EC8 Webinars
Second Generation of Eurocode 8

Design of interventions

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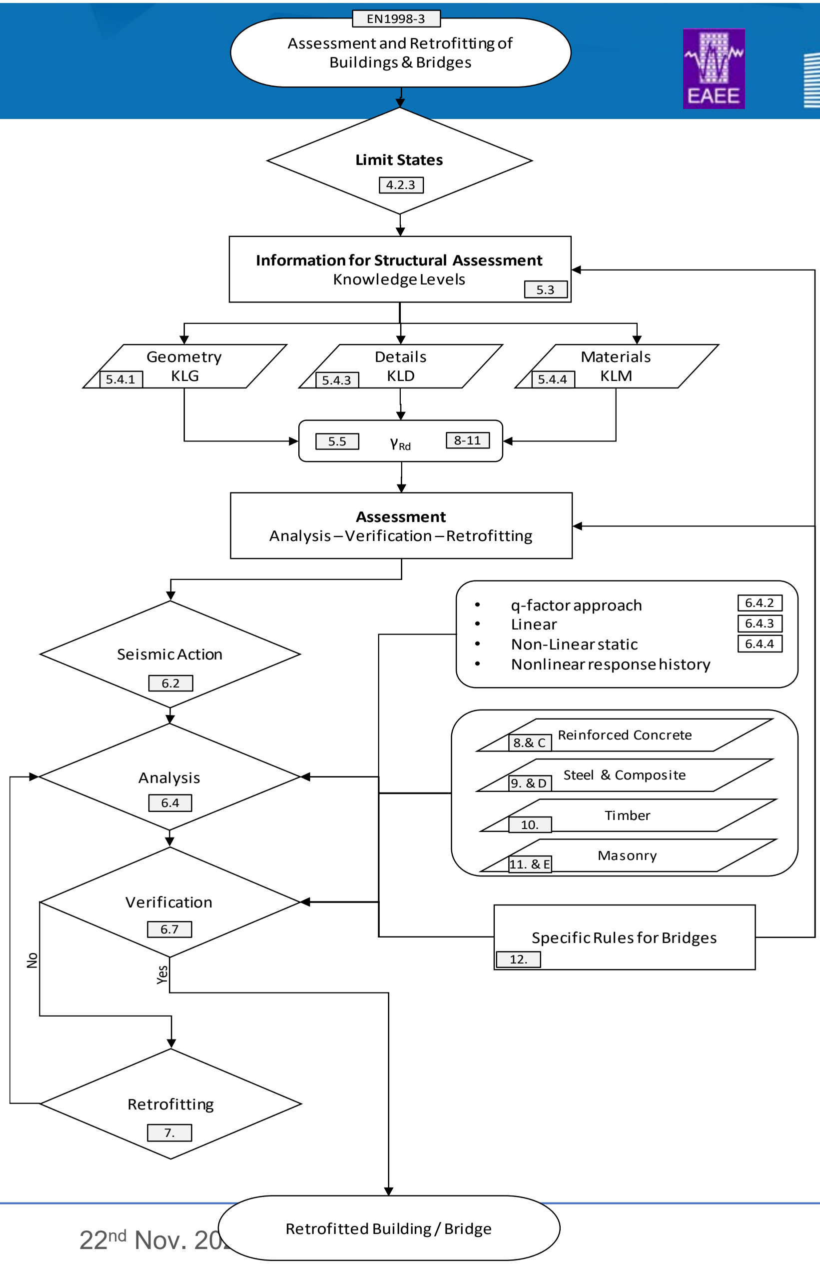
Outline of the assessment and retrofit procedure according to EC8-3 (2022)

1. Scope
2. Normative references
3. Terms, definitions, and symbols
4. Basis of design
5. Information for structural assessment
6. Seismic action, methods of analysis and verification
7. Design of structural intervention
8. Specific rules for reinforced concrete structures
9. Specific rules for steel and composite structures
10. Specific rules for timber structures
11. Specific rules for masonry structures
12. Specific rules for bridges



Key changes in Clause **7** (Design of structural intervention)

- Scope extended to cover bridges
- Detail was deliberately left out, to allow flexibility
  - the code should specify in detail how the (strengthened) structure is verified, not how the strengthening is made

    → but principles are included!
- Option of reducing demand given (passive systems, treated only in Parts 1-1 and 1-2)
- Still not properly covered the case that all seismic action is carried by new lateral system (existing system: classified as secondary elements)

cen bsi. NEN

Background Document for EN 1998-3

prepared by SC8.T3

Background to modifications in Clause 7

DESIGN OF STRUCTURAL INTERVENTIONS

Drafted by Andreas Kappos

24.5.2018

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7.1 Criteria for a structural intervention

- Identified local gross errors should be appropriately remedied
- In highly irregular buildings, structural regularity should be improved as much as possible, both in elevation and in plan
- Regularity can be improved by modification of strength and/or stiffness of an appropriate number of existing components, or by the introduction of new structural elements
- Increase in local ductility supply should be done where required to satisfy the verifications
- Increase in strength (due to intervention) should not reduce the available global ductility
- Specifically for masonry structures:
  - non-ductile lintels should be replaced
  - inadequate connections between floor and walls should be improved
  - out-of-plane horizontal thrusts against walls should be eliminated
- Option for reducing seismic action effects
  - seismic isolation and/or
  - supplemental damping

7.1.3 Types of intervention (may be used in combination)

- Local or overall modification of damaged or undamaged elements (repair, upgrading*, or full replacement), considering the stiffness, strength and/or ductility of these elements
- Addition of new structural elements (e.g. bracings; steel, timber or reinforced concrete belts in masonry construction; etc.) or infill walls
- Modification of the structural system (elimination of some structural joints; widening of joints; elimination of vulnerable elements; modification into more regular and/or more ductile arrangements)
- Addition of a new structural system to resist part of, or the entire, seismic action
- Possible transformation of existing ancillary** elements into structural elements
- Addition of passive protection devices → dissipative bracing and/or base isolation
- Mass reduction
- Restriction or change of use of the building
- Partial demolition

* strengthening → changed to 'upgrading'
** non-structural → changed to 'ancillary'

7.1.4 Ancillary elements

- Repair or upgrading of ancillary elements is also required whenever, in addition to functional requirements, the seismic behaviour of these elements may endanger the life of inhabitants or affect the value or integrity of goods stored in the building
- In such cases, full or partial collapse of these elements should be avoided by means of:
  - appropriate connections to structural elements
  - increasing the resistance of ancillary elements
  - taking measures of anchorage to prevent possible falling out of parts of these elements
- Consequences of these measures on the behaviour of structural elements should be taken into account

7.1.5 Justification of intervention type

- The documents relating to retrofit design shall include the justification of the type of intervention selected and the description of its expected effect on the structural response
  - this justification should be made available to the owner

7.2 Retrofit design procedure

Steps in Retrofit Design:

- Conceptual design
- Analysis
- Verifications

Conceptual design:

- possibly a preliminary analysis of the as-built structure to inform the selection
- selection of techniques and/or materials, and of type and configuration of the intervention
- preliminary estimation of dimensions of additional structural parts
- preliminary estimation of the modified stiffness of the retrofitted elements

Analysis (as per 6.4)

→ should account for the modified characteristics of the building

Verifications (as per 6.5 and 5.5)

→ should include both existing, modified and new structural elements

→ as a minimum, LS NC should be checked

- Information on the resistance of existing and retrofitted structural members can be found in the material-related Clauses 8, 9, 10, 11 and Annexes B, C and D

Resistance models for retrofitted R/C structures (§8.6)

Types of interventions covered:

- Reinforced concrete jackets
- Steel jackets
- FRP plating and wrapping

Information provided:

- Purpose and general principles
- Relationships for enhancement of strength, stiffness and deformation capacity
- Clamping of lap-splices
- Confinement action

➢ For jacketing, instead of verifying the interfaces between existing member and jacket, the simplifying concept of 'monolithicity factors' (term not in EC8-3) may be adopted

Relationships adopted in new EC8-3

$$M_y^* = (0.96 - 0.74\nu)\mathrm{M}_y$$

$$\theta_y^* = (1.26 + 0.28\nu)\theta_y$$

$$\theta_u^* = \theta_u$$

ν: normalised axial loading acting on the jacketed element

$$N/\left[b_c h_c f_{c,c} + \left(b_j h_j - b_c h_c\right) f_{c,j}\right]$$

(Thermou & Kappos, 2018, 2022)

Scope of current EC8-3 and Greek CSI

- Part 3 BD (2018):

'In applying EN1998-3 the engineer carrying out the design of a strengthening scheme will, most possibly, need guidance additional to that given in Clause 7, e.g. with regard to the most appropriate techniques to address a certain deficiency'

	OBJECTIVES		GREEK CODE (2012) DESIGN OF INTERVENTIONS	EC 8-PART 3 (2005) CAPACITY MODELS FOR STRENGTHENING
	1	Verification of the interface connection	Yes	No
	2	Interventions in critical regions of linear structural members	Yes	Yes
	3	Interventions to frame joints	Yes	No
	4	Interventions on shear walls	Yes	No
	5	Interventions on foundation elements	Yes	No
	6	Frame encasement	Yes	No
	7	Construction of external new shear walls	Yes	No

(Dritsos, 2013)

Appendix

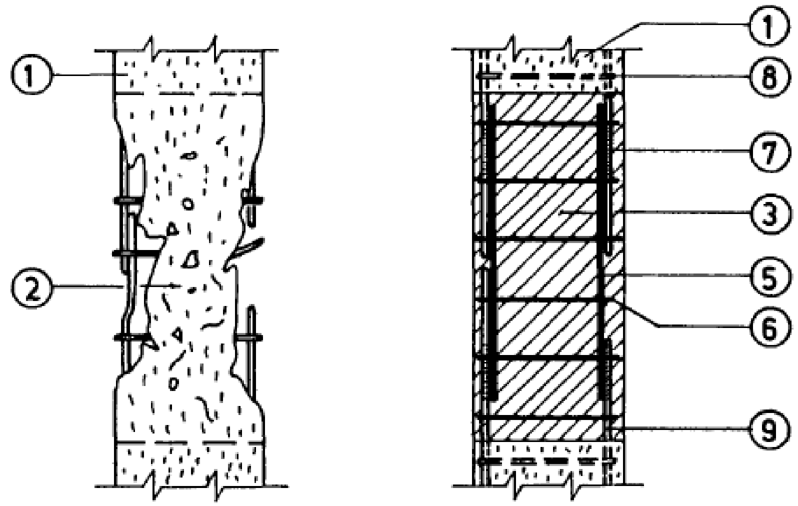
Techniques for repair and strengthening of existing R/C members

A. Kappos, 'Seismic retrofitting of reinforced concrete buildings', Keynote lecture, Eurocodes Balkan Summer School, 2021

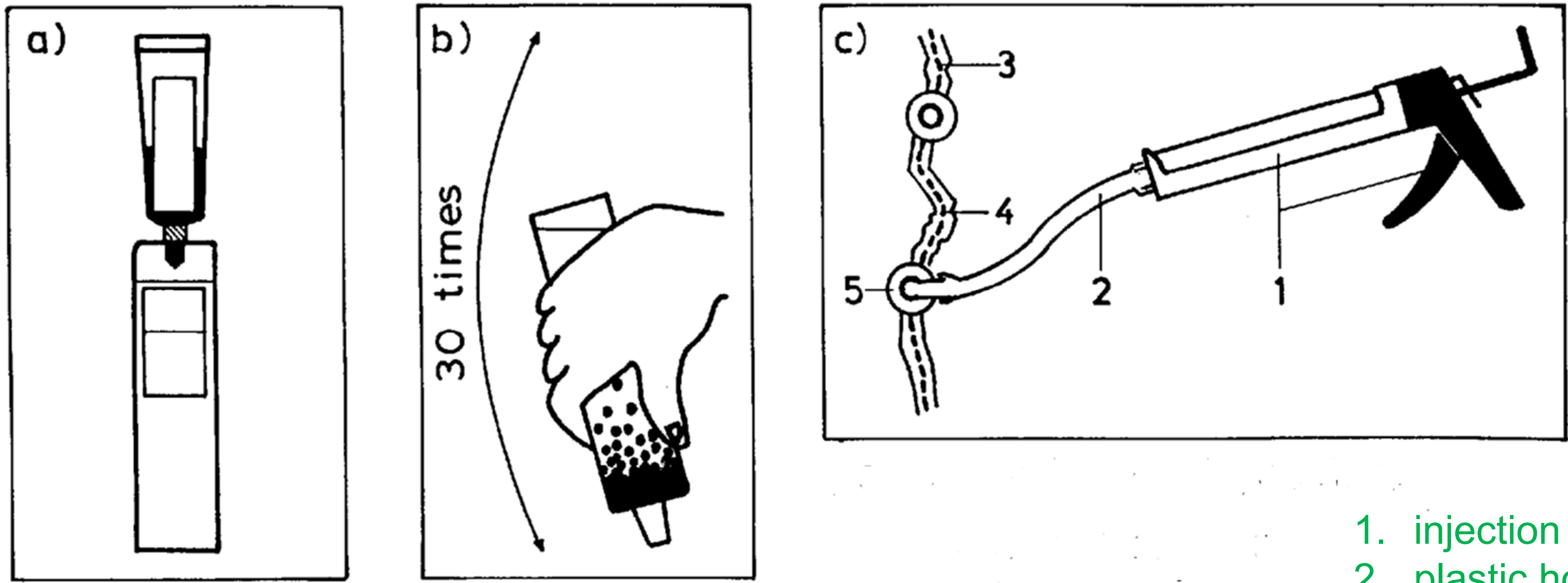
Local repair of damaged regions

- In lightly damaged R/C members, with a view to restoring the characteristics of the pristine member, intervention based on the ‘equal cross section’ concept is allowed, with or without the use of epoxy resins
- The locally repaired member may be considered as monolithic if the currently applicable technical specifications have been applied

from the UNDP/UNIDO Manual ‘Repair & strengthening of reinforced concrete, stone and brick masonry buildings’ (adopted by several Balkan countries)



1 - existing non-damaged concrete; 2 - existing damaged concrete; 2 - new concrete; 4 - buckled reinforcement; 5 - new reinforcement; 6 - new ties; 7 - welding; 8 - existing ties; 9 - existing reinforcement



1. injection gun
2. plastic hose
3. crack
4. sealer
5. nipples

Procedure for use of resins in repair of R/C members:

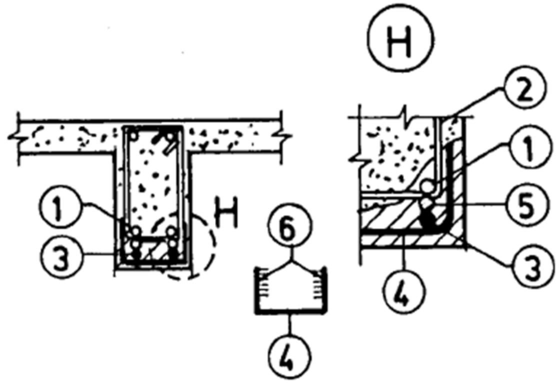
a. Mixing of resin with hardener

b. Homogenisation of resin and hardener

c. Carrying out the injection

(Penelis & Kappos, 2010)

Strengthening of tension zones



Addition of new R/C layer

- Increase of the flexural resistance with an additional R/C layer at the bottom (or the top)
- it can be applied to any type of R/C member (slab, beam, column, wall, foundation)
- Provided a number of conditions are met (roughening of the surface, dowels, …), the design of the intervention may be based on the monolithicity factor concept, i.e.

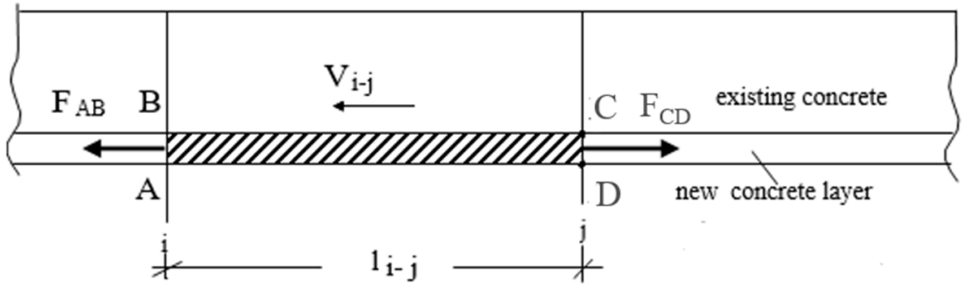
  $k_k = 0.80, \; k_r = 0.85, \; k_{\theta y} = 1.25, \; k_{\theta u} = 0.75$

- Sufficient shear resistance should be ensured at the interface (between the old and new concrete) even after possible detachment at the interface
  - ➢ this is satisfied if a min amount of transverse reinforcement is provided at the interface

$$\rho_{int} = \frac{A_{sd}}{A_{c,int} \sin\alpha} \geq 0.18 \frac{f_{ctm}}{f_{yk}}$$

- The new reinforcement should be properly anchored inside the existing member (either directly, or indirectly through steel plates, anchors, dowels, etc.)

Rigorous modelling of concrete interfaces



Shear force along the interface

$$V^{int.}_{Ed(i-j)} = V^{BC}_{Ed} = F_{AB} - F_{CD}$$

- the forces F_{AB}, F_{CD} are found from the corresponding bending moments, typically at the location of maximum (positive or negative) BM and at supports

$$V^{int.}_{Ed(i-j)} = \Delta M_{(i-j)} / z$$

- Interface shear resistance may consist of:
  - concrete-to-concrete bond (if applicable)
  - concrete to resin bond
  - concrete-to-concrete friction at the interface under compression
  - dowel resistance
  - resistance of links between existing and new reinforcement
- Relationships for the various resistance mechanisms may be found in sec. 6 of the GCSI (2017), e.g. for dowels

$$V_{Rd} = 0.65 d_b^2 \sqrt{f_{cd} f_{yd}} \le \frac{A_s f_{yd}}{\sqrt{3}} \quad [mm, MPa]$$

Addition of steel strips or FRP (fibre-reinforced polymer) strips/fabric

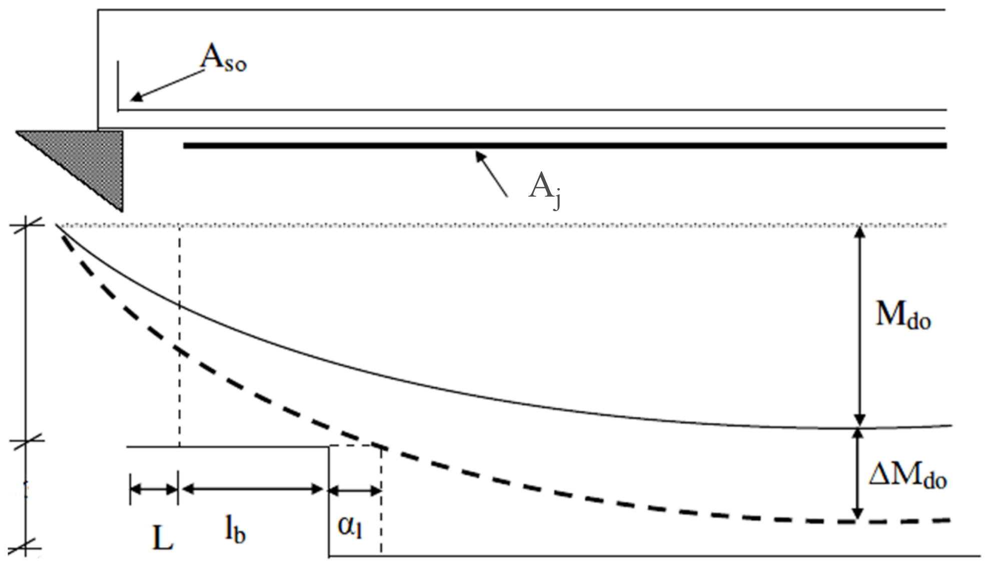
- Applied mainly to slabs and beams, rarely to columns or walls
- The strips or fabric are glued on the tension face using resin (+dowels in the case of steel strips)
- In the case of FRP strips or fabric, use of special anchors or dowels is allowed, provided that they are properly documented by testing
- FRP strengthening is allowed when the existing member (prior to strengthening) can carry the bending moment due to permanent loads → to ensure integrity of the member subsequent to accidental failure of the FRP (e.g. due to fire)
- Use of excessive amount of strengthening material should be avoided, as it may lead to premature failure of the compression zone
- Provided all the above conditions are met, the strengthened member may be considered as monolithic (with external reinforcement)

- The new external reinforcement (steel strips or FRP) should be designed so that together with the existing reinforcement (steel bars) it carries the tensile forces due to the total bending moment in the member
  - as an approximation, for the preliminary design of the required additional reinforcement

$$A_j = \frac{\Delta M_{do}}{z\,\sigma_{jd}}$$

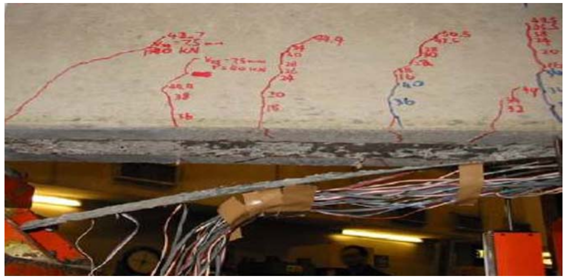
BM carried by the existing reinforcement

BM carried by the new (external) reinforcement



Strengthening of tension zones

- The design value of the effective stress σ_{jd} of the added reinforcement is estimated on the basis of a critical value of stress $\sigma_{j,crit}$
- The critical mode of failure is either of:
  - failure of the strengthening material per se: $\sigma_{j,crit} = f_{jk} \rightarrow \quad \sigma_{jd} = \frac{1}{\gamma_m} \cdot f_{jk}$
  - debonding of the strengthening material: $\sigma_{jd} = \sigma_{j,crit} / \gamma_{Rd}$



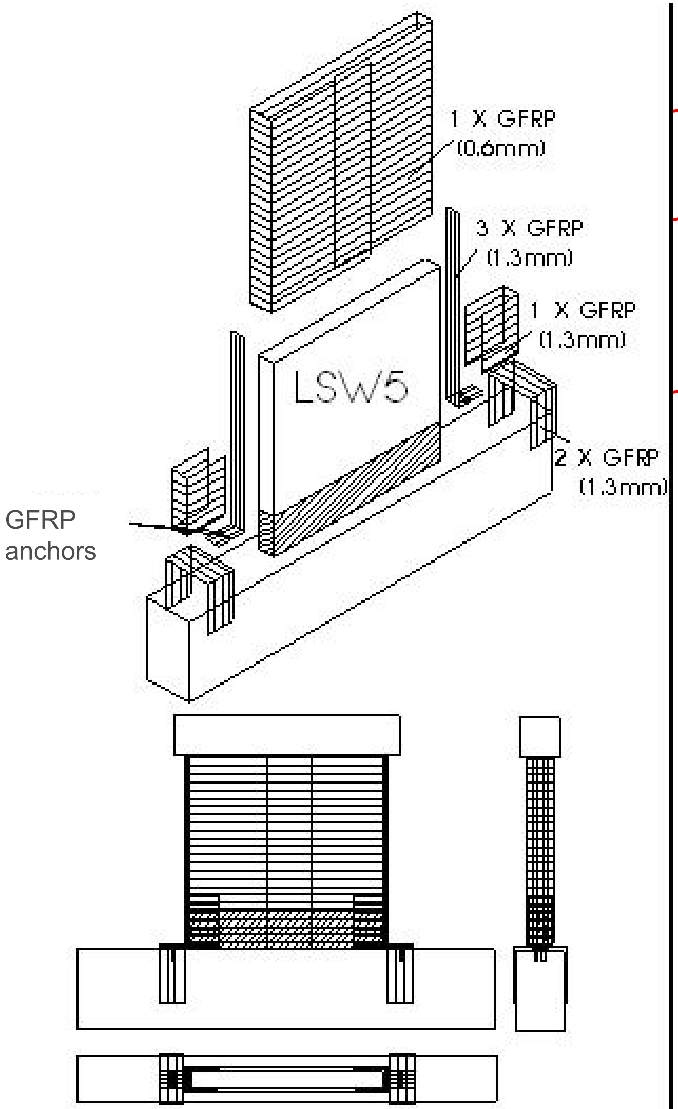
$$\sigma_{j,crit.} \cong \beta \frac{\tau_b^{deb.}}{t_j} L_e \approx \beta_w \beta_L \frac{f_{ctm}}{t_j} L_e$$

- effective anchorage length $\quad L_e = \sqrt{\frac{E_j\ t_j}{2 f_{ctm}}}$
- coefficient re. the width of the FRP reinforcement $\quad \beta_w = \sqrt{\frac{2 - b_j / b_w}{1 + b_j / b_w}}$
- coefficient re. the available anchorage length $\quad \beta_L = \sin\left(\frac{\pi\lambda}{2}\right) \cong \lambda(2-\lambda), \quad \lambda = \frac{L_{av}}{L_e} \leq 1$

Flexural + shear strengthening or R/C walls with FRP

(Antoniades et al. 2003, 2005)

Strengthening of tension zones



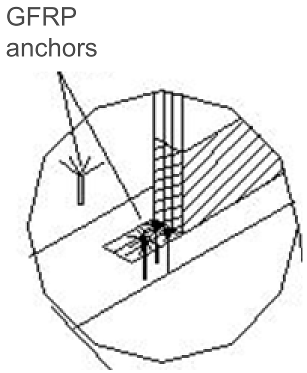
0.6mm GFRP full jacket (1 layer)

3 layers of 1.30mm GFRP (applied prior to the jacketing)

Π-shaped FRP strip (for anchorage)

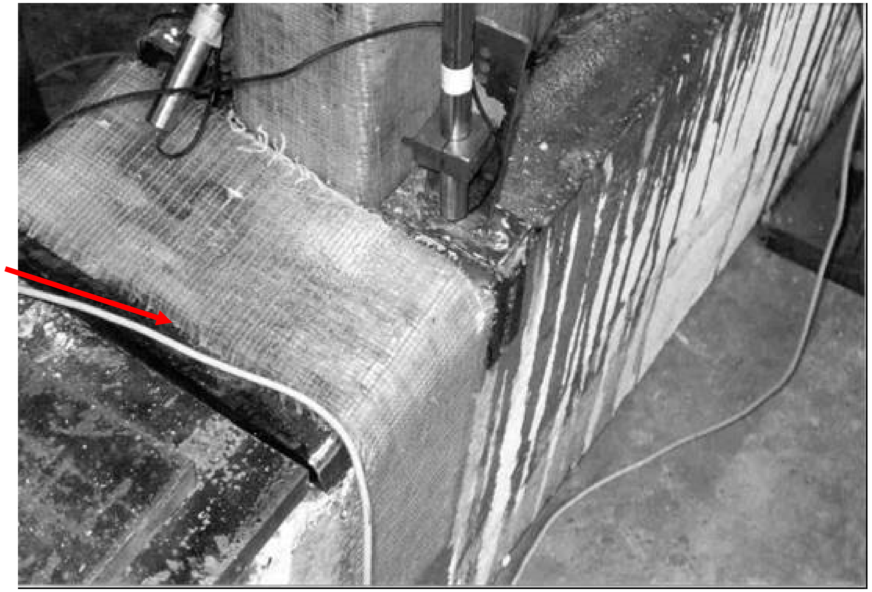
FRP reinforcement in specimen FRP-LSW5

CFRP anchors with fan (inserted in holes filled with resin) in the middle and close to the folding of the FRP fabric + Π-shaped FRP strip

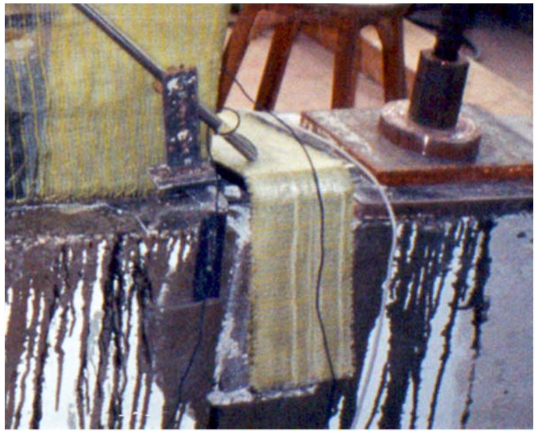


Strengthening of tension zones

FRP anchoring strips, similar to those of the fabric

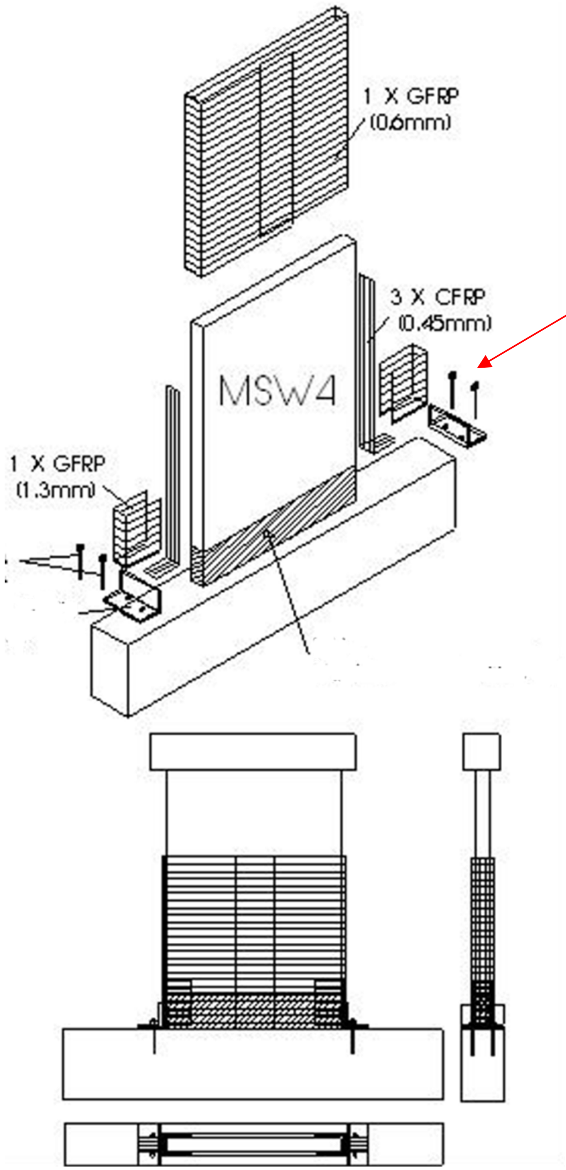


Combination of steel plates and Π-shaped FRP anchoring strip



failure

Strengthening of tension zones



Anchoring of GFRP strips through steel bracket and chemical anchors (without Π-strips)

FRP reinforcement in specimen FRP-MSW4

failure

Strengthening of tension zones

h/d=1

Specimen	Virgin V_{R0}(kN)	Strengthened V_{meas}(kN)	Strength Increase (%) $(V_{meas}- 0.94V_{R0})/(0.94V_{R0})$
FRPLSW1	262.0	325.4	32
FRPLSW2	191.0	200.8	12
RLSW3	191.0 (250.0 when N=165kN)	178.9 (N=0kN)	0
FRPLSW4	232.0	244.9	12
FRPLSW5	247.0	236.9	2

h/d=1.5

Specimen	Virgin V_{R0}(kN)	Strengthened V_{meas}(kN)	Strength increase (%) $(V_{meas}- 0.94V_{RO})/(0.94V_{RO})$
FRPMSW1	197.0	243.9	32
FRPMSW2	124.0	172.4	48
FRPMSW3	124.0 (176.0 when N=165kN)	164.3 (N=0kN)	41
FRPMSW4	158.0	180.8	22
FRPMSW5	187.0	210.8	20
FRPMSW6	202.0	200.2	5

Measured strength of initial and strengthened specimens

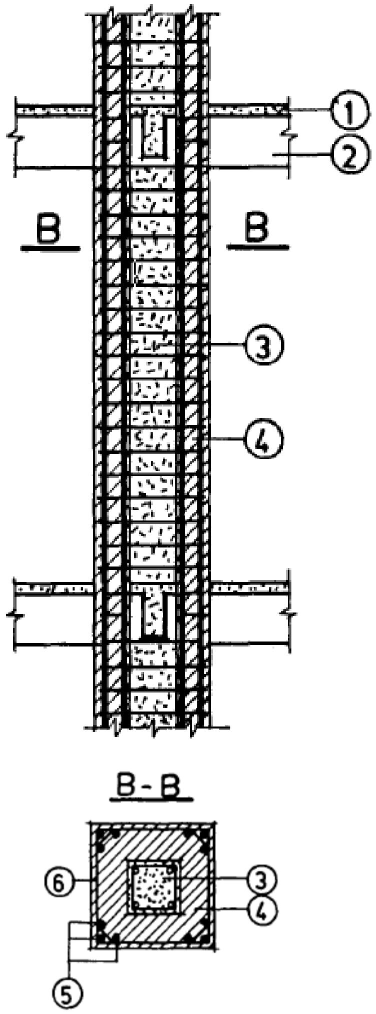
(Antoniades et al. 2003, 2005)

Simultaneous strengthening in tension & compression - Jackets

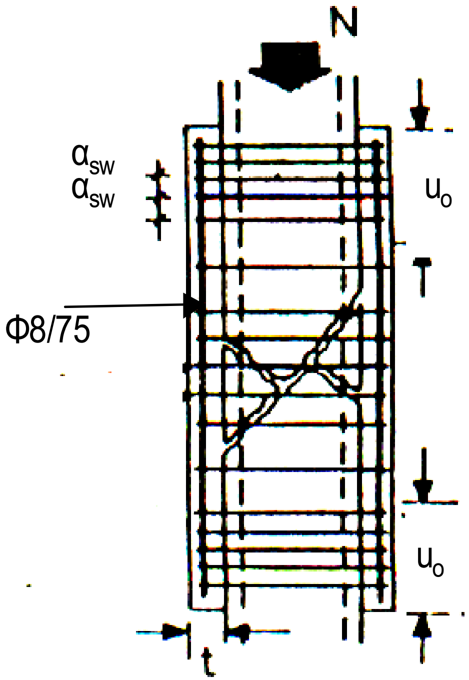
- Use of full jackets (around the entire perimeter) is recommended
- In the critical areas of columns the jacket should be extended to include the joint area
- Transfer of forces from the existing element to the jacket should be ensured through appropriate construction measures and be verified by calculation
  - the compression force F_{cm} of the jacket is transferred as shear force at the interface through friction, welded ‘suspensors’, and dowels, within a transfer length u_0

$$F_{cm} = \underbrace{4 u_o \mu \, f_{ctd} \, t}_{\text{friction}} + \underbrace{10 n_b \frac{A_{sb}}{h_s}}_{\text{suspensors}} + \underbrace{n_D \, F_{uD}}_{\text{dowels}} \qquad (\text{kN, mm})$$

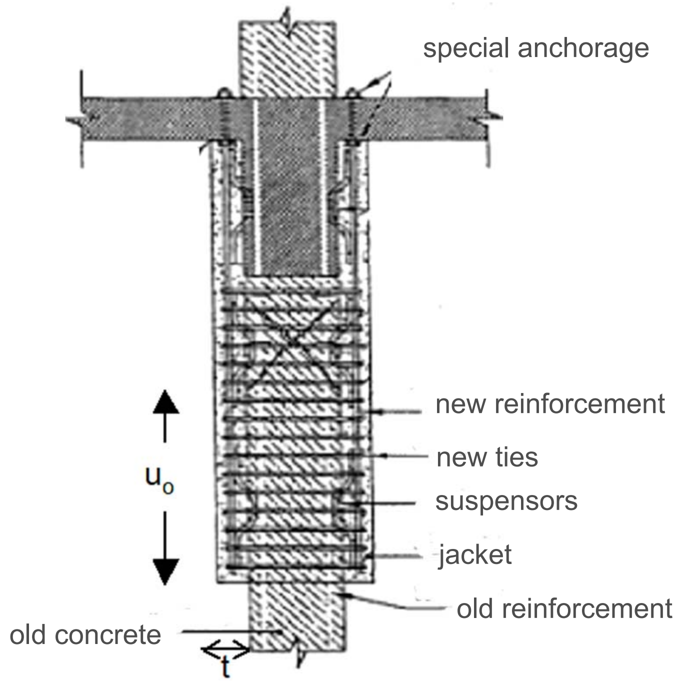
$$F_{ud} = d_b^2 \sqrt{f_{cd} f_{yd}} \leq \frac{A_s f_{yd}}{\sqrt{3}}$$



- If the transfer length u_0 at the end of the jacket is insufficient for transferring F_{cm}, special construction measures are required



jacket with sufficient u_0 at both ends (rare)



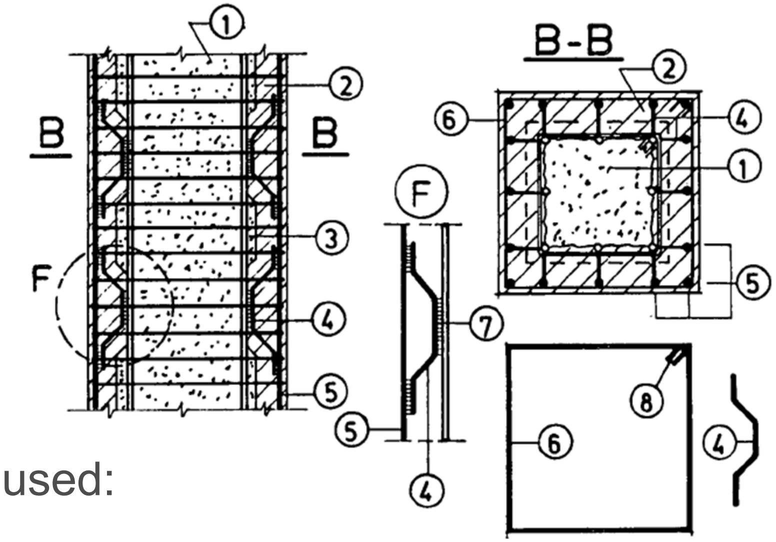
jacket with insufficient u_0 at either end (common)

- To carry tensile stresses along u_0 in the jacket, closely spaced ties should be provided ($\rightarrow$ to carry at least f_{ctm})

$$\frac{A_{sw}}{\alpha_{sw}} \geq \frac{t \cdot f_{ctm}}{f_{ywd}}$$

t: jacket thickness

  - max tie spacing: $\alpha_{sw} \leq 0.8\left(\frac{f_{ywd}}{f_{ctm}}\right) \cdot \frac{d_h^2}{t}$ min Φ8/75



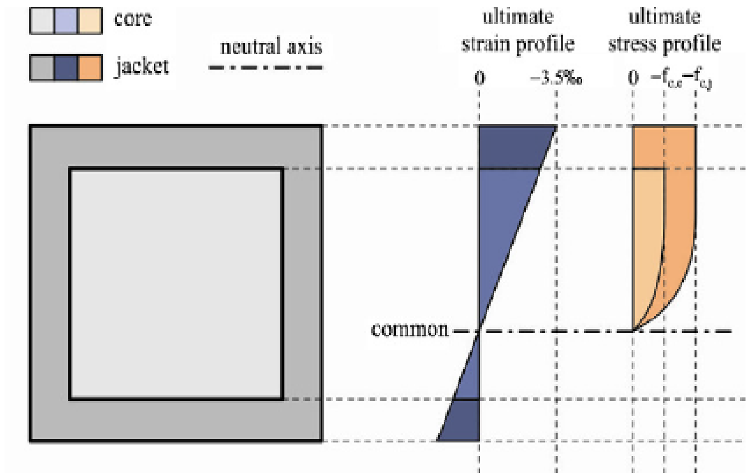
④: welded suspensor

- Subject to a number of conditions ($\Delta M_R \leq 2M_{R0}$, careful roughening of the interface), monolithicity factors may be used:

$$k_k = 0.80,\ k_r = 0.90,\ k_{\theta y} = 1.25,\ k_{\theta u} = 0.80 \quad \text{(GCSI, 2017)}$$

- If the resistance of a damaged column is ignored, the addition of a jacket is deemed equivalent to the addition of a new column
  - in this case special care is needed for full transfer of the internal forces, also to the adjacent members (beams) on either side of the 'new' column

EC8-3 expressions for capacity of R/C jacketed elements



- The jacketed element is assumed to behave monolithically, with full composite action between old and new concrete
- The fact that axial load is originally applied to the old column alone ('preloading') is disregarded, and full N is assumed to act on the jacketed element
- The concrete properties of the jacket are assumed to apply over the full section of the element

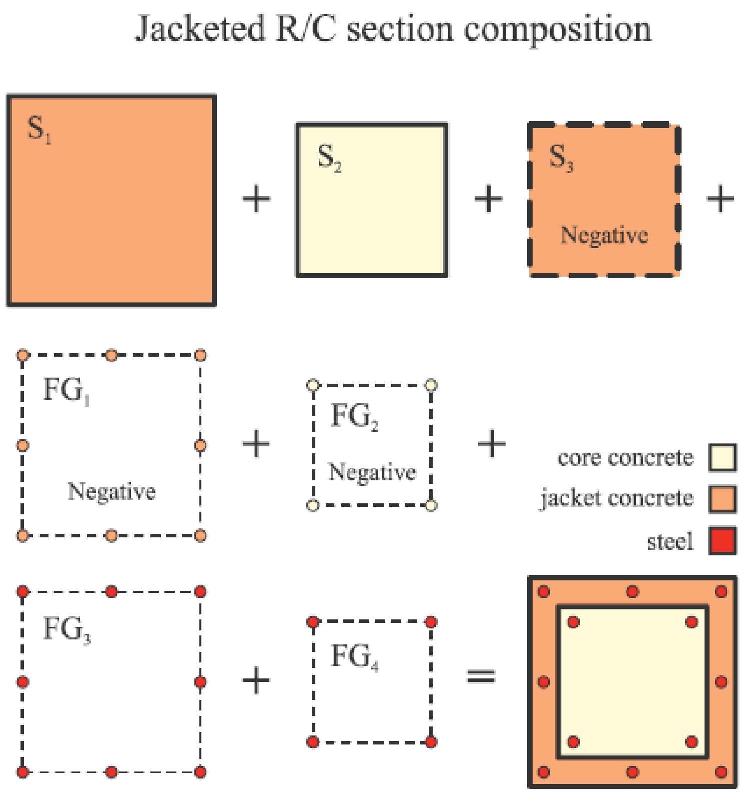
$$M_y^* = M_y; \quad V_R^* = V_R; \quad \theta_y^* = 1.05\theta_y; \quad \theta_u^* = \theta_u$$

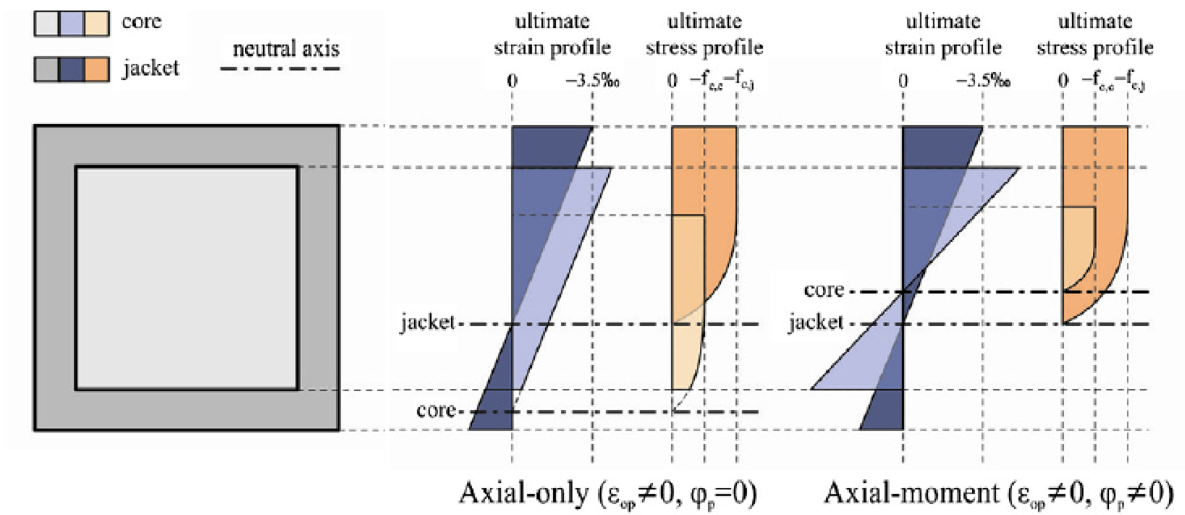
- For M_y^* θ_y^*, θ_u^* use mean value for existing steel (divided by CF), and nominal value for new concrete and steel; same for V_R^*, but, in primary elements, nominal strength of added materials should be divided by γ_m for steel & concrete

$$\theta_y = \phi_y \frac{L_V + a_V z}{3} + 0{,}0014\left(1 + 1{,}5\frac{h}{L_V}\right) + \frac{\varepsilon_y}{d - d'}\frac{d_{bL} f_y}{6\sqrt{f_c}}$$

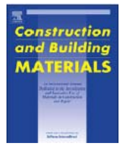
$$\theta_{um} = \frac{1}{\gamma_{el}} 0{,}016 \cdot (0{,}3^{\nu}) \left[\frac{\max(0{,}01;\omega')}{\max(0{,}01;\omega)} f_c\right]^{0{,}225} \left(\min\left(9;\frac{L_V}{h}\right)\right)^{0{,}35} 25^{\left(\alpha \rho_{sx}\frac{f_{yw}}{f_c}\right)} \left(1{,}25^{100\rho_d}\right)$$

Computer analysis of jacketed column sections





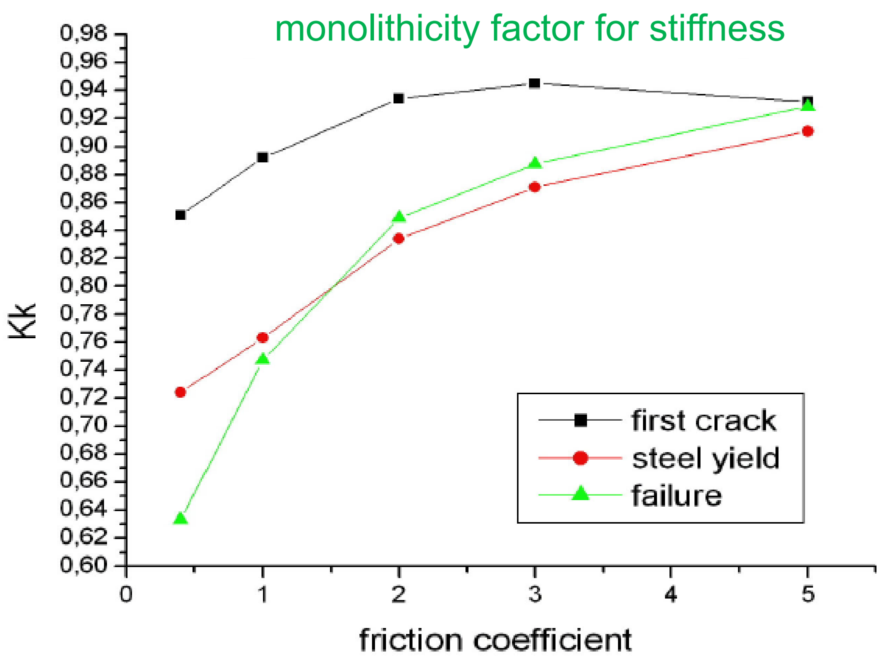
Jacketed section analysis including preloading effects

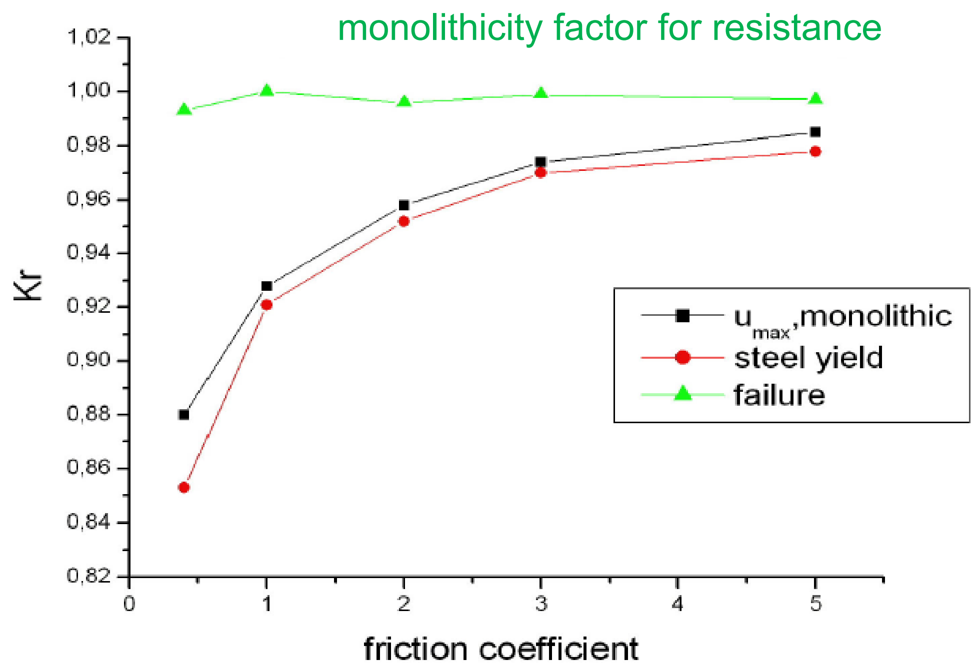


The effect of preloading on the strength of jacketed *R/C* columns

Vassilis K. Papanikolaou *, Sotiria P. Stefanidou, Andreas J. Kappos

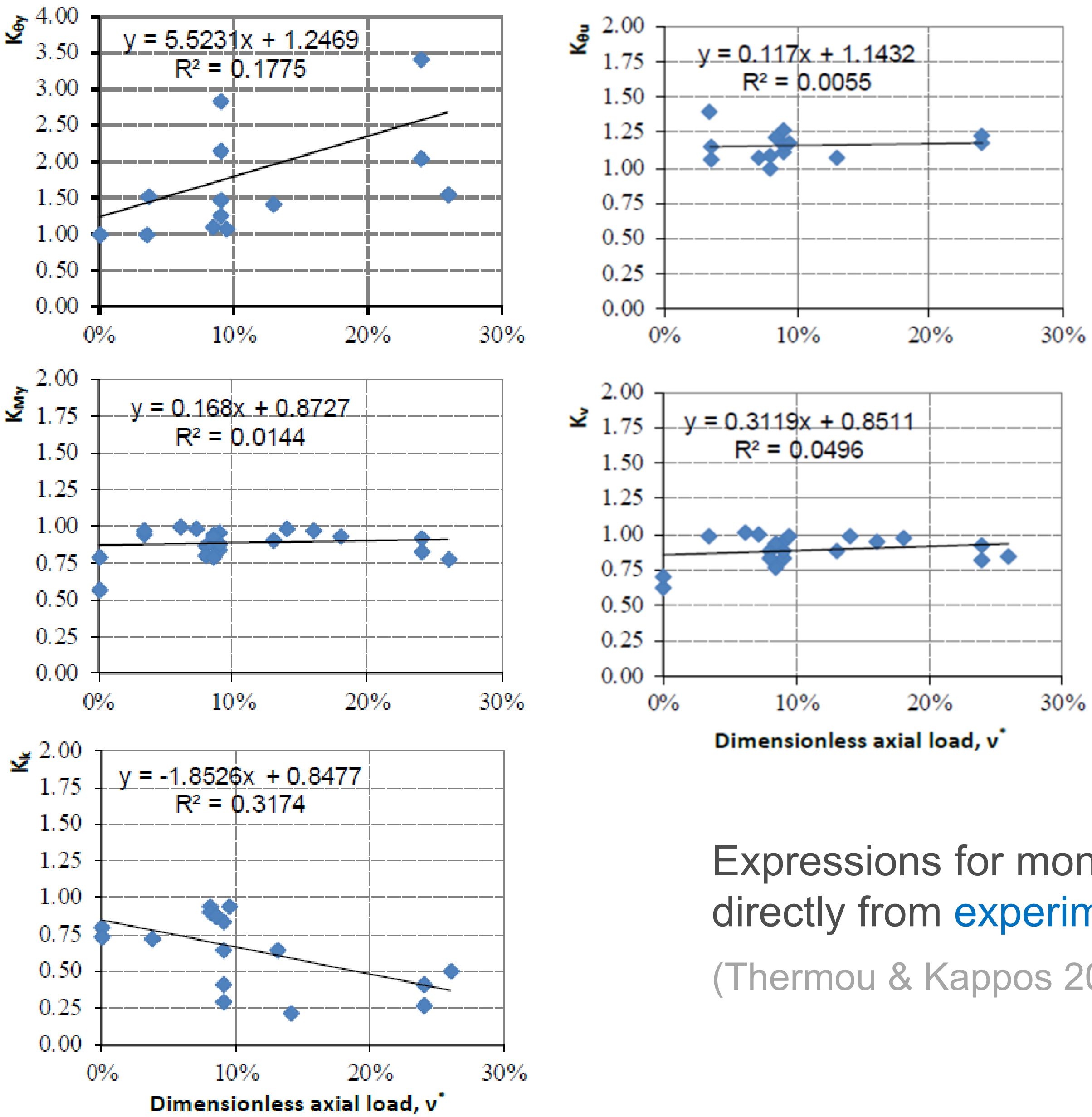
Effect of degree of interface roughening on monolithicity factor (Economou et al. 2003)





Experimental values of monolithicity coefficients (factors) (Thermou & Kappos 2018)

Reference	$K_{\theta y}$	$K_{\theta u}$	K_{My}	K_v	K_k
Gomes & Appleton (1998)	0.84	0.73, 1.07	0.99, 1.00	0.99, 1.00	1.18, 1.20
Ilki et al. (1998)	0.77, 1.00	0.72, 0.92	0.57, 0.79	0.62, 0.70	0.74, 0.79
Vandoros & Dritsos (2006a, 2006b, 2008)	1.49~4.54	0.75~1.26	0.78~0.99	0.82~0.98	0.22~0.64
Júlio et al. (2005)	-	-	0.96~1.32	-	-
Bousias et al. (2007a, 2007b, 2008)	0.26~1.41	0.88~1.21	0.79~1.06	0.76~1.02	0.64~3.65
Júlio & Branco (2008)	0.71~1.53	0.97~1.41	0.98~1.13	0.98~1.17	0.72~1.56
min/max	0.26/4.54	0.72/1.41	0.57/1.32	0.62/1.17	0.22/3.65
Mean	1.09	1.03	0.93	0.94	1.06



Strengthening in tension & compression - Jackets

Expressions for monolithicity factors derived directly from experimental database

(Thermou & Kappos 2018, 2022)

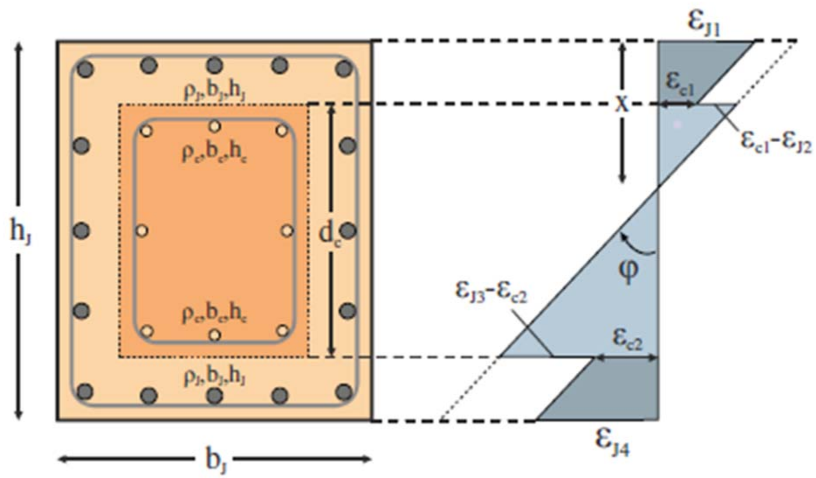
Strengthening in tension & compression - Jackets

Jacket thickness	Core Concrete strength	Jacket long. reinf.	K_k
t_J=75mm	$f_{c,o}$<20MPa	ρ_J=1%	0.84-0.95·v
		ρ_J=2%	0.69-0.50·v
	$f_{c,o}$>20MPa	ρ_J=1%	0.83-0.64·v
		ρ_J=2%	
t_J=125mm	$f_{c,o}$<20MPa	ρ_J=1%	0.57-0.70·v
		ρ_J=2%	0.46-0.33·v

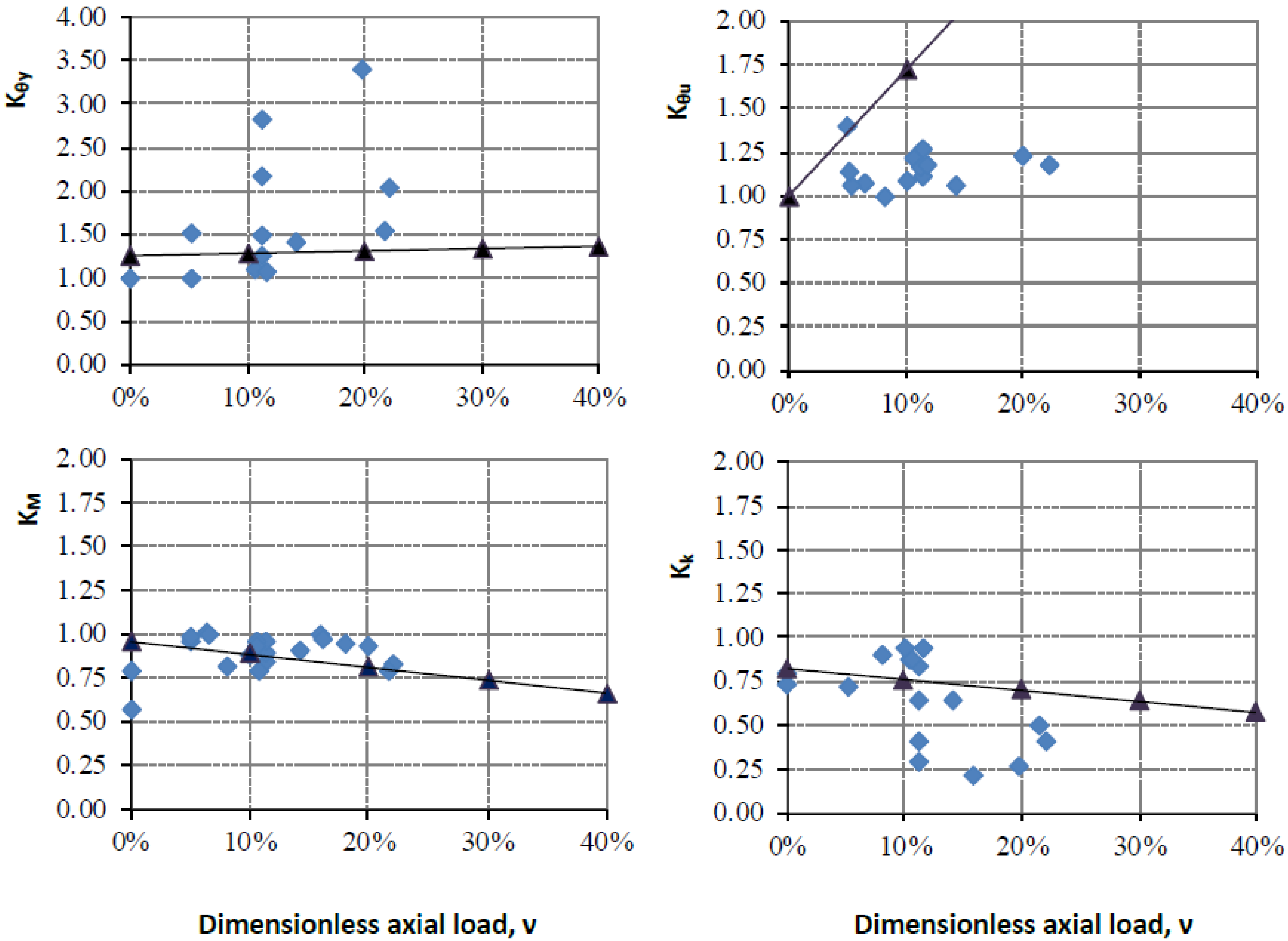
Expressions for monolithicity factors derived from refined parametric nonlinear analysis

(Thermou et al. 2014)

Jacket thickness	Core Concrete strength	Jacket long. reinf.	K_M
t_J=75mm	$f_{c,o}$<20MPa	ρ_J=1%	0.87-0.81·v
		ρ_J=2%	0.68-0.46·v
	$f_{c,o}$>20MPa	ρ_J=1%	0.96-0.74·v
		ρ_J=2%	
t_J=125mm	$f_{c,o}$<20MPa	ρ_J=1%	0.70-0.78·v
		ρ_J=2%	0.55-0.49·v



Strengthening in tension & compression - Jackets



Comparison between experimental values of K_i and the ones based on expressions proposed by Thermou & Kappos (2018)

◆ Experimental data utilized for the derived expressions

▲ Expressions based on analytical model

Relationships adopted in new EC8-3

$$M_y^* = (0.96 - 0.74\nu)M_y$$

$$\theta_y^* = (1.26 + 0.28\nu)\theta_y$$

$$\theta_u^* = \theta_u$$

ν: normalised axial loading acting on the jacketed element

$$N / \left[b_c h_c f_{c,c} + \left(b_j h_j - b_c h_c \right) f_{c,j} \right]$$

Remedying insufficient lap splice length

- When the available lap splice length (ℓ_s) is less than the required ($\ell_s < \ell_{s0}$), improvement of force transfer between bars may be achieved through:
  - welding of the lapped bars, or extension of existing ones through welding of additional bars (following Technical Specifications)
  - if $\ell_s \geq \{0.3\ell_{s0};\ 15d_b\}$, application of external confinement to the member, to prevent premature failure of the lap splice area due to splitting of the cover concrete

- Required confinement reinforcement:

$$A_j / s = \gamma_{Rd} \frac{(1-\lambda_s)}{\beta} \frac{1}{\mu} \frac{f_{yk}}{\sigma_{jd}} \frac{A_b}{\ell_s}$$

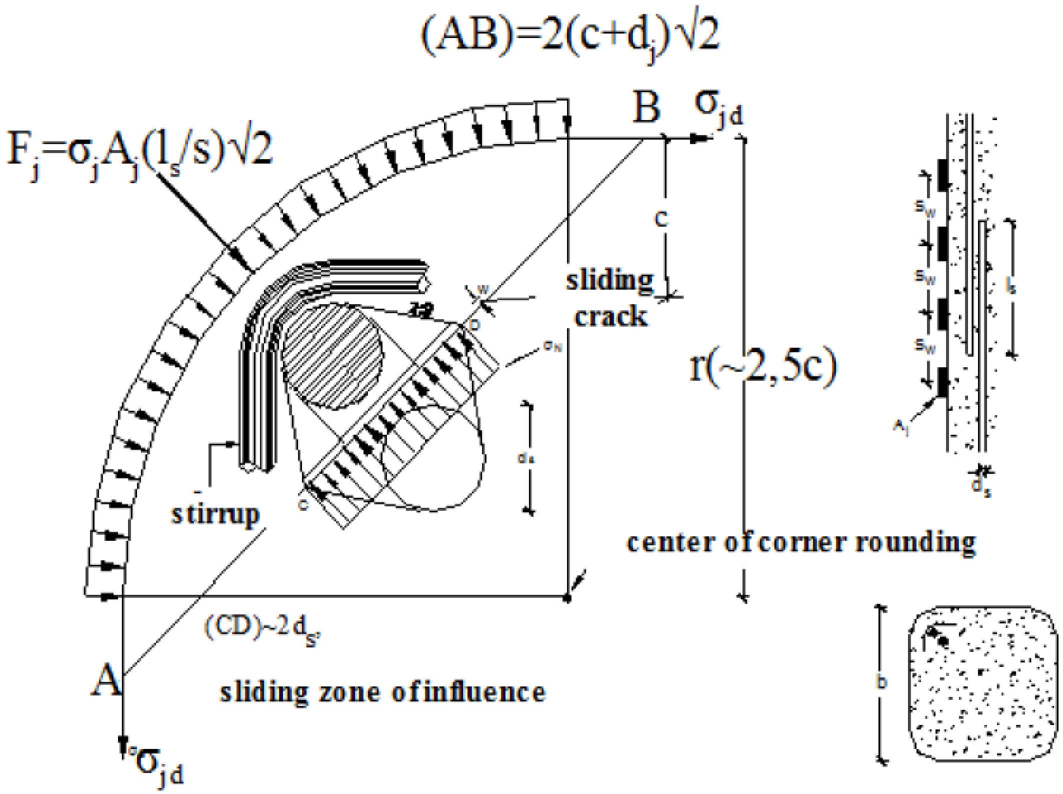
where $\lambda_s = \dfrac{\ell_s}{\ell_{s0}} \leq 1$

(required length ℓ_{s0} may be taken as $15d_b$ for smooth bars with 180^o hooks at the ends)

$A_j = t_j \cdot w_j$ is the cross-sectional area of the confinement reinforcement in the form of (FRP) collars (thickness t_j, width w_j)

$\beta \approx 1$ for corner bars

$\beta \approx 0.5$ for intermediate bars



- Model adopted by GCI for activation of external confinement in the area of a lap-spliced corner bar
  - ➢ required confinement reinforcement:

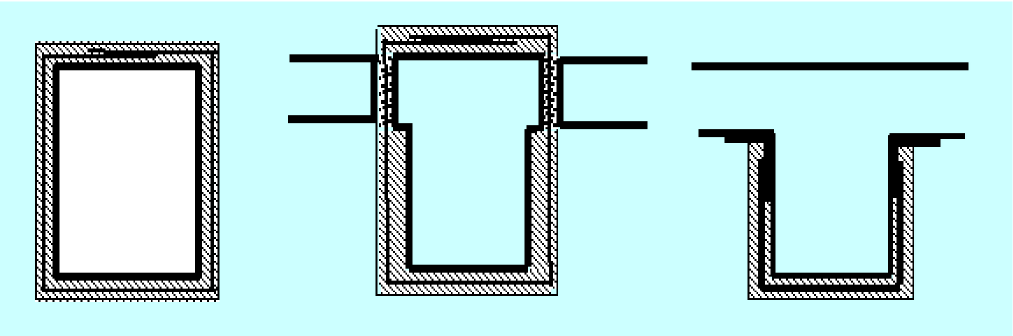
$$(A_j/s)_{req} = \frac{7}{\delta^{5/3}}[(1-\lambda_s)d_s/\ell_s]^3 \frac{f_{yk}^3}{E_j f_{ck}^2}\bar{b}(c+d_s)$$

(simpler version used in design, see previous slide)

Strengthening against shear

Strengthening against diagonal compression

- In the (~rare) case that $V_{Ed} > V_{Rd,max}$, two options exist:
  - confinement through transverse reinforcement (not effective for beams) $\rightarrow f_{cc} > f_c$
  - addition of concrete layers, preferably in the form of a full jacket



residual strength of existing member

$$V_{Ed} \leq \frac{1}{\gamma_{Rd}} \left(V_{Rd,r} + V_{Rd,j} \right) \qquad \gamma_{Rd} = 1.25$$

$V_{Rd,max}$ of new layers or jacket

- In the case of 'open-form' strengthening (should cover at least 3 sides) it should be verified that the ends of the jacket ties are properly anchored in the existing concrete member

Strengthening against diagonal tension

- When the existing shear reinforcement ($V_{Ed}>V_{Rds}$) is insufficient, the options are:
  - ➢ construction of reinforced concrete jacket
  - ➢ addition of externally bonded steel or FRP strips/collars (external ties)
    - steel: collars (in the form of rebars) or straps
    - FRP: fabric strips or sheets (fibres in hoop direction)

  - ➢ open-form strengthening on three sides (U-form reinforcement)
    - conditions for U-form strengthening with anchorage through resin only:

      a) high quality control

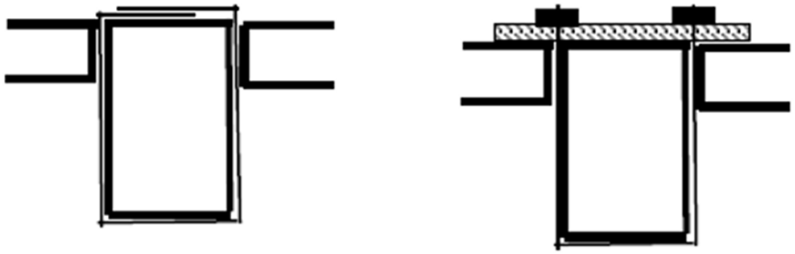
      b) existing member is able to carry service load (G+Q)

      c) height (h) of existing member available for bonding the strips (height h_j) is adequate for the transfer of force to be resisted by the new transverse reinforcement

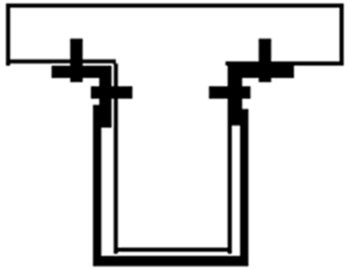
      → satisfied if $h \geq h_j \geq 2L_e$

Strengthening against shear

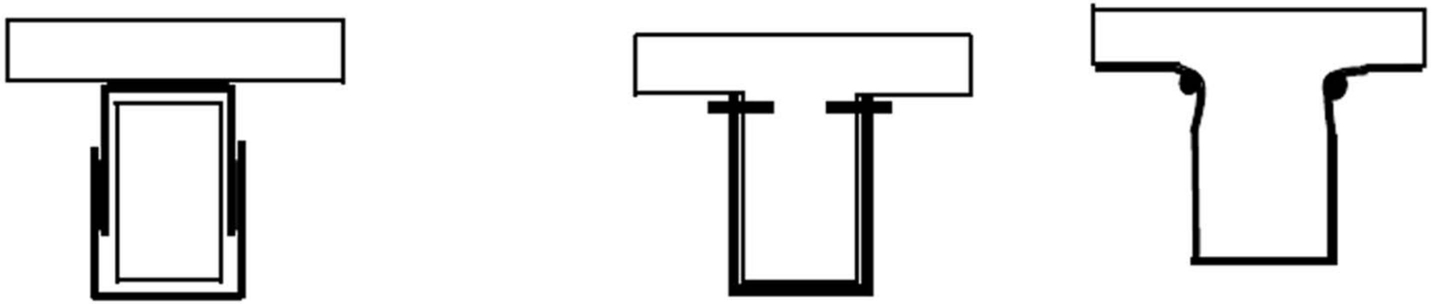
Shear strengthening schemes for R/C beams



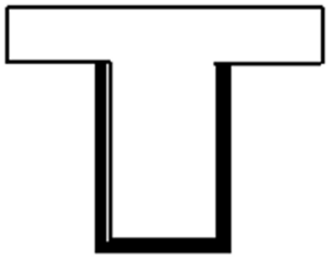
closed-form strengthening



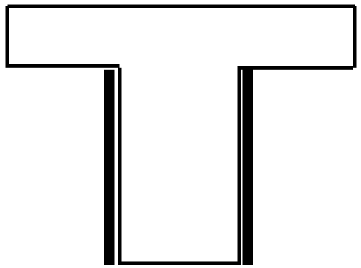
open-form strengthening (anchored ends)



open-form strengthening (anchored ends)



open-form strengthening (resin-bonding only)



EC8-3 allows two-side FRP strengthening…

Design of strengthening with externally-bonded elements

- Total shear resistance: $V_{R,existing} + V_{R,FRP}$
- Diagonal compression: $V_{Ed} \leq V_{R,max} = \alpha_{cw}\, b_w\, z\, \nu_1\, f_{cd}/(\cot\theta + \tan\theta)$ (from EC2)
  - for short R/C walls and columns (shear span ratio, $L_V/h \leq 2$)
    - limit for walls:

$$V_{R,max} = \frac{0{,}85\left(1 - 0{,}06\min\left(5;\ \mu_\Delta^{pl}\right)\right)}{\gamma_{el}}\left(1 + 1{,}8\min\left(0{,}15; \frac{N}{A_c f_c}\right)\right)\left(1 + 0{,}25\max\left(1{,}75;\ 100\rho_{tot}\right)\right)\left(1 - 0{,}2\min\left(2; \frac{L_V}{h}\right)\right)\sqrt{f_c}\, b_w z$$

    - limit for columns:

$$V_{R,max} = \frac{4/7\left(1 - 0{,}02\min\left(5;\ \mu_\Delta^{pl}\right)\right)}{\gamma_{el}}\left(1 + 1{,}35\frac{N}{A_c f_c}\right)\left(1 + 0{,}45\left(100\rho_{tot}\right)\right)\sqrt{\min\left(40; f_c\right)}\, b_w z \sin 2\delta$$

Rectangular members

- Diagonal tension: $$V_{Rd,tot} = \frac{A_{sw}}{s} z\, f_{ywd} \cot\theta + V_{Rd,f}$$
  - for full wrapping with FRP, or for U-shaped FRP strips or sheets:

$$V_{Rd,f} = 0.9\, d\, (2\, t_f)\, \frac{w_f}{s_f}\, f_{fdd,e} (\cot\theta + \cot\beta)$$

(do not use equation A.22 of current version, there is a mistake!)

where:

d is the effective depth;

θ is the strut inclination angle with respect to the element longitudinal axis ($22^o \leq \theta \leq 45^o$)

β is the angle between the (strong) fibre direction in the FRP sheet or fabric and the axis of the member

$f_{fdd,e}$ is the effective design FRP debonding strength

t_f is the thickness of the FRP strip, sheet or fabric (on single side);

w_f is the width of the FRP strip or sheet, measured orthogonally to the (strong) direction of the fibres
for sheets, $w_f = \min[0{,}9\, d; h_w] \sin(\theta+\beta)/\sin\theta$

s_f is the spacing of FRP strips, measured orthogonally to the (strong) fibre direction

$$f_{\mathrm{fdd,e,W}} = f_{\mathrm{fdd}} \cdot \left[1 - k\frac{L_e \sin\beta}{2z}\right] + \frac{1}{2}\left(f_{\mathrm{fu,W}}(R) - f_{\mathrm{fdd}}\right) \cdot \left[1 - \frac{L_e \sin\beta}{z}\right] \qquad (A.24)$$

where:

$z = 0{,}9d$ is the internal lever arm,

$k = \left(1 - \frac{2}{\pi}\right)$, and:

$$f_{\mathrm{fdd}} = \frac{1}{\gamma_{\mathrm{fd}}}\sqrt{0{,}6\frac{E_f\, f_{\mathrm{ctm}}\, k_b}{t_f}} \qquad \text{(units: N, mm)} \qquad (A.25)$$

is the design debonding strength, with:

γ_{fd} the partial factor for FRP debonding,

NOTE The value ascribed to γ_{fd} for use in a country can be found in its National Annex. The recommended value is γ_{fd}=1,5.

E_f the FRP sheets/plates modulus,

f_{ctm} the concrete mean tensile strength,

$k_b = \sqrt{1{,}5 \cdot (2 - w_f/s_f)/(1 + w_f/100\ \mathrm{mm})}$ the covering coefficient,

in which:

w_f, s_f, t_f are as defined in **(4)** and

$f_{fu,W}(R)$ is the ultimate strength of the FRP strip or sheet wrapped around the corner with a radius R, given by:

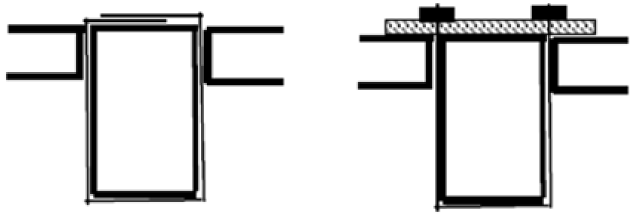
$$f_{\mathrm{fu,W}}(R) = f_{\mathrm{fdd}} + \langle \eta_R \cdot f_{\mathrm{fu}} - f_{\mathrm{fdd}} \rangle \qquad (A.26)$$

where the term in $\langle\cdot\rangle$ should be taken only if positive and where the coefficient η_R depends on the rounding radius R and the beam width b_w as:

$$\eta_R = 0{,}2 + 1{,}6\frac{R}{b_w} \qquad 0 \le \frac{R}{b_w} \le 0{,}5 \qquad (A.27)$$

Strengthening against shear

Definition of debonding strength $f_{fdd,e}$ for fully wrapped or properly anchored (in the compression zone) jackets:



L_e is the effective bond length:

$$L_e = \sqrt{\frac{E_f \cdot t_f}{\sqrt{4 \cdot \tau_{max}}}} \qquad \text{(units: N, mm)}$$

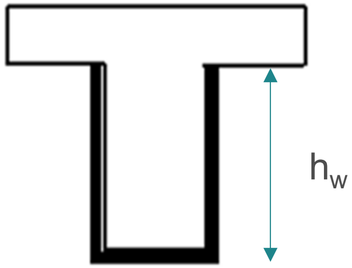
with:

$\tau_{max} = 1{,}8 f_{ctm} k_b$ = maximum bond strength.

- for U-shaped FRP strips or sheets:

$$f_{fdd,U} = f_{fdd}\left(1 - k\frac{L_e \sin\beta}{\min\left[0.9\,d\,;h_w\right]}\right)$$

(parameters defined as for full jackets)



Members with circular section (having diameter D)

$$V_f = 0.5A_c \cdot \rho_t \cdot E_t \cdot \varepsilon_{f,ed}$$

where

A_c is the column area ($\pi D^2/4$)

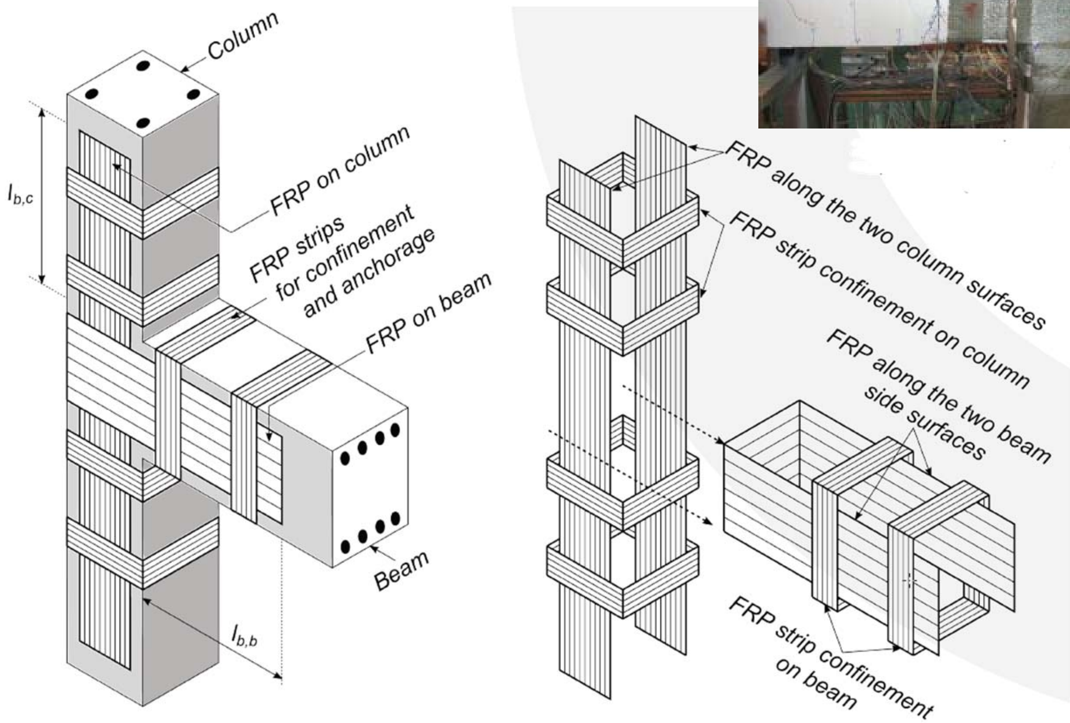
$\rho_f = 4t_f/D$ is the volumetric ratio of the FRP

$\varepsilon_{f,ed} = 0.004$ is the effective strain of the FRP

Strengthening against shear

Strengthening of beam-column joints

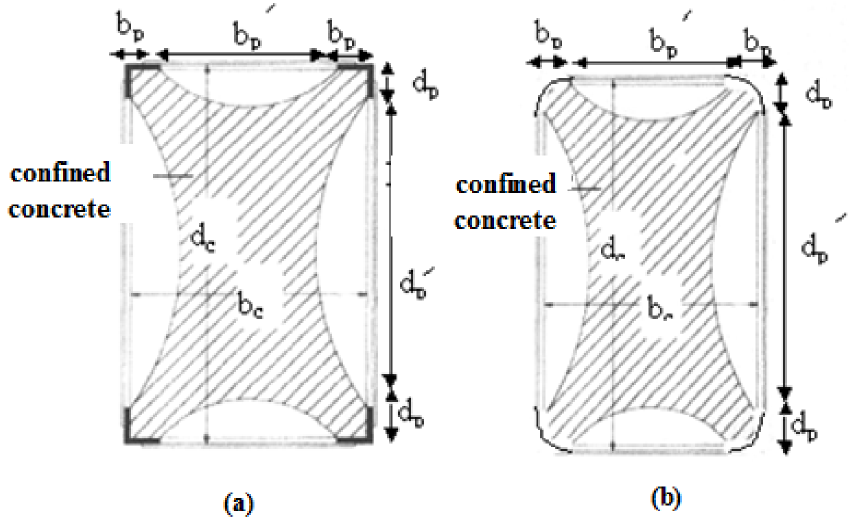
strengthening with metal plates



strengthening with FRP strips

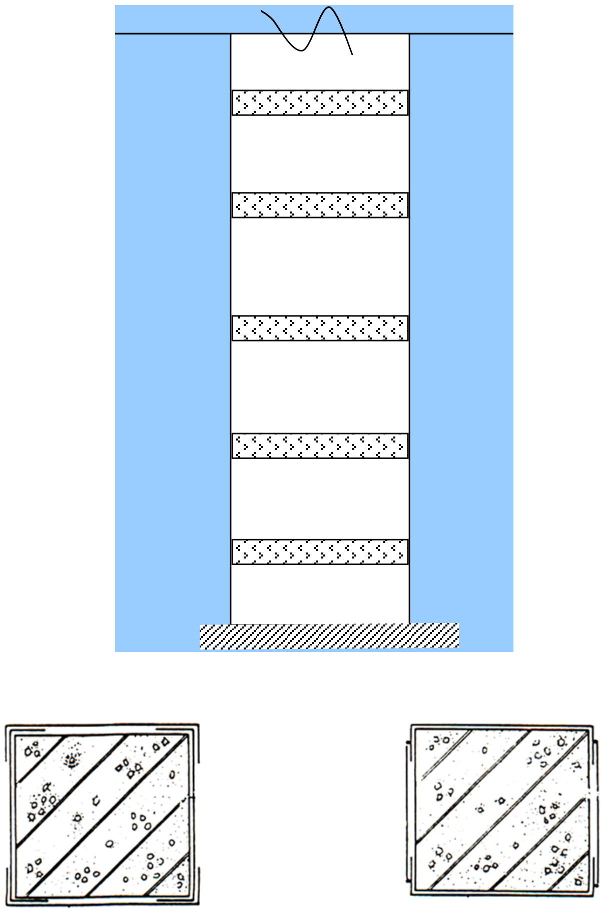
Increasing available ductility

- Local ductility of existing R/C members is typically achieved through external confinement
- Confinement is mainly applied to columns, and is feasible for circular or rectangular sections
- Available options:
  - bonded collars (steel straps or FRP strips)
  - prestressed collars (steel brackets or FRP strips)
  - spiral reinforcement (metal strap or FRP)
  - full jacket (metal sheets or FRP fabric)
  - metal cage (vertical brackets + horizontal collars, or full steel sheets)



confinement through:
(a) steel brackets
(b) FRP (with corner rounding)

Increasing available ductility



confinement through
FRP or steel collars

confinement through
steel cage

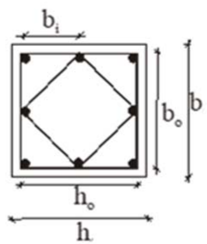
confinement through
FRP jacket or strips

Increasing available ductility

- The required amount of confinement is estimated in terms of mechanical ratio (ω_{wd}) that provides the ε_{cu} needed to develop the target local ductility ($\mu_{\varphi,tar}$)
  - curvature ductility ratio $I_x = \mu_{\varphi,targ} / \mu_{\varphi,avail}$
  - required confinement pressure

$$f_l = 0.4 I_x^2 \frac{f_c \varepsilon_{cu,c}^2}{\varepsilon_{ju}^{1.5}}$$

$$\varepsilon_{cu,c} = \varepsilon_{cu} + 0.2\, f_l / f_c$$



$$\mu_\varphi = \frac{\varepsilon_{cu,c}}{3\varepsilon_{sy,d}(\nu_d + \omega_{vd})(b / b_0)}$$

mechanical ratio of reinforcement between tension and compression side

- circular cross-sections wrapped with continuous sheets:

$$f_l = \frac{1}{2} \rho_f E_f \varepsilon_{ju}$$

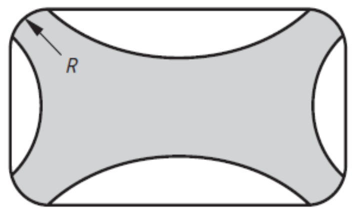
geometric ratio of FRP jacket $\rho_f = 4t_f / D$

- rectangular sections with corners rounded (radius R) to allow FRP sheet wrapping

$$f_l = \left(\frac{2R}{D}\right) \cdot \left(\frac{2E_f \varepsilon_{ju} t_f}{D}\right) \qquad D = \max\{b, h\}$$

- wrapping through FRP strips with spacing s_f

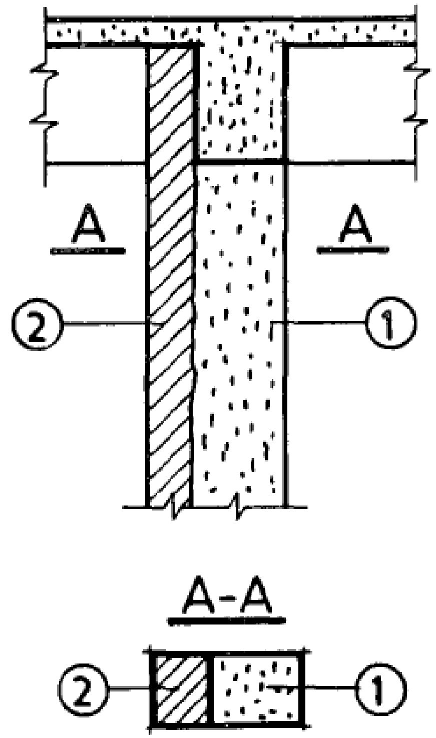
$$f_l = (1 - s_f / 2D)^2 \cdot \left(\frac{2E_f \varepsilon_{ju} t_f}{D}\right)$$



Increasing available stiffness

- The stiffness of existing R/C members may be increased (e.g. for drift control) through
  - addition of new concrete layers
  - addition of new members
- The stiffness increase may be estimated
  - from detailed analysis, considering the stiffened member as a composite member
  - approximately, using appropriate monolithicity factors (provided that reliable data is available)

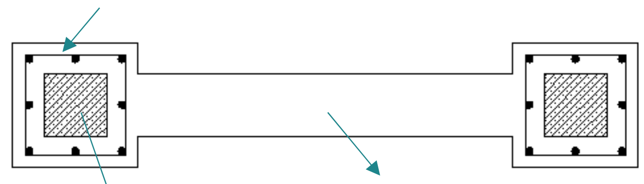
    (e.g. see section on Addition of new layers)
- For columns in R/C frames, the preferred stiffening scheme is the addition of (full) R/C jackets



Encasement of frames

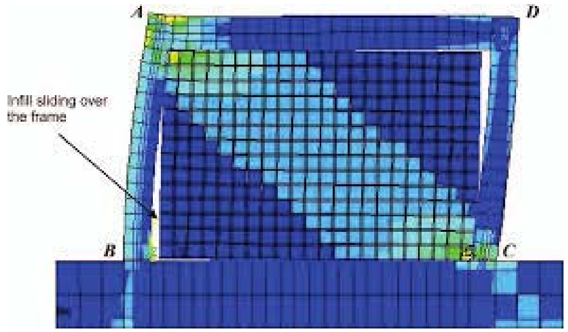
- It is applied to one or more storeys which have a significantly lower strength and/or stiffness than the others; the encasement may consist of
  - walls (with/without proper connection to the existing frame)
  - (metal) bracing
- Encasement aims at:
  - significant increase in the stiffness and/or resistance of the structure
  - strengthening of existing infill walls
- The effect of encasement on
  - columns and the joints of the frame
  - foundation members (and their settlement)

  should always be checked!



Addition of simple fillings

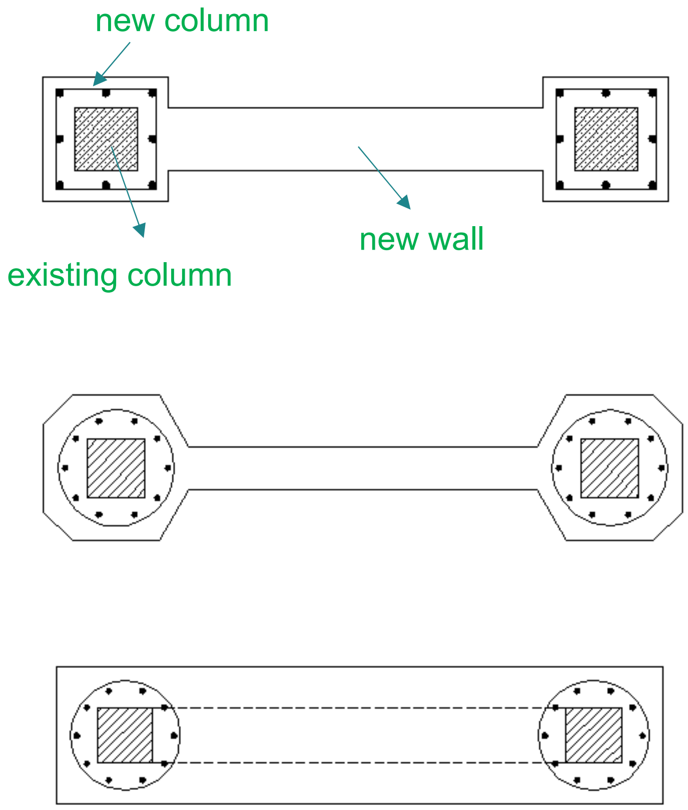
- The fillings (unconnected infill panels) may be:
  - plain or reinforced concrete panels (in-situ or prefabricated)
  - masonry infill panels (with or without reinforcement)
- For estimating the contribution of fillings to the resistance:
  - for concrete infills EC2 may be used
  - for masonry infills EC6 may be used
- In all cases:
  - shear forces induced (by the panel) to the beams and columns should be taken into account
  - proper construction measures should be implemented to ensure activation of the friction mechanism between the fillings and the surrounding frame



Conversion of frames to shear walls

- The key is the proper connection of the infill wall with the surrounding frame, e.g. through:
  - ➢ anchorage of wall reinforcement inside the frame
  - ➢ special connection measures (dowels, welding)
- It is good practice to form a jacket around the columns of the existing frame, even if this is not necessary for strength purposes

Encasement of frames



encasement with thickness greater than the width of the beam

Verification of infill wall

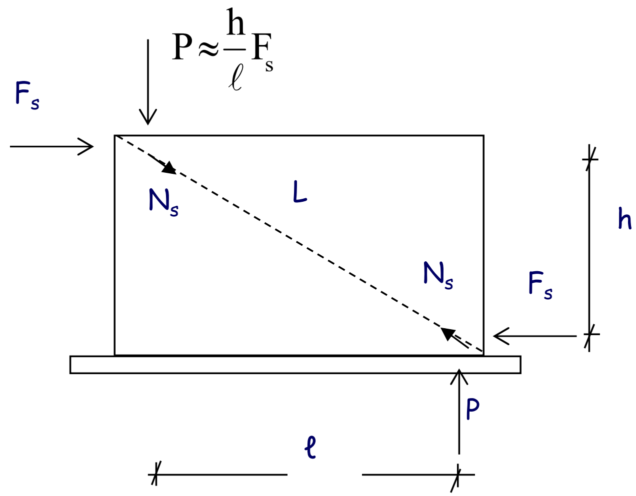
- Forces acting on the panel:

$$F_s = V_s - \frac{2V_{Rc}}{\gamma_{sd}} \qquad N_s = \frac{L}{\ell} \cdot F_s$$

V_s : total shear of the encased frame

V_{Rc}: shear resistance of each column formed at the edges of the new shear wall (jackets included)

γ_{Sd}=1.3 uncertainty factor



- Panel resistance verification
  - compression of diagonal strut: $N_R = \lambda(0.6 f_c) t_w b_w$

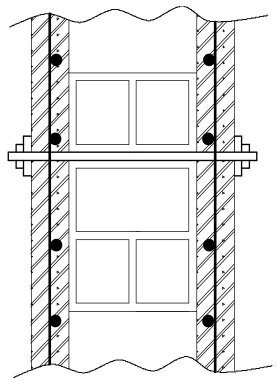
    $(t_w \times b_w)$

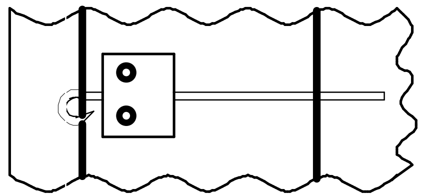
    $\lambda \approx 0.4$ coefficient of residual resistance of the diagonal strut
  - shear along the panel – column interface: $F_{d,\,horiz.} = F_s - \frac{\ell}{L} N_R > \frac{1}{2} n_b F_{R,d}$ $\qquad F_{d,\,vert.} = F_s - \frac{\ell}{L} N_R > \frac{1}{2} n_c F_{R,d}$

n_b, n_c: number of dowels along the length of the beam/column; $F_{R,d}$: dowel strength

Strengthening of masonry infills

- Strengthening of existing brick masonry infills may include shotcrete layers on both sides:
  - ➢ min layer thickness: 50 mm
  - ➢ reinforcement mesh from high-ductility steel or textile
  - ➢ for corrosion protection:
    - shotcrete strength ≥ 30MPa
    - use of corrosion inhibitors
- Anchorage of infill wall reinforcement inside the surrounding beams and columns
  - ➢ reinforcement extended beyond the wall and nailed to the surrounding beams and columns
  - ➢ the mesh is covered with shotcrete also in the anchorage areas

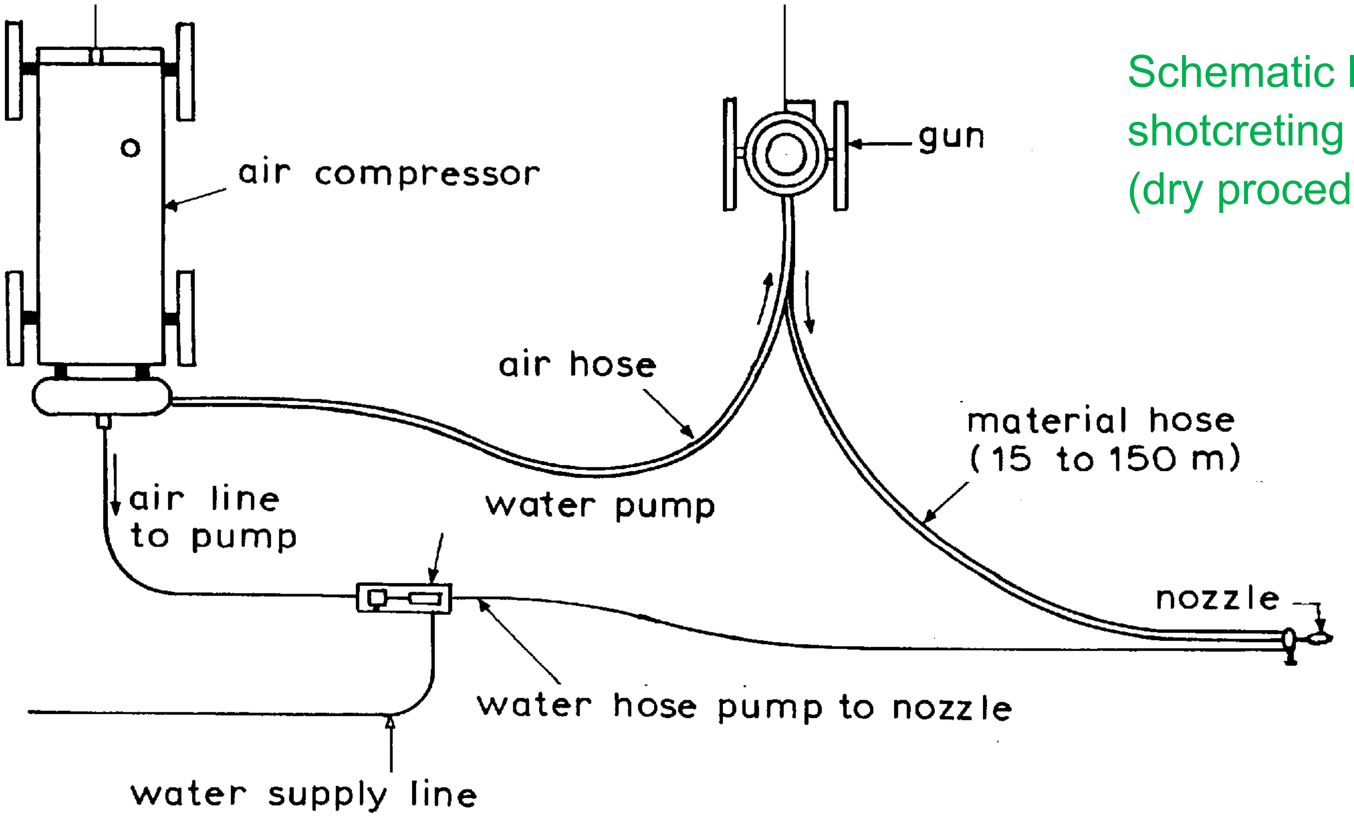




anchorage of horizontal reinforcement

Encasement of frames

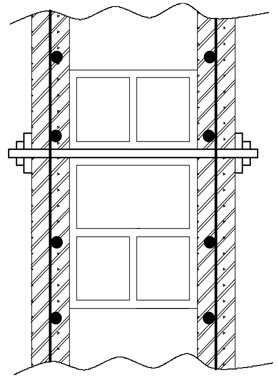
Schematic layout of shotcreting installation (dry procedure)

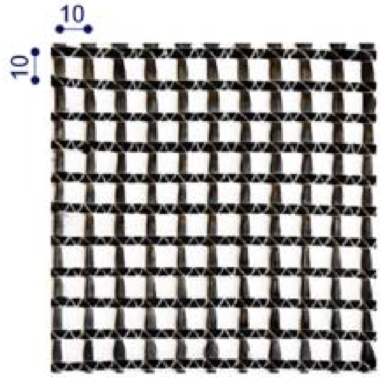


(Penelis & Kappos, 2010)

Encasement of frames

- The existing masonry wall and the added shotcrete layers should jointly carry out the applied loads
  - ➢ the meshes on each side should be connected, removing some bricks and connecting the meshes through S-links and filling of the gaps with cement mortar
  - ➢ verification of interface shear transfer may be made assuming (conservatively) a shear strength 0.1 MPa at the interface
- The infill walls should be verified for shear (failure of web) due to in-plane actions (seismic)
- The strengthened infill wall should also be verified against bending moments due to out-of-plane actions (wind/seismic)
  - ➢ verification of the capacity of the nailing of the mesh bars to carry out-of-plane actions through anchors or dowels





carbon fibre mesh

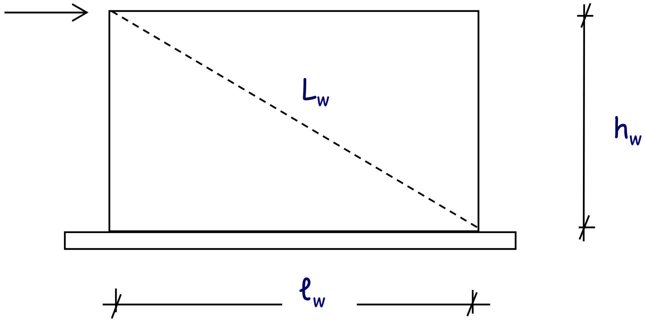
Encasement of frames

- Resistance of strengthened infill wall against in-plane shear
  - compression of diagonal strut

$$V_{R,strut} = 0.1 L_w (t_{w0} f_{wcd,0} + 2 t_m f_{mcd})$$

  - 'distributed' shear failure of web

$$V_{R,web} = \left[\frac{0.3}{\sqrt{\alpha_s}} (f_{wtd} + \sigma_0) + \lambda f_{syd} \right] \ell_w t_w \leq 0.7 V_{R,strut}$$



$\alpha_s = h_w : \ell_w$

f_{wtd} = design tensile strength of the masonry (can be taken equal to 1/15 of the compressive strength)

$\sigma_0 = N : t_w \ell_w$ (practically zero)

ℓ_w, h_w, t_w = length, height and thickness of the masonry

$\rho = \rho_v = \rho_h$ ποσοστό οπλισμού κορμού

f_{syd} = design yield strength of the reinforcement

$\lambda = \sigma_s : f_{syd}$, coefficient of the mobilized reinforcement stress (depending on the efficiency of the reinforcement anchorage) which can be approximately estimates as follows:

$$\lambda = 1 - \frac{0,6}{k_b} \frac{f_{syd}}{f_{mtd}} \frac{d_s}{\ell}$$

where:

$\ell = \min\{\ell_w, h_w\}$

d_s = diameter of the rebars

f_{mtd} = design tensile strength of the jacket concrete

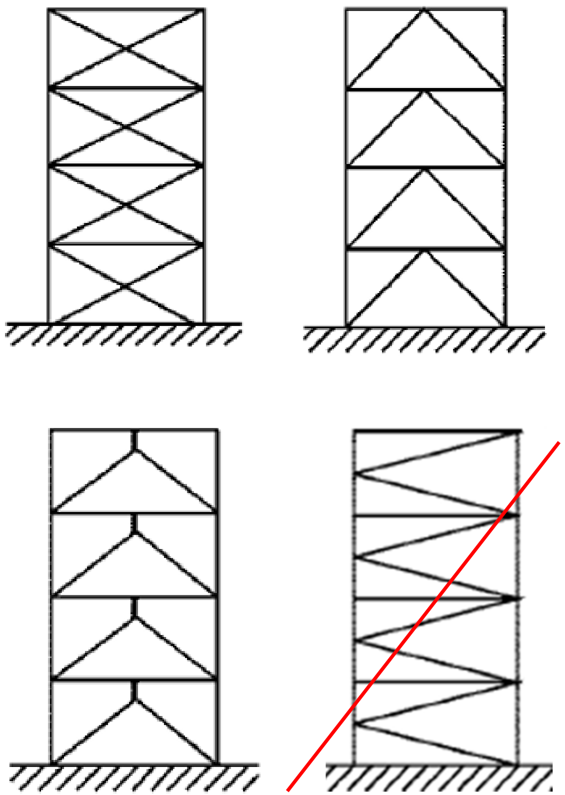
$k_b = 1$, without any additional care regarding the anchorage of the reinforcement

2, in case of "nailing" on the masonry

3, in case of "nailing" on the perimeter frame members (not recommended)

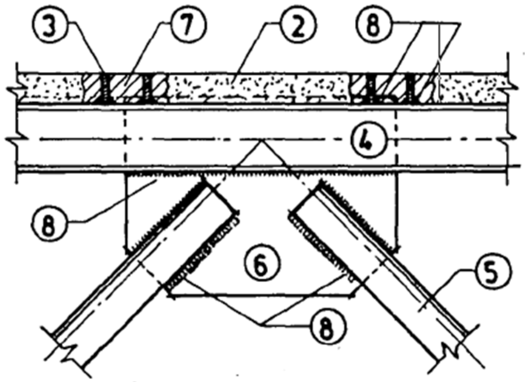
Addition of bracing

- Bracing is typically configured in such a way that, together with existing vertical and horizontal frame members, it forms a truss
- Energy dissipation takes place in those members where seismic action causes primarily axial tension
- Recommended bracing systems:
    - diagonal or cross-diagonal (X) braces
    - V or Λ braces, with inclined parts having one edge connected to a frame joint, and the other edge connected ("with eccentricity") to an intermediate point of a horizontal frame member
    - Y or inverted Y braces, with inclined parts connected to frame joints and a vertical part connected to an intermediate point of a beam through a short vertical 'seismic link'
- K braces, connected to an intermediate point of a column, should be avoided (in seismic retrofitting)



Addition of bracing

- The design and detailing of the braces aim at the control of their post-buckling performance (affected by lateral-torsional and local buckling of the components of the brace, weld fracture, failure of dowels/anchors etc.)
  - control of local buckling: the cross-sections of the braces should satisfy the EC3 and EC8 requirements for width-to-thickness ratios (c/t), which is related to q
  - to prevent concentration of inelastic deformation at the locations of holes in bolts → net area ratio of tension braces $A_{net}/A \geq 1.26 f_y/f_u$
  - to prevent premature failure of connections → brace connections should satisfy EC8 requirements (§ 6.5.5)
- The GCSI includes details (q, capacity design, detailing) for the design of steel braces with or without eccentricity



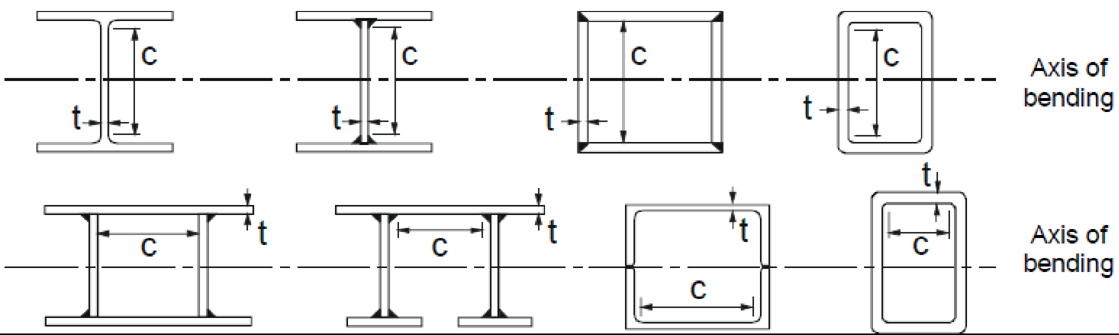
Addition of bracing

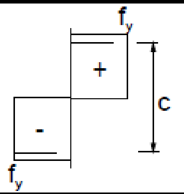
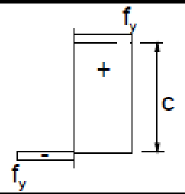
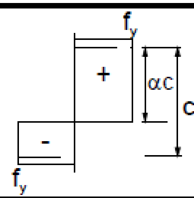
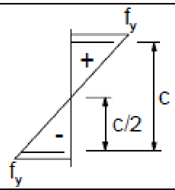
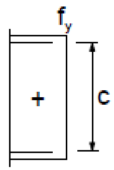
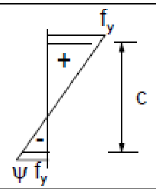
Steel cross-section classes (EN1993-1-1):

Maximum width-to-thickness ratios (c/t) for compression parts (webs and flanges)

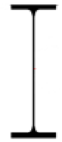
$$\varepsilon = \sqrt{235/f_y}$$

Internal compression parts

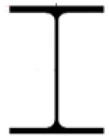


Class	Part subject to bending	Part subject to compression	Part subject to bending and compression
Stress distribution in parts (compression positive)			
1	$c/t \le 72\varepsilon$	$c/t \le 33\varepsilon$	when $\alpha > 0{,}5$: $c/t \le \dfrac{396\varepsilon}{13\alpha - 1}$ when $\alpha \le 0{,}5$: $c/t \le \dfrac{36\varepsilon}{\alpha}$
2	$c/t \le 83\varepsilon$	$c/t \le 38\varepsilon$	when $\alpha > 0{,}5$: $c/t \le \dfrac{456\varepsilon}{13\alpha - 1}$ when $\alpha \le 0{,}5$: $c/t \le \dfrac{41{,}5\varepsilon}{\alpha}$
Stress distribution in parts (compression positive)			
3	$c/t \le 124\varepsilon$	$c/t \le 42\varepsilon$	when $\psi > -1$: $c/t \le \dfrac{42\varepsilon}{0{,}67 + 0{,}33\psi}$ when $\psi \le -1$*) : $c/t \le 62\varepsilon(1-\psi)\sqrt{(-\psi)}$

examples:



IPE (class 2)



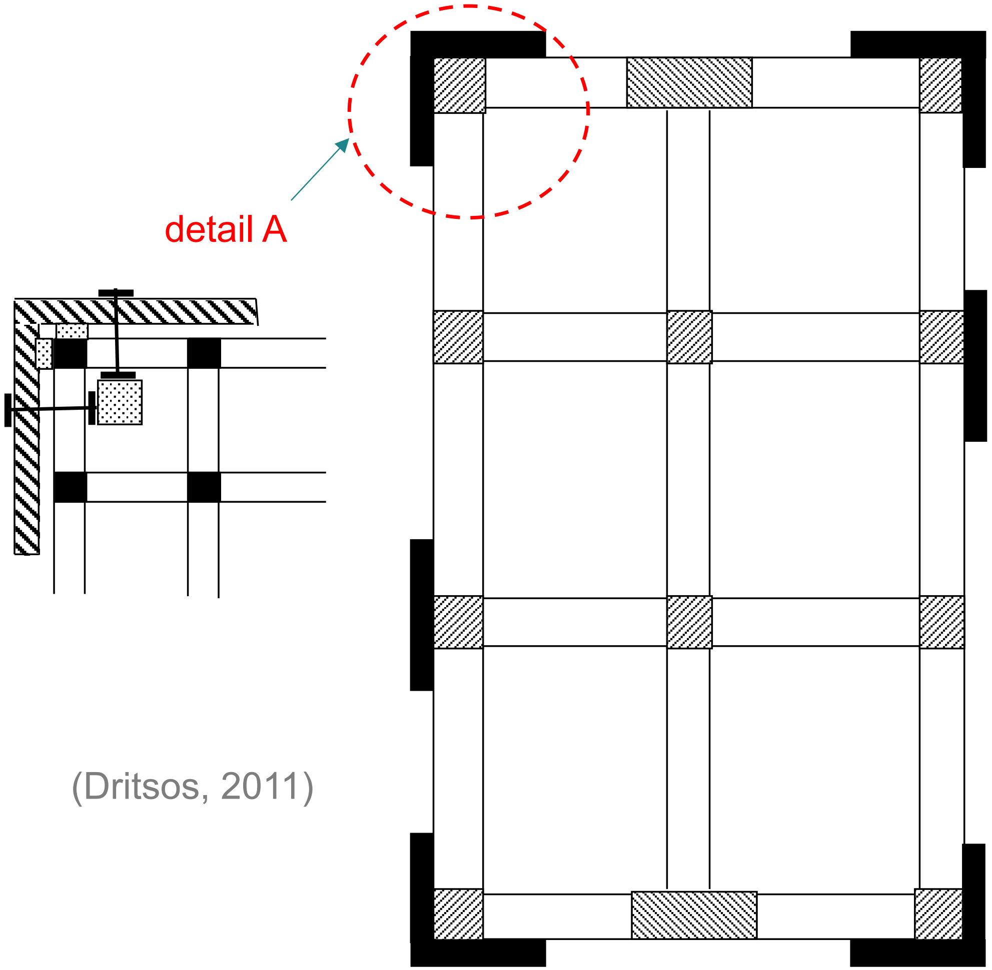
HEA360 (class 1)

from Table 6.3 EC8:

Reference value of behaviour factor q	Required cross-sectional class
$1{,}5 < q \le 2$	class 1, 2 or 3
$2 < q \le 4$	class 1 or 2
$q > 4$	class 1

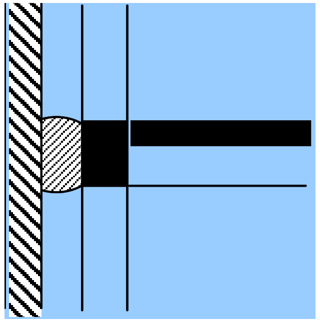
Addition of ‘side’ R/C walls

- R/C walls are added side-by-side with the existing structural system and are properly connected to it and to the existing foundation
- The common locations are the external corners of the building (L walls)
- In the interior of the building it is preferable and relatively easier to add walls as encasements (see section Conversion of frames to shear walls)

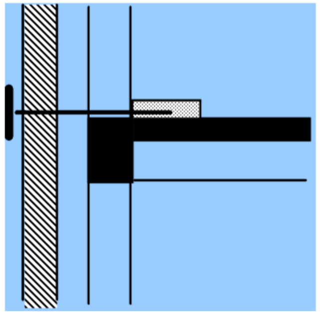


(Dritsos, 2011)

- Transfer of forces between the existing building and the added side walls is made through proper connections
  - ➢ located at the level of the floor diaphragms, along the beams or close to the columns
  - ➢ may work in tension, compression, or shear
- All connections should remain elastic under the design seismic action (overstrength factor $\gamma_{Rd}=1.4$)
- It is recommended to combine the foundation of the added walls with the existing foundation, and to increase the wall axial load N
- The diaphragm action of the existing floor slabs should be verified

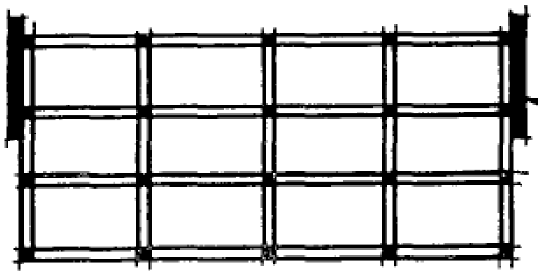


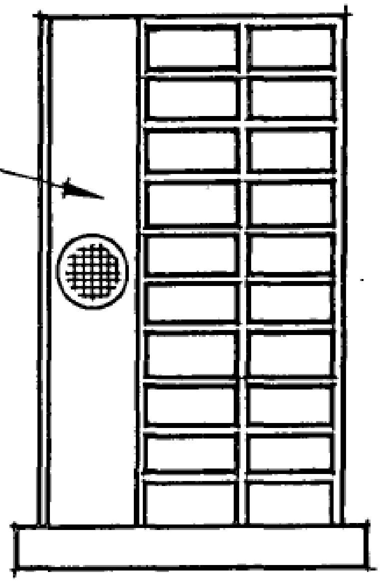
schematic detail of compression connection



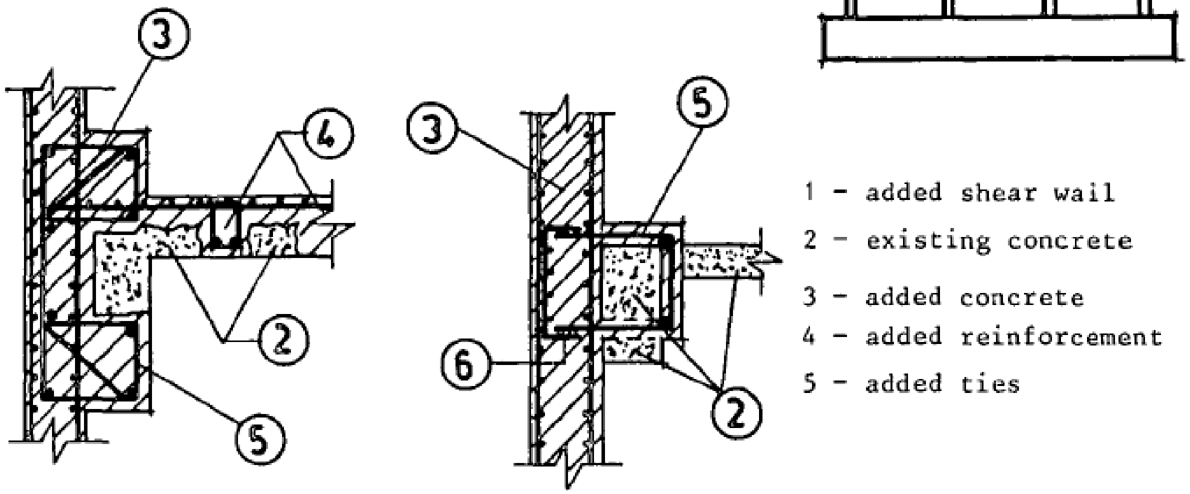
schematic detail of tension connection

Addition of ‘side’ R/C walls





(UNDP/UNIDO 1985)



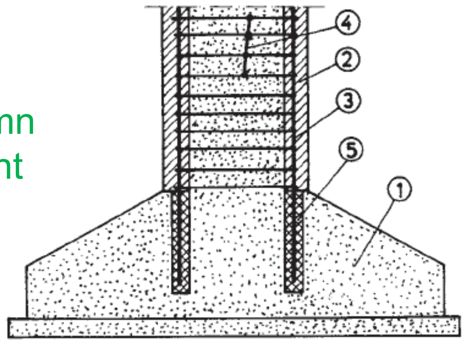
- the main vertical edge reinforcement for flexure and the web reinforcement for shear pass continuously along the entire height of the wall
- connection can be performed by ties anchored into the floor structure, diagonally placed in plan, or beams formed from the shear walls and anchored into the floor structure by additional cast-in-situ reinforced slab

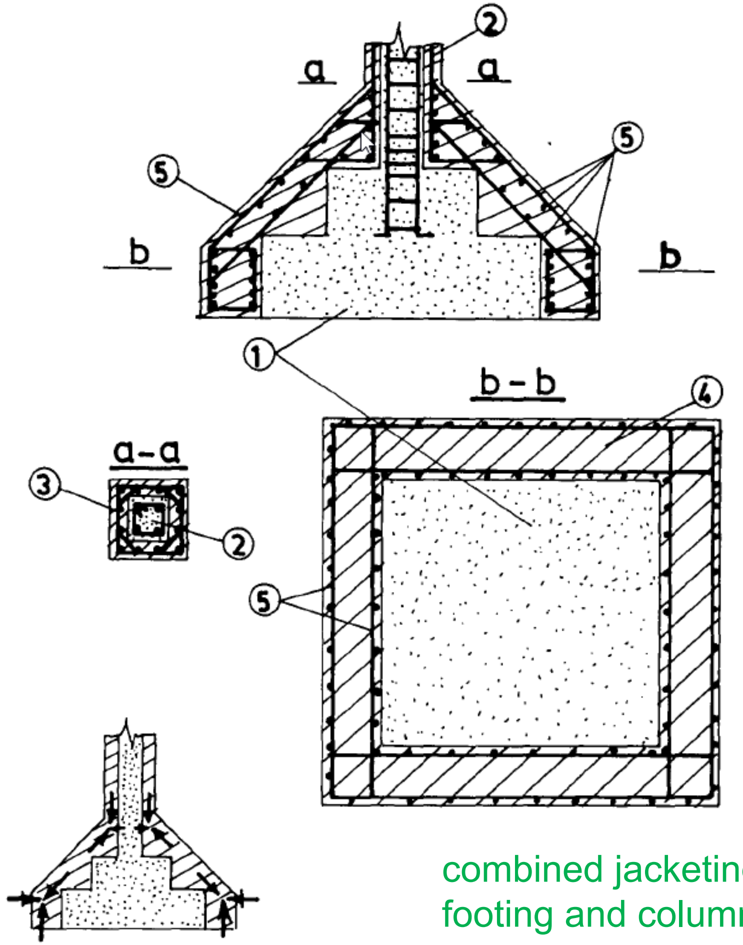
Retrofit of foundations

- Insufficient resistance of foundation members may be increased through additional layers (partial jackets)
- Foundation jacketing is usually combined with column jacketing
- Suggested monolithicity factors:

  $k_k = 0.7$, $k_r = 0.9$, $k_{\theta y} = 1.3$ $k_{\theta u} = 0.8$

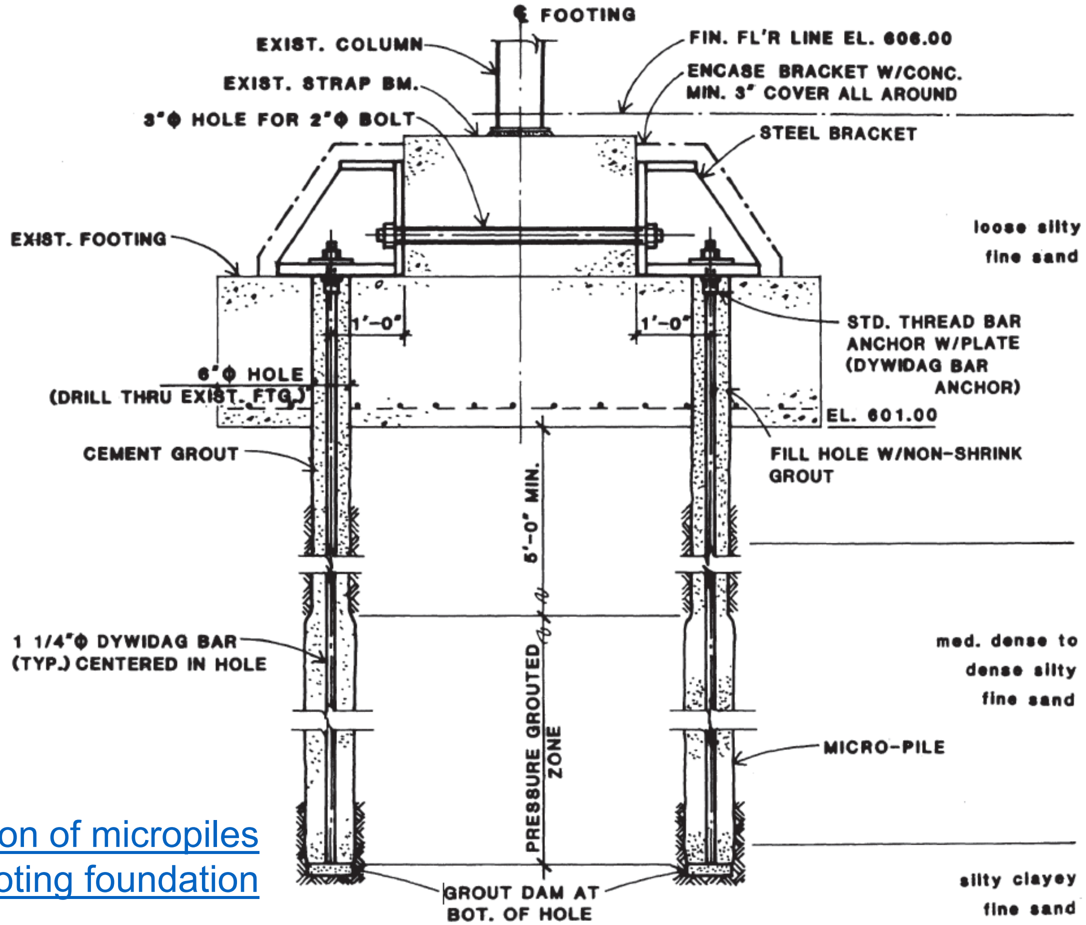
anchorage of column jacket reinforcement into the footing





combined jacketing of footing and column

- An efficient solution for increasing the bearing capacity of existing foundations is the use of micropiles
  - typically needed when walls are added (e.g. through encasement)



addition of micropiles to footing foundation

Main sources of figures and related material

- Antoniades, K. K., Salonikios, T. N. and Kappos A. J. (2003) Cyclic tests on seismically damaged R/C walls strengthened using FRP reinforcement, *ACI Structural Journal*, Vol. 100, No. 4,, 510-518
- Antoniades, K.A., Salonikios, T.N. and Kappos, A.J., "Evaluation of Hysteretic Response and Strength of Repaired R/C Walls Strengthened with FRPs", *Engineering Structures*, V. 29, No. 9, Sep. 2007, 2031-2418
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- Penelis, G.G. and Kappos, A.J. (2010), "Earthquake-resistant Concrete Structures", Taylor & Francis, London (2nd printing)
- Thermou, G. & Kappos, A.J. (2018) Monolithicity coefficients for the design of reinforced concrete columns strengthened with reinforced concrete jackets; *Background to modifications in Clause 8 Specific rules for reinforced concrete structures – Appendix A.*
- Thermou, G. & Kappos, A.J. (2022) "Background to the monolithicity factors for the assessment of jacketed reinforced concrete columns", *Buildings*, V. 12, no 1, Jan. 2022, https://doi.org/10.3390/buildings12010055.
- UNDP/UNIDO Project RER/79/015 (1985) Building construction under seismic conditions in the Balkan region - Vol. 5: Repair and strengthening of reinforced concrete, stone and brick-masonry buildings. UNDP, Vienna.

Thank you for your kind attention

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