} + 0.8\right]\sqrt{\frac{\sigma_{\ell ud,b}}{f_{cd}}} \qquad \sigma_{\ell ud,b} = \boxed{\frac{t_f}{d}}\boxed{\alpha_f}\boxed{f_{fde}}$$

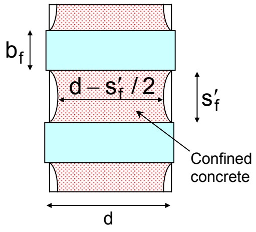
$$\alpha_f = \alpha_n \times \alpha_s \times \alpha_a \leq 1$$

Effectiveness coefficient

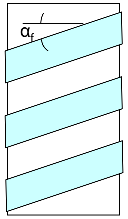
$$\alpha_f = \alpha_n \times \alpha_s \times \alpha_a \leq 1$$



$$\alpha_n = \frac{A_e}{A_g} = 1 - \frac{b'^2 + d'^2}{3A_g\left(1 - \frac{A_s}{A_g}\right)}$$



$$\alpha_s = \frac{\left(1 - \frac{s_f'}{2d}\right)^2}{1 - \frac{A_s}{A_g}}$$



$$\alpha_a = \frac{1}{1+(\tan\alpha_f)^2}$$

EXAMPLES

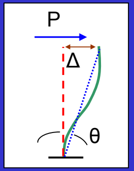
f_{cd} = 20 MPa E_c = 33.5 GPa

Target : Increase strength to 35 MPa, ultimate strain to ε_{ccu} = 0.025

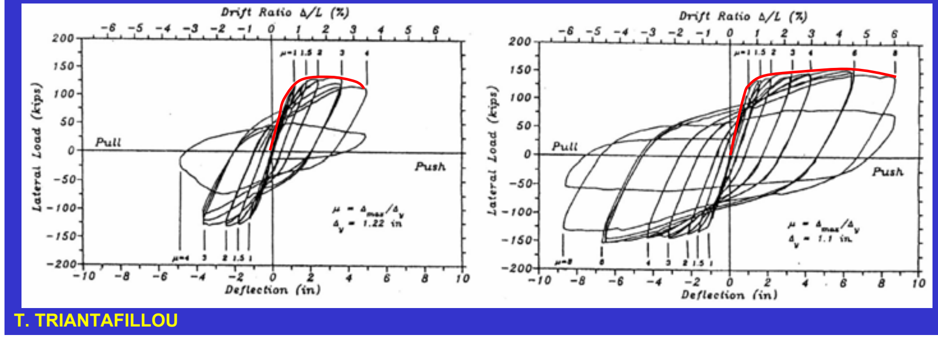
Carbon fibers, E_f = 230 GPa, f_{fde} = 2460 MPa. Glass fibers, E_f = 70 GPa, f_{fde} = 1330 MPa

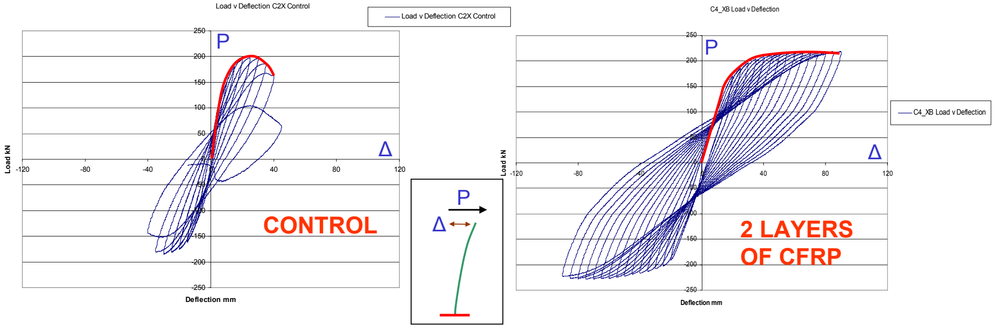
Section	R (mm)	A_g (cm²)	α_f (effectiveness)	Required jacket thickness t_f (mm)			
				Carbon fibers		Glass fibers	
				for f_{ccd} = 35 MPa	*for ε_{ccu} = 0.025*	for f_{ccd} = 35 MPa	*for ε_{ccu} = 0.025*
 300 300	20	896.5	*0.50*	0.39	*0.31*	0.82	*0.12*
 250 500	20	1246.5	*0.32*	0.74	*0.56*	1.56	*0.22*
 300 300	40	886.2	*0.64*	0.31	*0.24*	0.64	*0.10*

INCREASE OF DEFORMABILITY

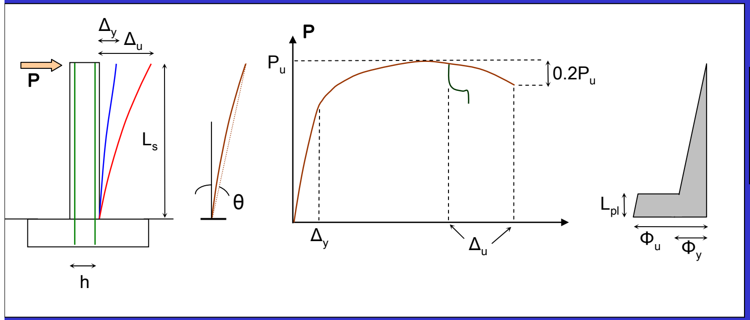


- CHORD ROTATION
- CHORD ROTATION (OR DISPLACEMENT) DUCTILITY FACTOR
- CURVATURE DUCTILITY FACTOR





DESIGN OF JACKET FOR A TARGET CHORD ROTATION



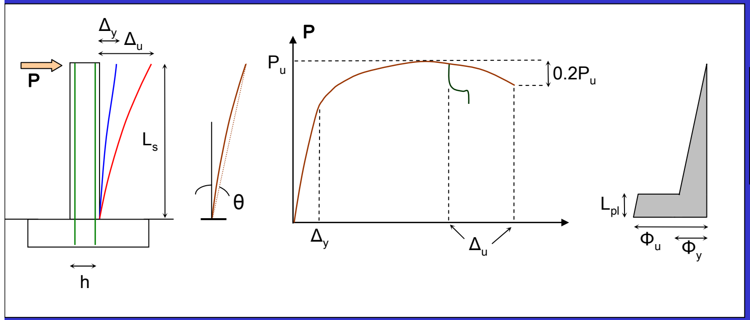
Chord rotation at ultimate θ_u

$$\theta_u \approx \theta_y + (\phi_u - \phi_y)L_{pl}\left(1 - 0.5\frac{L_{pl}}{L_s}\right) \qquad L_{pl} = 0.1L_s + 0.17h + \frac{0.24f_y}{\sqrt{f_c}}d_b \qquad \phi_u = \varepsilon_{ccu} / x_u$$

Expressed in terms of jacket thickness through the confinement model

$$\theta_y \approx \phi_y \frac{L_s}{3} + 0.0013\left(1 + 1.5\frac{h}{L_s}\right) + 0.13\phi_y \frac{f_y}{\sqrt{f_c}}d_b$$

DESIGN OF JACKET FOR A TARGET CHORD ROTATION - EMPIRICAL EQUATION

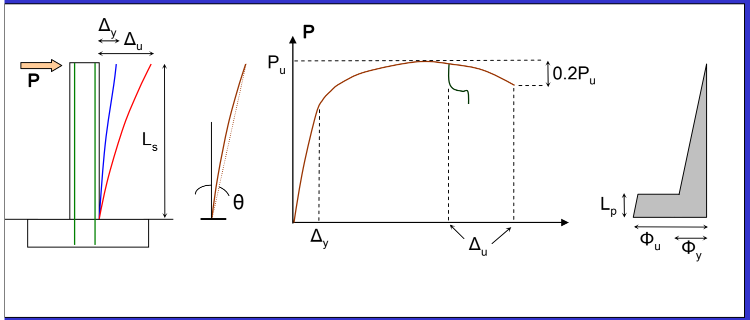


Chord rotation at ultimate θ_u

$$\theta_u = 0.016\left(0.3^{v}\right)\left[\frac{\max(0.01,\omega')}{\max(0.01,\omega)}f_c\right]^{0.225}\left(\frac{L_s}{h}\right)^{0.35} 25^{\left(\alpha\rho_{sx}\frac{f_{yw}}{f_c} + \alpha_f\rho_{fx}\frac{f_{fe}}{f_c}\right)}\left(1.25^{100\rho_d}\right)$$

$$f_{fe} = \min(f_f, \varepsilon_{fu}E_f)\left[1 - 0.7\min(f_f, \varepsilon_{fu}E_f)\frac{\rho_{fx}}{f_c}\right]$$

DESIGN OF JACKET FOR DUCTILITY



Chord rotation (or displacement) ductility factor

$$\mu_\Delta = \frac{\Delta_u}{\Delta_y} = \mu_\theta = \frac{\theta_u}{\theta_y}$$

Tastani & Pantazopoulou (2002)

Alternative but very conservative approach

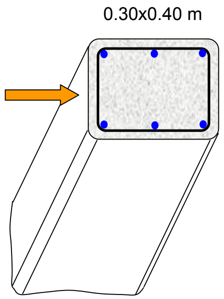
$$\boxed{\mu_\Delta} = \mu_\theta = 1.3 + 12.4\left(\frac{\sigma_{\ell u,b}}{f_c} - 0.1\right) \geq 1.3$$

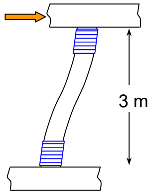
$$\sigma_{\ell u,b} = \alpha_f \frac{2\boxed{t_f}}{d} f_{fe}$$

EXAMPLE

Corner radius R = 25 mm

f_c = 11 MPa, longitudinal reinforcment 6Φ18, f_y = 350 MPa





Carbon fibres,
E_f = 230 GPa ,
f_{fe} = 3150 MPa ,
t_{fib} = 0.12 mm

Effectiveness coefficient

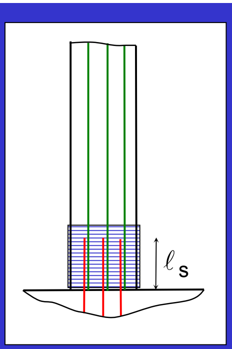
$$\alpha_n = 1 - \frac{35^2 + 25^2}{3 \times 1195 \times \left(1 - \frac{15.25}{1195}\right)} = 0.48$$

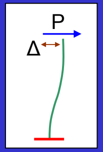
Required jacket thickness t_f for μ_Δ = 4

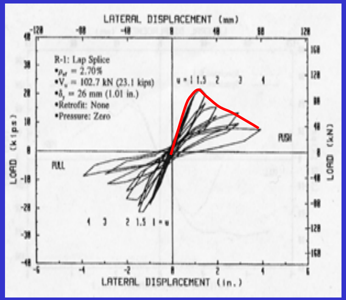
$$4 = 1.3 + 12.4\left(\frac{0.48 \times \frac{2t_f}{300} \times 3150}{11} - 0.1\right)$$

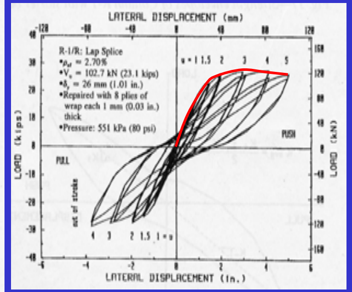
t_f = 0.35 mm → 3 layers → μ_Δ = 4.15

CONFINEMENT AT LAP SPLICES

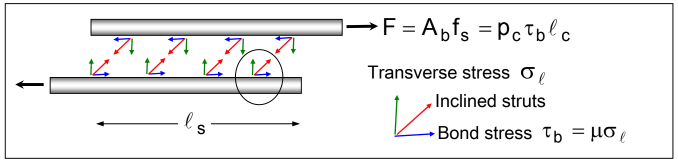








DESIGN OF JACKET TO PREVENT LAP-SPLICE FAILURE

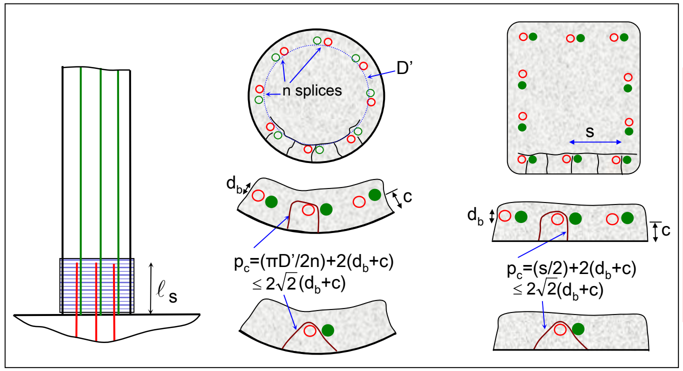


$F = A_b f_s = p_c \tau_b \ell_c$

Transverse stress σ_ℓ

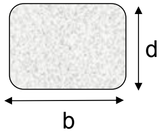
Inclined struts

Bond stress $\tau_b = \mu\sigma_\ell$



p_c=(πD'/2n)+2(d_b+c) $\leq 2\sqrt{2}$(d_b+c)

p_c=(s/2)+2(d_b+c) $\leq 2\sqrt{2}$(d_b+c)



$$\boxed{t_f} = \gamma_{Rd}\frac{\left(1 - \frac{\ell_s}{\ell_{s,min}}\right) bdA_b f_y}{\alpha_f (b+d) p_c \mu f_{fe} \ell_s}$$

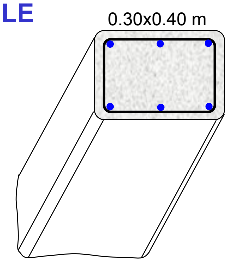
$f_{fe} \leq 0.001 \times E_f$

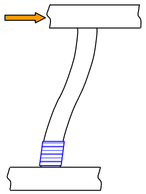
EXAMPLE

Radius at corners R = 25 mm , concrete cover c = 30 mm

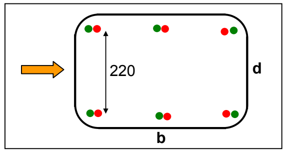
f_c = 11 MPa, longitudinal steel 6Φ16, f_y = 230 MPa

Lap splice 0.25 m, $\ell_{s,min}$= 0.90 m





Carbon fibers,
E_f = 230 GPa ,
f_{fe} = 2600 MPa ,
t_{fib} = 0.12 mm

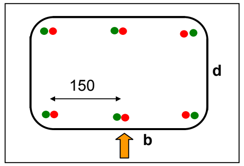


$$p_c = \min\left(\left[(220/2) + 2(18+30)\right], 2\sqrt{2}(18+30)\right) = 136\text{ mm}$$

$$A_b = \left(\pi \times 16^2\right)/4 = 200\text{ mm}^2$$

$$f_{fe} = \min(2600, 0.001 \times 230000) = \min(2600, 240) = 240\text{ MPa}$$

$$\boxed{t_f} = \frac{(\gamma_{Rd} = 1.5) \times \left(1 - \frac{0.25}{0.35}\right) \times 300 \times 400 \times 200 \times 230}{0.48 \times (300+400) \times 136 \times 1.4 \times 240 \times 500} = 0.31\text{mm} \rightarrow \boxed{3\text{ layers}}$$



$$p_c = \min\left(\left[(150/2) + 2(18+30)\right], 2\sqrt{2}(18+30)\right) = 136\text{mm}$$

$$\boxed{t_f} = 0.33\text{ mm} \rightarrow \boxed{3\text{ layers}}$$

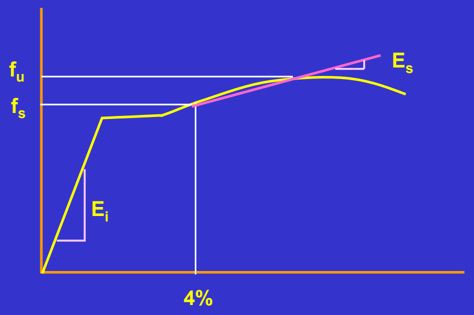
DELAY OF REBAR BUCKLING

$$t_f = \gamma_{Rd}\frac{0.45nf_s^2d}{4E_{ds}E_f\alpha_f} \approx \gamma_{Rd}\frac{10nd}{E_f\alpha_f}$$

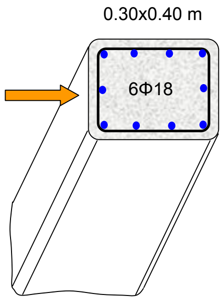
n = Total number of longitudinal rebars

d = Depth of cross section parallel to the plane of bending

$$E_{ds} = \frac{4E_sE_i}{\left(\sqrt{E_s}+\sqrt{E_i}\right)^2}$$ "Double" modulus



EXAMPLE

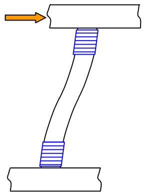


Carbon fibers,
E_f = 220 GPa ,
t_{fib} = 0.12 mm

Required jacket thickness

$$t_f = \frac{(\gamma_{Rd} = 1.5)\times 10\times 10\times 400}{230000\times 0.48} = 0.54\text{ mm}$$

5 layers



Glass fibres,
E_f = 70 GPa ,
t_{fib} = 0.17 mm

Required jacket thickness

$$t_f = \frac{(\gamma_{Rd} = 1.5)\times 10\times 10\times 400}{70000\times 0.48} = 1.77\text{ mm}$$

11 layers

SIMPLE DESIGN PROCEDURE

GIVEN THAT "STIFFENING" IS NOT A REQUIREMENT, THE JACKET SHOULD BE DESIGNED FOR:

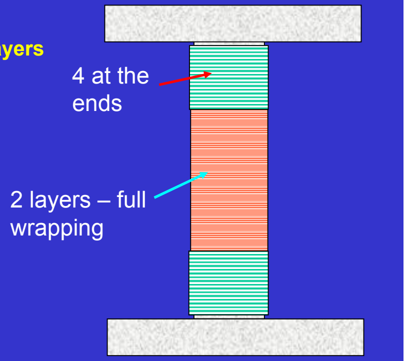
(a) the target deformability (chord rotation or ductility factor),

(b) the target shear resistance (such that flexural failure preceeds shear failure).

The jacket thickness in step (a) should be checked (and modified, if needed) for rebar buckling and lap splice failure.

EXAMPLE OF JACKET DESIGN

	Required number of layers
Deformability	4
Lap splices	2
Rebar buckling	3
Shear	2



NO IMPROVEMENTS REGARDING :

- Stiffening
- Second order (P-Δ) effects
- Flexural strengthening

IN ORDER TO HAVE A “FEELING” OF DIMENSIONS ...

2 layers of “standard” CFRP fabric (0.13 mm thick) is equivalent to S500 Φ8/10 stirrups

3 layers will provide a chord rotation ductility factor $\mu_\theta = \mu_\Delta > 4\text{-}5$ and will prevent lap splice failures in many “common” cases

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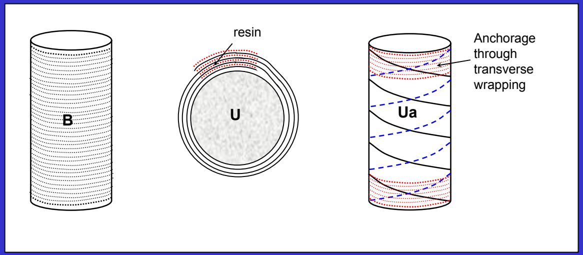
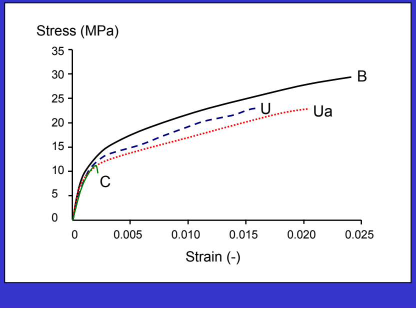
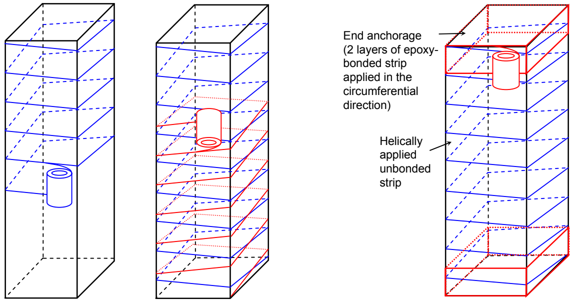
ALTERNATIVE CONFINEMENT SYSTEMS

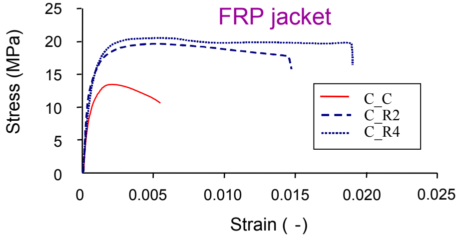




Helically applied unbonded strips



Classical FRP jacket



Helically applied unbonded strips with end anchorage