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CNR-DT 200 R1 Guidelines for Strengthening of Masonry Structures with FRP in Italy

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Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Existing Structures

National Research Council

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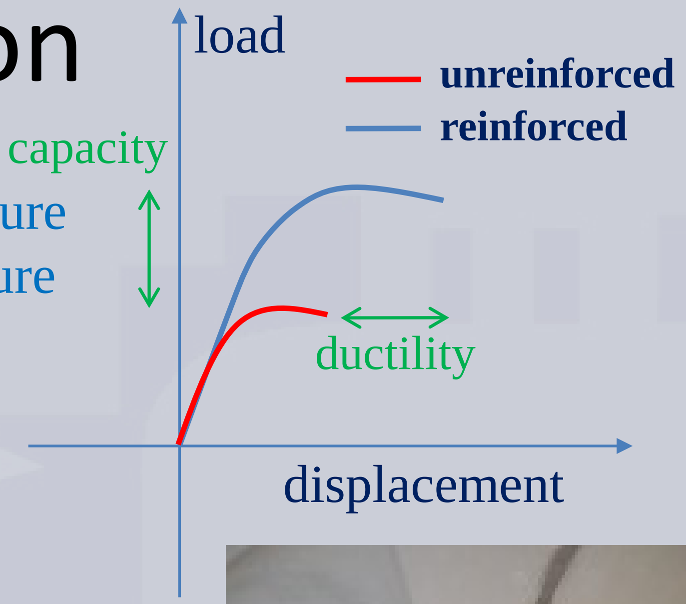


Scope

- to increase the capacity of the masonry structure
- to enhance the structural displacement at failure

Strengthening of historical and monumental buildings

- justified and carefully detailed
- in compliance with the theory of restoration

FRP strengthening design criteria

- strengthening on consolidated masonry
- FRP in tension

Design assumptions

Structural modeling

- (justified) nonlinear / linear / simplified models

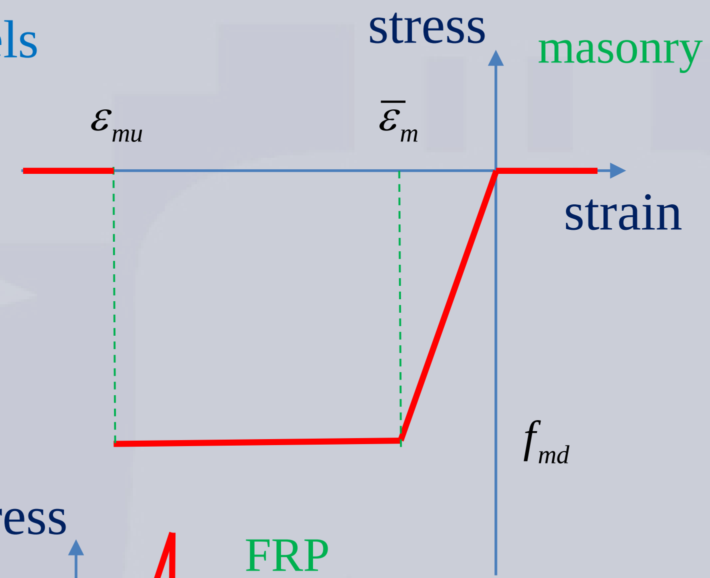
Failure modes

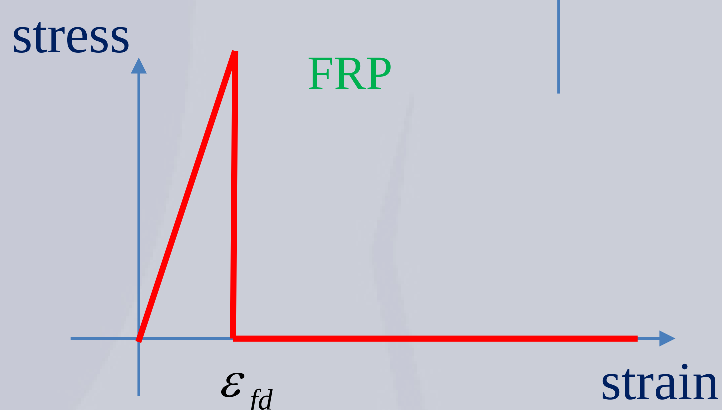
- Tensile cracking; crushing; shear-slip; FRP rupture; debonding.

Design requirements

- $\bar{\varepsilon}_m$ design strain
- ε_{mu} ultimate strain (3.5 ‰)
- f_{md} design stress

- $\varepsilon_{fd} =$ FRP maximum design strain max{failure, debonding}

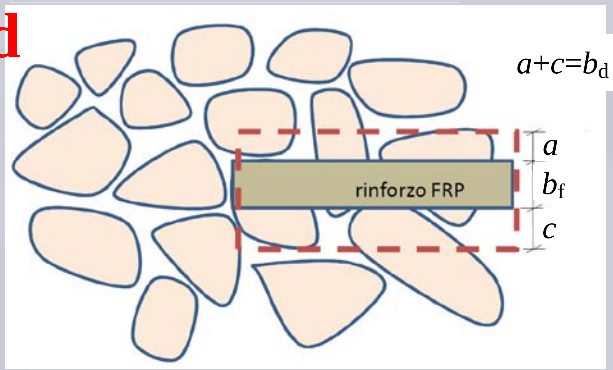




Evaluation of debonding strength

Warning: relevance of masonry-FRP bond

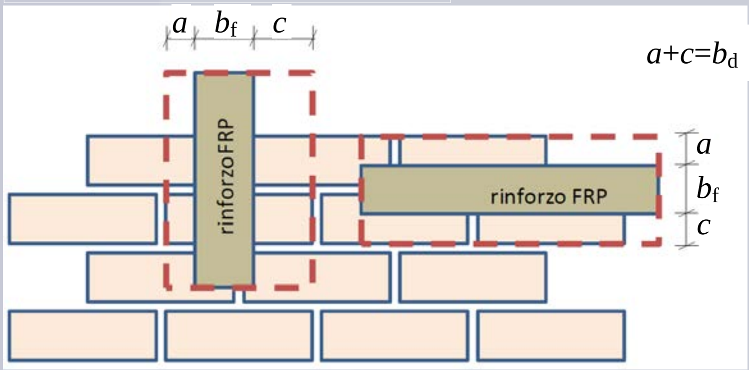
- **brittle failure mode**



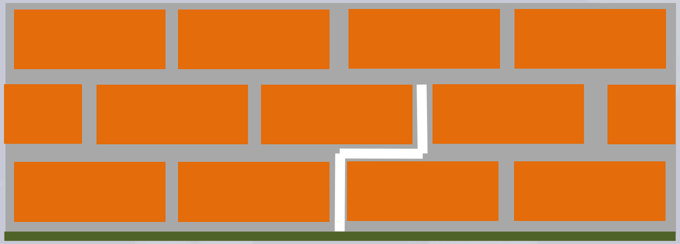
General considerations and failure modes

Design strength for laminate/sheet end debonding

Design strength for intermediate debonding



cracked masonry



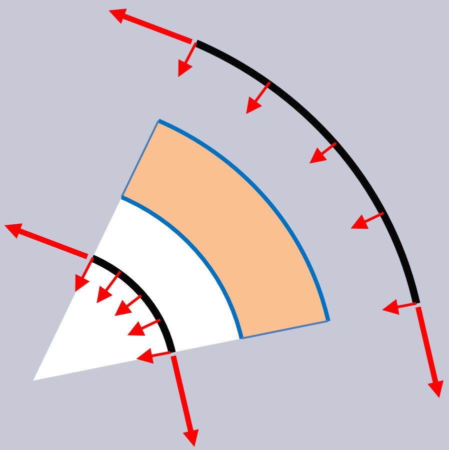
intermediate debonding

Evaluation of debonding strength

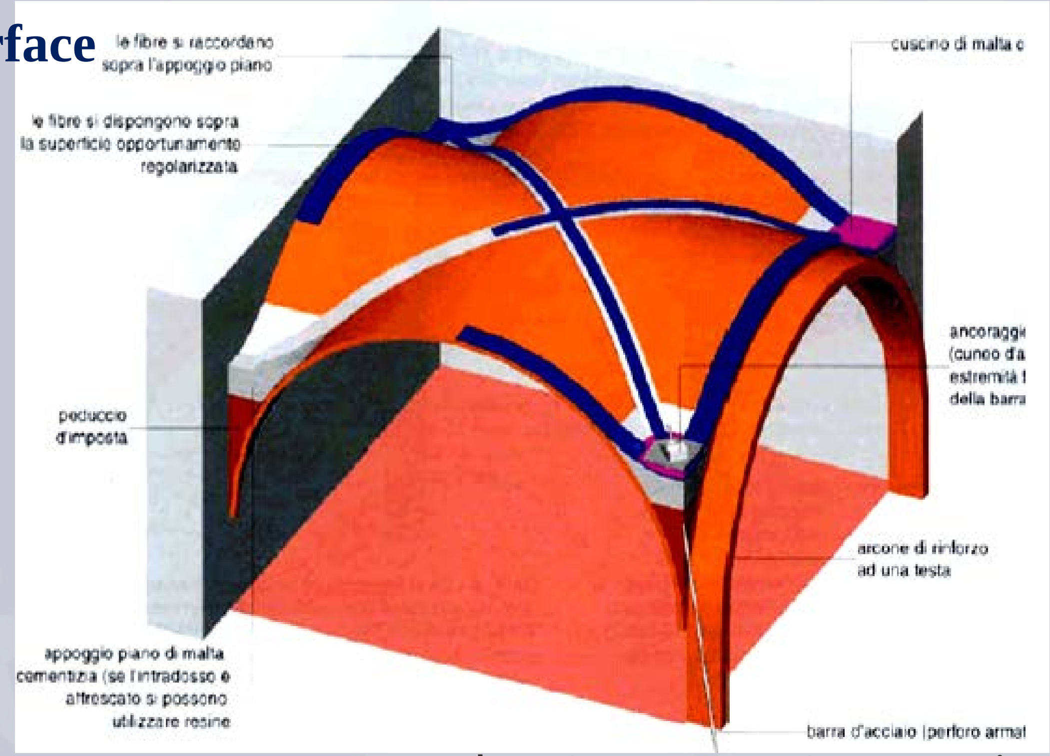
Warning: relevance of masonry-FRP bond

- **brittle failure mode**

Bond strength with stresses perpendicular to the bond surface



Mechanical anchorage devices



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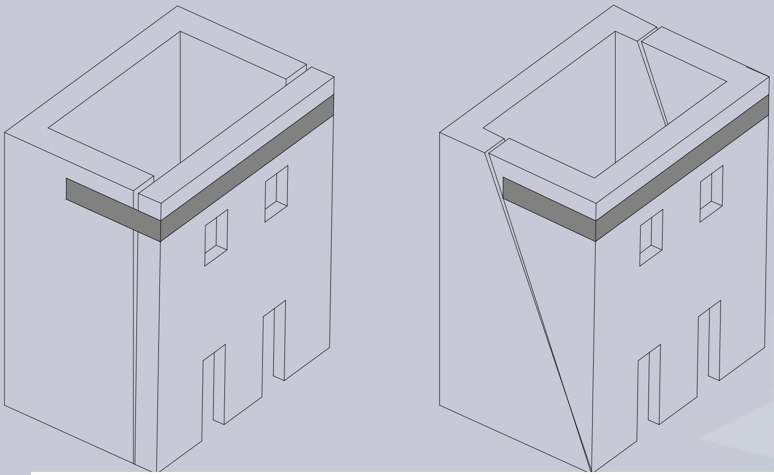
Strengthening of Masonry Structures

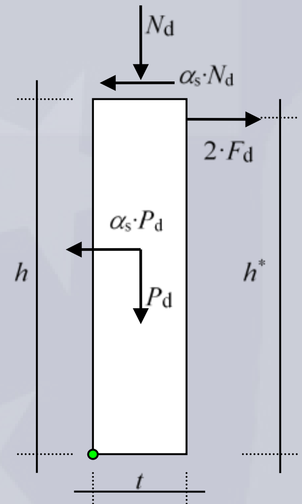
Safety requirements

Strengthening of masonry panels

Strengthening for out-of-plane loads

simple overturning





checks:

- FRP tensile strength
- Rip-off of FRP from orthogonal walls

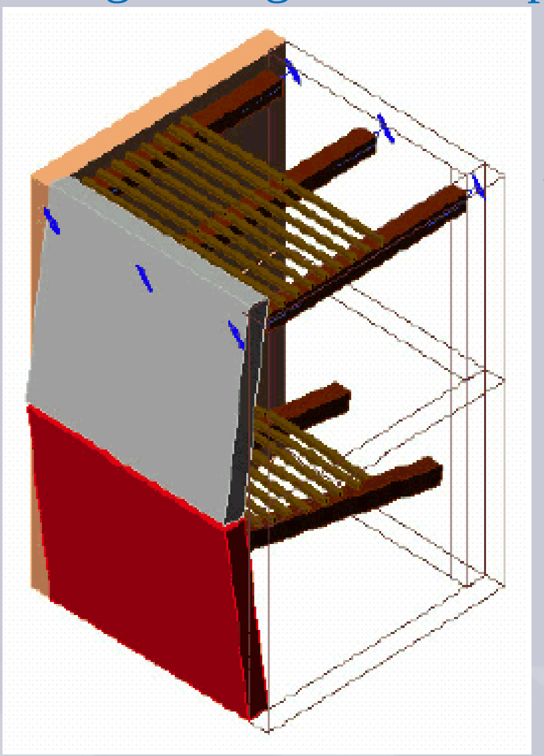
- P_d panel self-weight,
- N_d axial force acting at the top of the panel,
- α_s ratio between vertical and horizontal loads,
- F_d force exerted on the masonry panel by the FRP system.

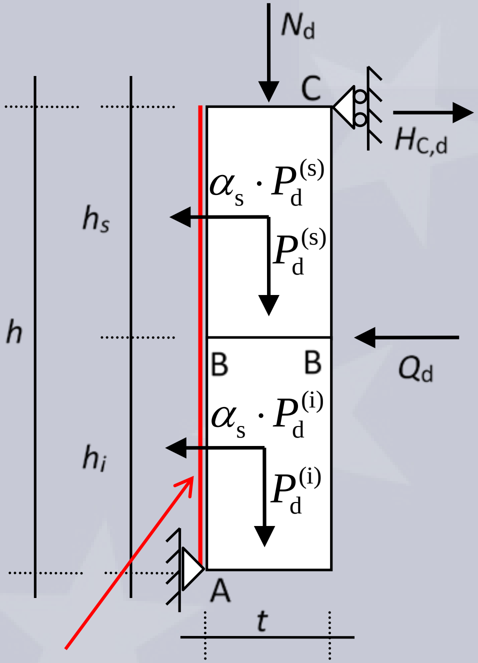
Safety requirements

Strengthening of masonry panels

Strengthening for out-of-plane loads

vertical flexural failure





applied FRP

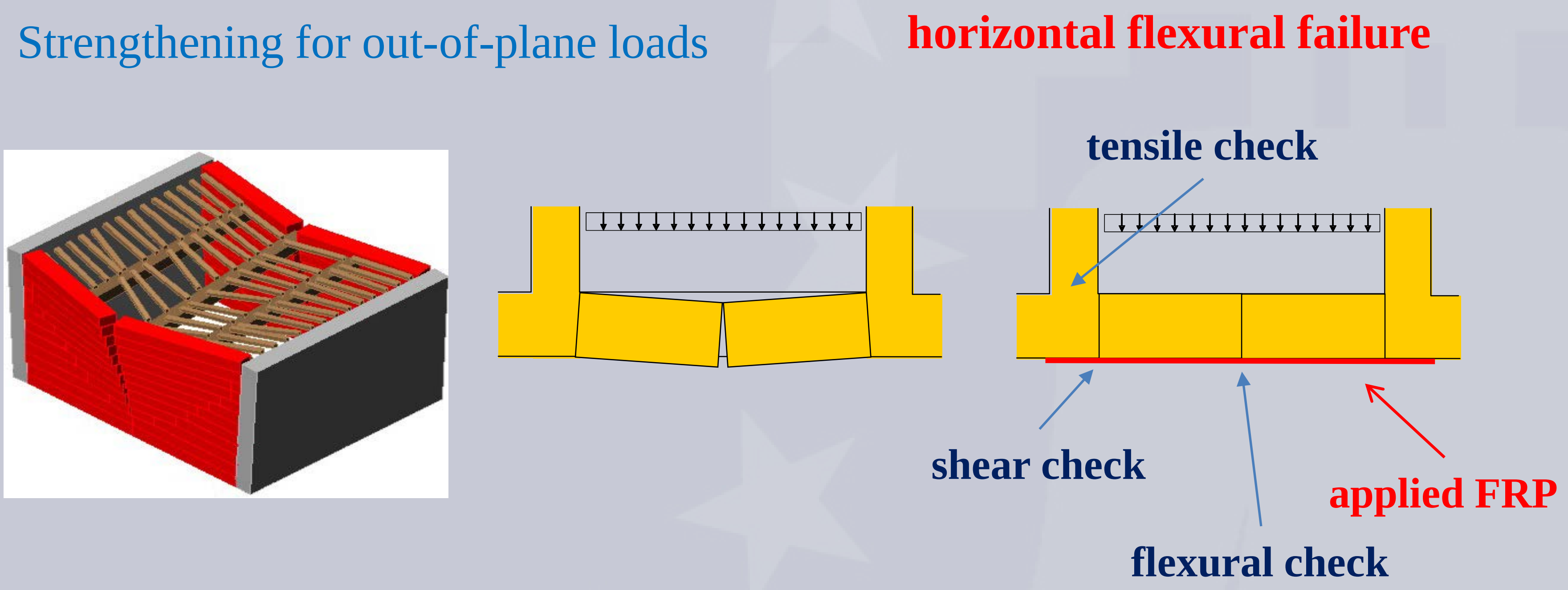
check: $M_{Sd} \leq M_{Rd}$

determined as a function of the mechanical characteristics of the masonry and FRP, the thickness of the masonry panel, the value of the applied axial force and the partial factor for resistance models, that is equal to 1.

Safety requirements

Strengthening of masonry panels

Strengthening for out-of-plane loads

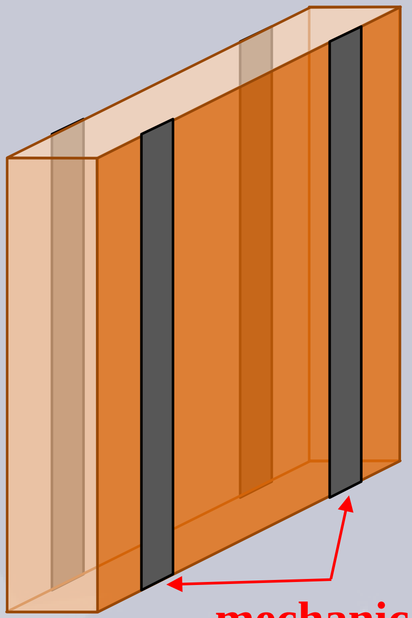


Safety requirements

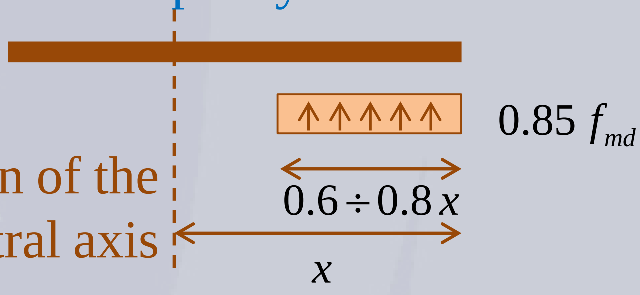
Strengthening of masonry panels

Strengthening for in-plane loads

in-plane combined bending and axial load



- vertical FRP symmetrically installed on both panel sides
- simplified procedure to evaluate the combined bending and axial capacity:



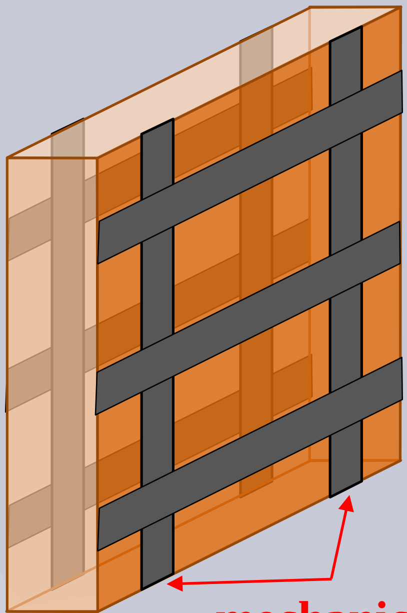
- FRP contribution neglected if mechanical anchorage devises are not present.

Safety requirements

Strengthening of masonry panels

Strengthening for in-plane loads

shear capacity



- FRP applied to both sides with fibers parallel to the shear direction
- formation of truss mechanism
- design shear capacity

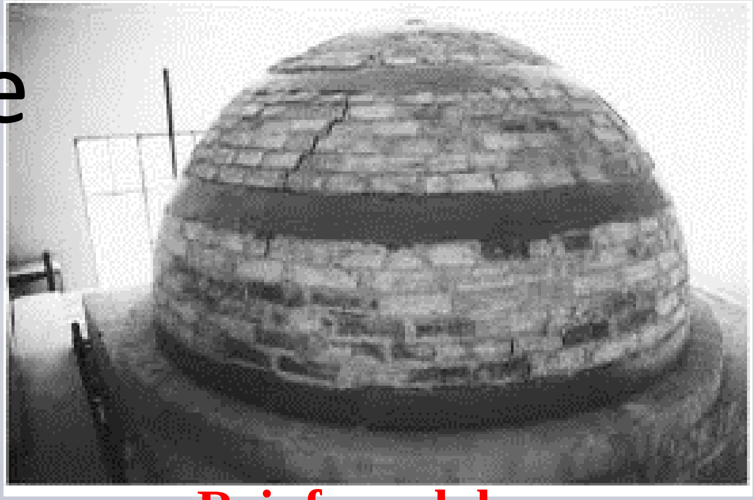
$$V_{Rd} = \min\left\{ V_{Rd,m} + V_{Rd,f} \, ; V_{Rd,max} \right\}$$

masonry & FRP contributions

failure of the compressed strut of the truss

Strengthening of structural members with single or double curvature

- Formation of hinges generated by the negligible tensile strength of the masonry.
- FRP used as external strengthening of a structure to prevent the formation of certain hinges and failure mechanisms.
- FRP reinforcement not recommended when collapse is controlled by shear failure or crushing of the masonry.
- FRP strengthening systems can also improve the capacity and stability of non structural vaults.

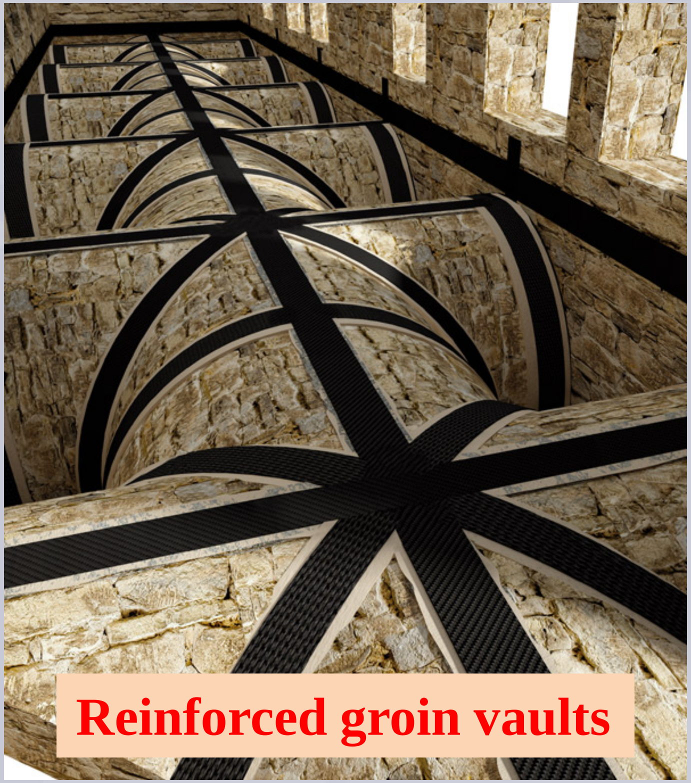


Reinforced dome

Reinforced barrel vault

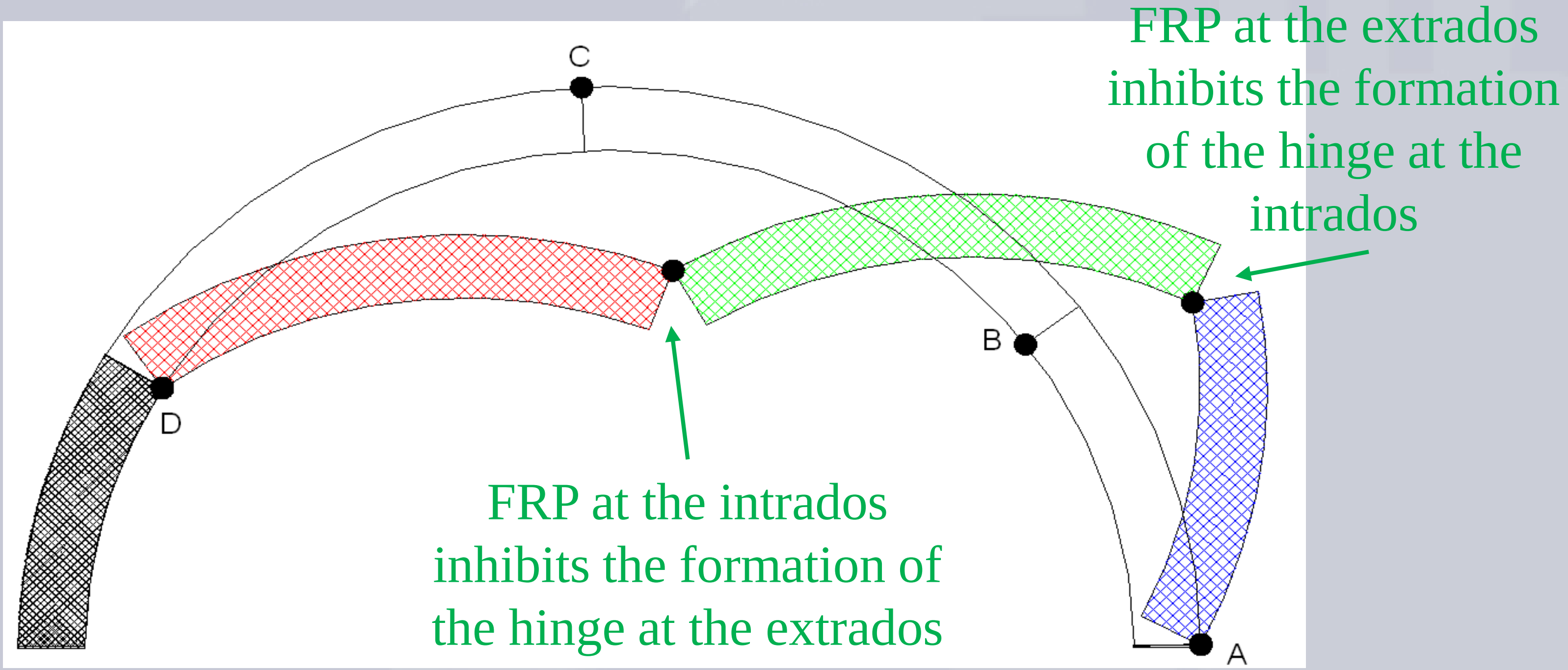
Strengthening of structural members with single or double curvature

- **Arches**
  - Arch scheme
  - Arch-pier scheme
- **Single curvature vaults (barrel vaults)**
- **Double curvature vaults: domes**
  - Membrane-type stresses
  - Flexural-type stresses
- **Double curvature vaults on a square plane**

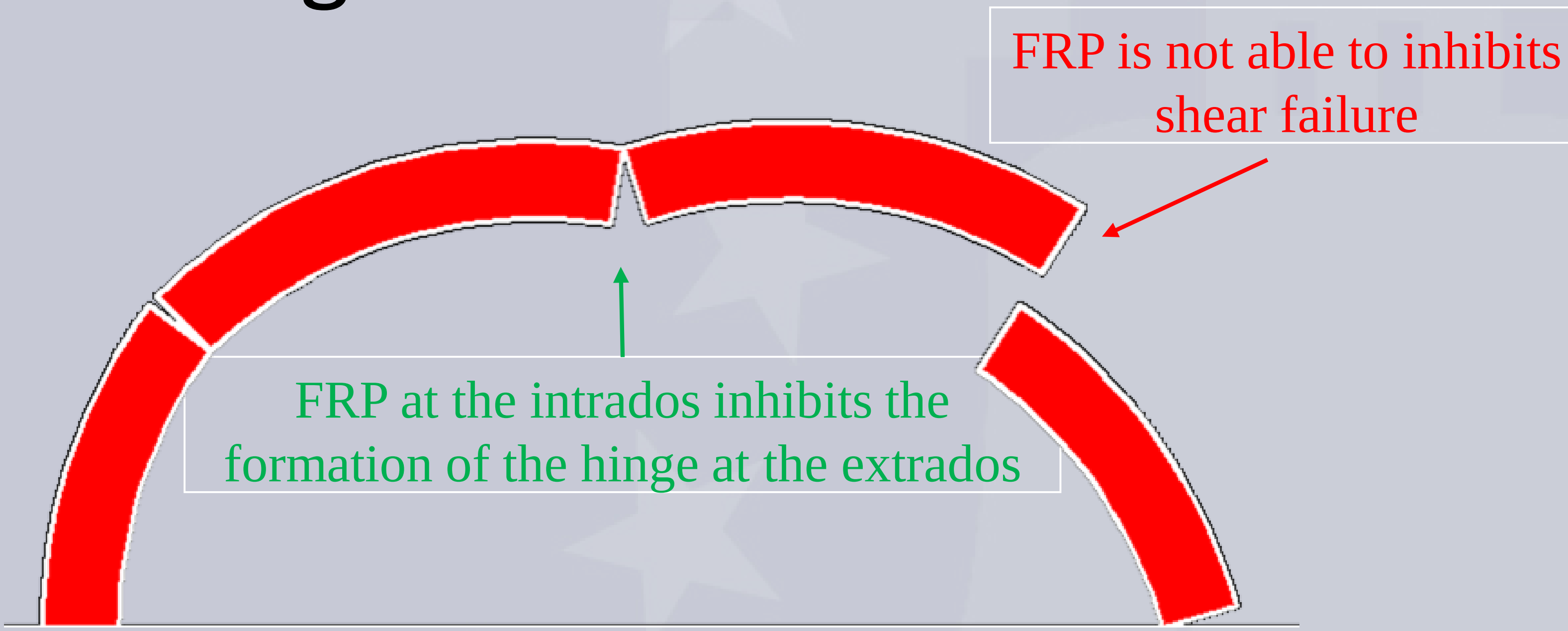


Reinforced groin vaults

Strengthening of structural members with single or double curvature



Strengthening of structural members with single or double curvature



Confinement of masonry columns

- **FRP sheets** installed by **wrapping** of the member
- **FRP bars** inserted in spread holes drilled through the member

→ beneficial effect on the **lateral strain** of the column by providing **tri-axial confinement**.

Design of axially loaded confined members

design axial force due to the applied loads lower than the axial capacity

$$N_{\mathrm{Sd}} \leq N_{\mathrm{Rmc,d}} = \frac{1}{\gamma_{\mathrm{Rd}}} \cdot A_{\mathrm{m}} \cdot f_{\mathrm{mcd}} \geq A_{\mathrm{m}} \cdot f_{\mathrm{md}}$$

design compressive strength

$$f_{\mathrm{mcd}} = f_{\mathrm{md}} \cdot \left[1 + k' \cdot \left(\frac{f_{\mathrm{l,eff}}}{f_{\mathrm{md}}} \right)^{\alpha_1} \right] \qquad k' = \alpha_2 \cdot \left(\frac{g_m}{1000} \right)^{\alpha_3},$$

g_{m} **masonry mass-density**

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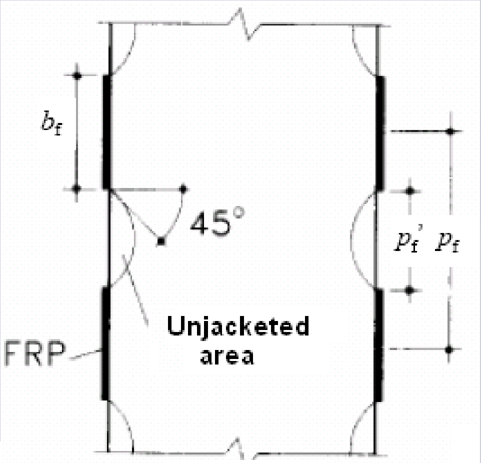
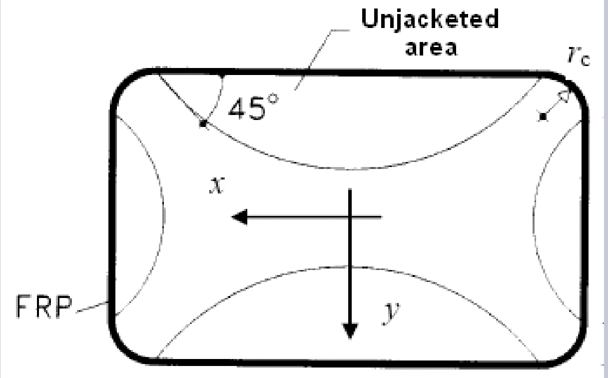
Confinement of masonry columns

Confinement of circular columns

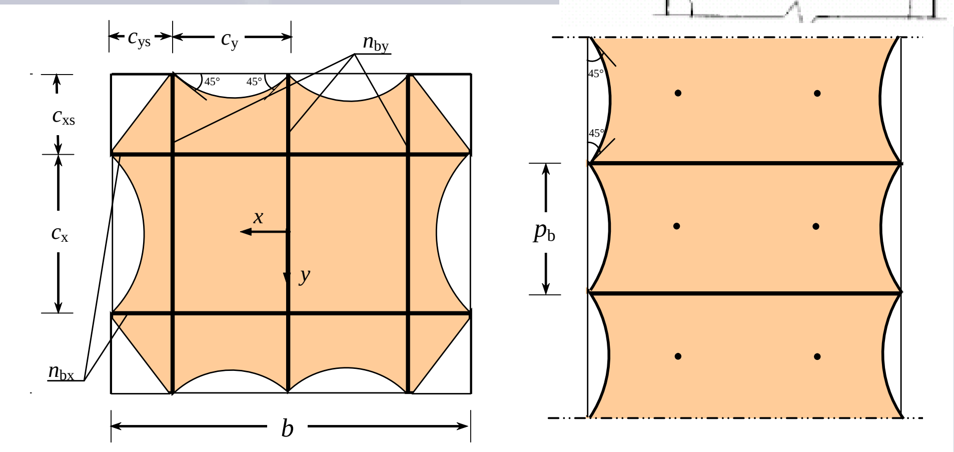
Confinement of prismatic columns

- confining pressure
- reduction of the confined volume





arch-effect for rectangular section externally wrapped with FRP



effect of FRP bars for rectangular

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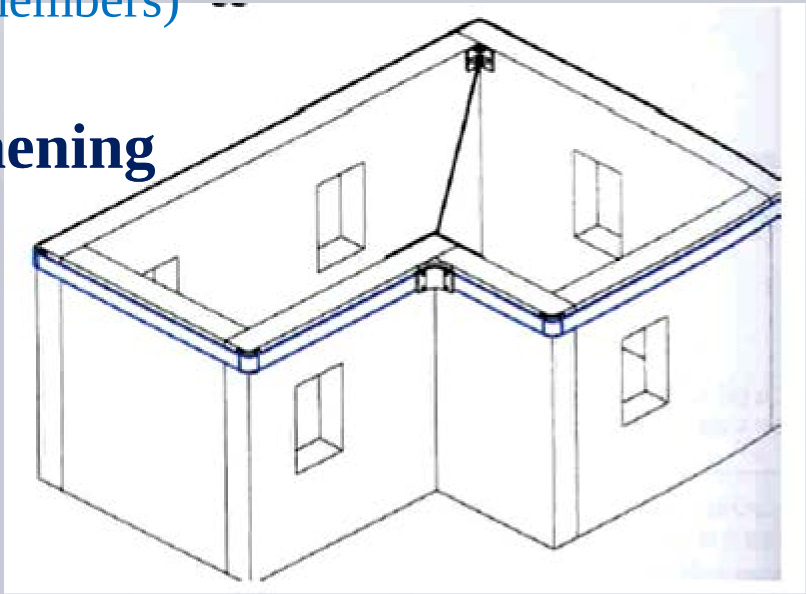
Design for seismic applications

Design objectives

- evaluation of seismic safety (verification of limit states)
- methods of analysis
- verification criteria (ductile and brittle members)



Selection criteria for FRP strengthening

- masonry walls shall be connected
- connections between floors/roof and vertical elements
- constrained horizontal forces generated from roofs, arches, and vaults
- rigid floors
- FRP strengthened members enhancing local ductility

Installation and construction details

Quality control and substrate preparation

- evaluation of substrate deterioration
- removal and reconstruction of defective masonry supports
- substrate preparation

Recommendations for the installation

- humidity and temperature conditions in the environment and substrate
- construction details
- protection of FRP systems

Numerical example (Appendix H)

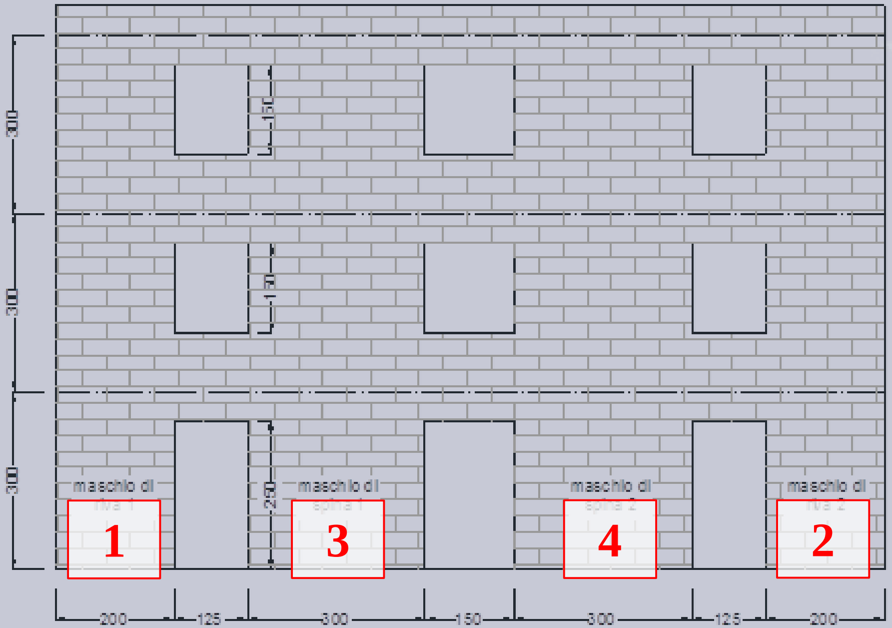


Table 14-1 – Masonry data.

Young modulus of elasticity	E [N/mm^2]	4000
Shear modulus	G [N/mm^2]	1000
Specific weight	γ [kN/m^3]	18.0
Factor of confidence	FC	1.0
Partial factor	γ_M	2
Compressive strength of masonry in the horizontal direction		
Characteristic strength	f_{mk} [N/mm^2]	8.0
Design strength	f_{md} [N/mm^2]	4.0
Shear capacity		
Characteristic strength without any axial load	f_{vk0} [N/mm^2]	0.8
Masonry block strength		
Mean value of compressive strength	f_{bm} [N/mm^2]	38
Mean value of tensile strength	f_{btm} [N/mm^2]	3.8

Table 14-3–Partial factors and design values of the FRP.

Partial factor for debonding	$\gamma_{f,d}$ (Section 3.4.1)	1.2
Partial factor for ULS	γ_f (Section 3.4.1)	1.1
Conversion factor for environment	η_a (Section 3.5.1)	0.95
Ultimate tensile strain	$\eta_a \cdot \varepsilon_{fk} / \gamma_f$ (Section 5.2.3)	0.0151
Width of the bond strength distribution area	b_d [mm] (Section 5.3.2)	250
Geometrical corrective factor	k_b (Section 5.3.2)	1.363
Interface slip at full debonding	s_u [mm] (Section 5.3.2)	0.4
Corrective factor	k_G [mm] (Section 5.3.2)	0.031
Specific fracture energy	Γ_{Fd} [N/mm] (Section 5.3.2)	0.5077

Table 14-2–FRP geometry and mechanical properties.

Thickness	t_f [mm]	0.165
Width	b_f [mm]	100
Young modulus of elasticity in the fiber direction	E_f [GPa]	230
Ultimate strain	ε_{fk}	0.0175
Spacing	p_f [mm]	500

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Numerical example (Appendix H)

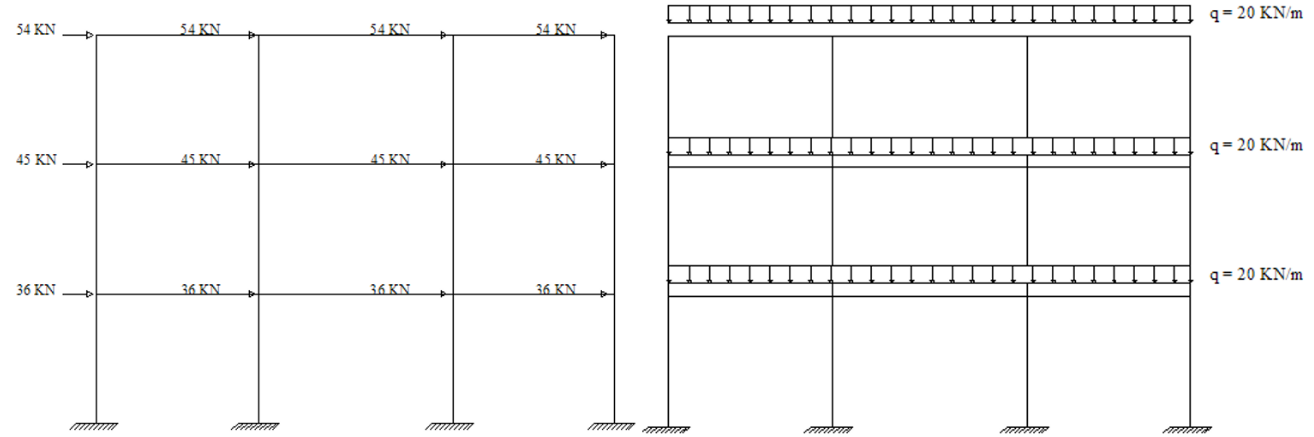

Figure 14-2 – Frame model and loads.

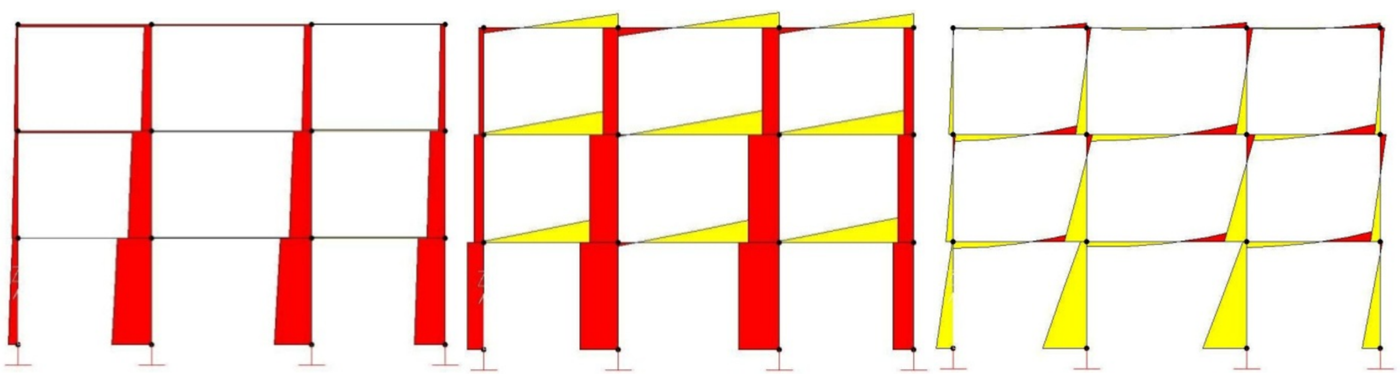

Figure 14-3 – Axial, shear and moment diagrams.

Numerical example (Appendix H)

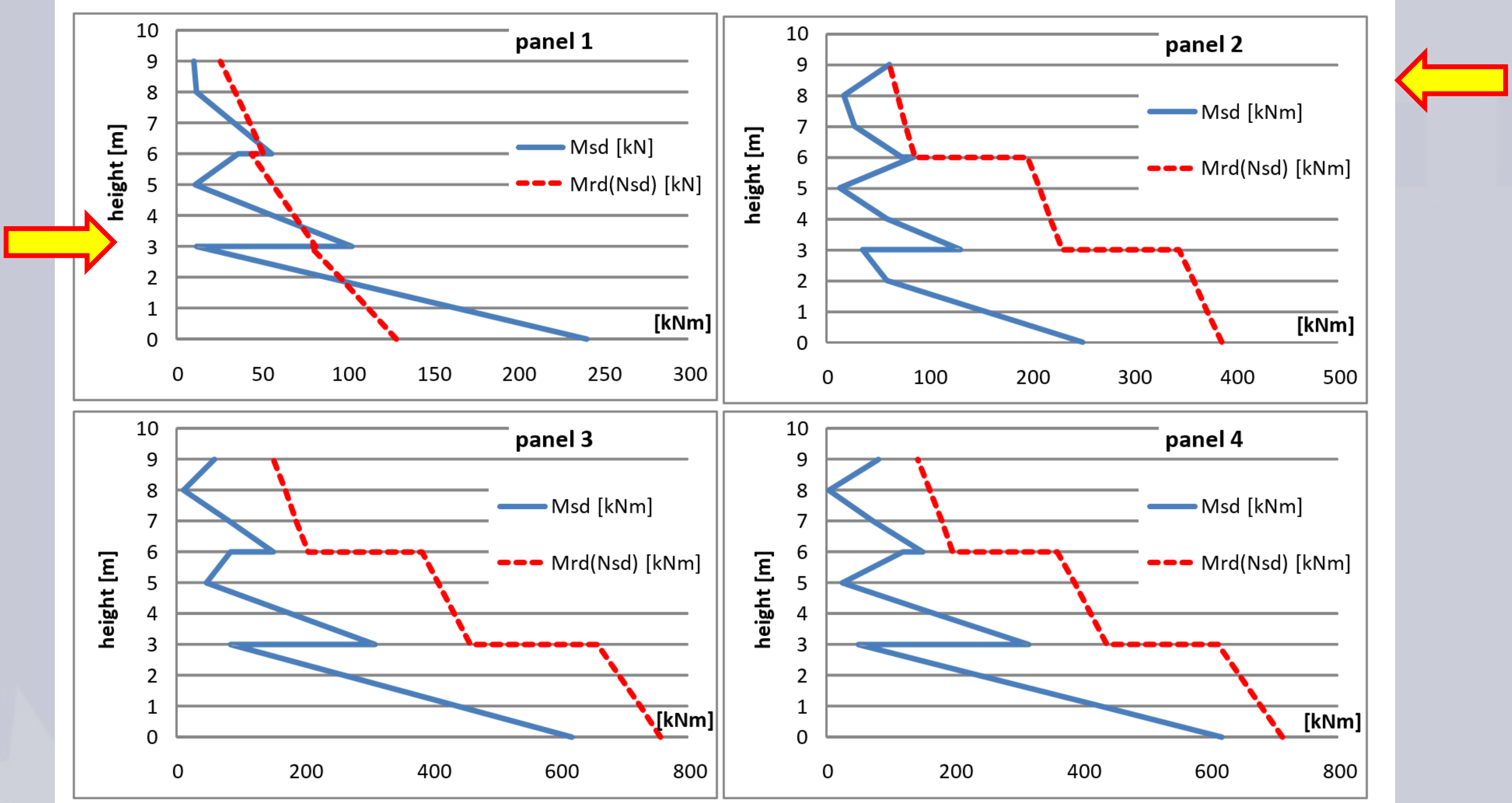

Figure 14-4– Flexural capacity and factored moment.

Numerical example (Appendix H)

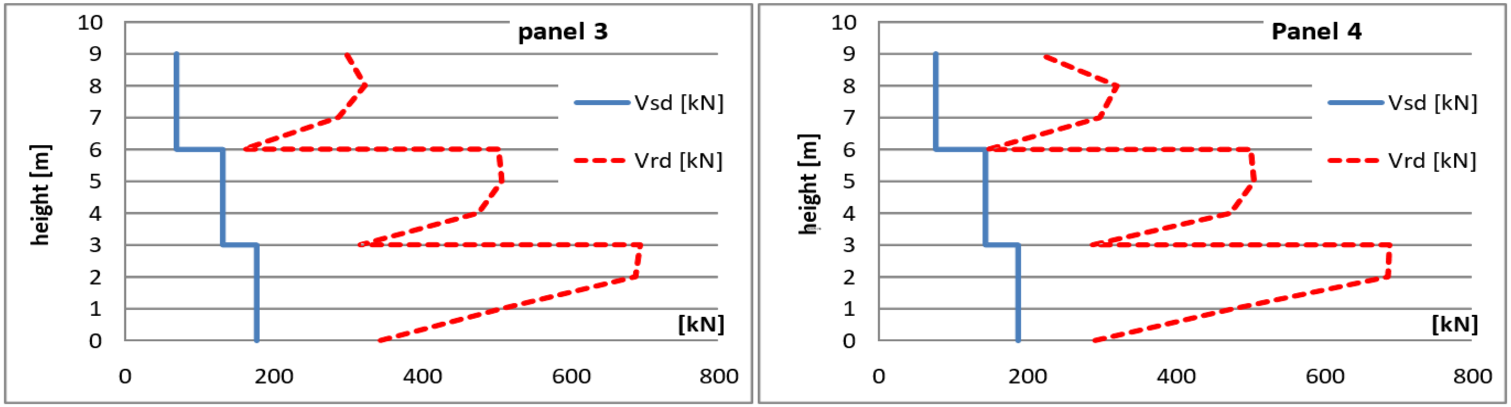

Figure 14-5 – Shear capacity and factored shear diagrams of panels 3 and 4.

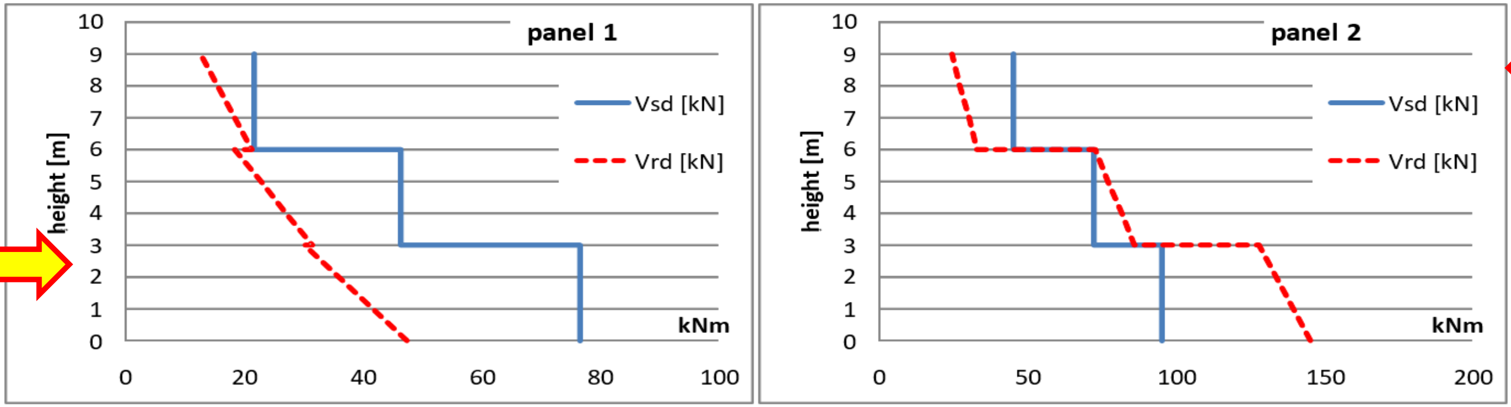

Figure 14-6 – Shear capacity and factored shear diagrams of panels 1 and 2.

Numerical example (Appendix H)

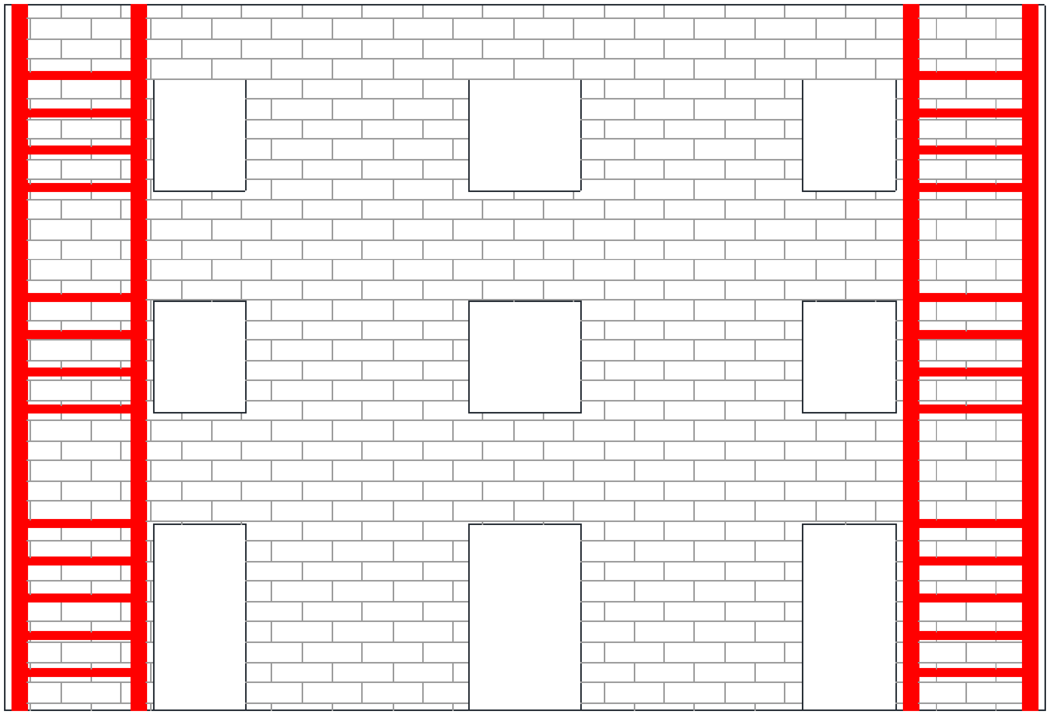

Figure 14-7 – Layout of the FRP installation.

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Numerical example (Appendix H)

Table 14-12 –Combined axial and bending capacity of the FRP strengthened panel 1

Level [m]	FRP failure	ε_{fd}	$M_{Rd}(N_{Sd})$ [kN m]	$M_{Rd}(N_{Sd}) \geq M_{Sd}$
0	FRP failure	0.0151	335.8	verified
1	intermediate debonding	0.0086	231.6	verified
2	intermediate debonding	0.0086	215.4	verified
3	intermediate debonding	0.0086	199.1	verified
3	intermediate debonding	0.0086	200.6	verified
4	intermediate debonding	0.0086	188.6	verified
5	intermediate debonding	0.0086	176.6	verified
6	intermediate debonding	0.0086	164.3	verified
6	intermediate debonding	0.0086	169.8	verified
7	intermediate debonding	0.0086	162.0	verified
8	intermediate debonding	0.0086	154.0	verified
9	end debonding	0.0043	86.5	verified

Numerical example (Appendix H)

Table 14-13 – Combined axial and bending capacity of the FRP strengthened panel 2.

Level [m]	FRP failure	ε_{fd}	$M_{Rd}(N_{Sd})$ [kN m]	$M_{Rd}(N_{Sd}) \geq M_{Sd}$
0	FRP failure	0.0151	577.0	verified
1	intermediate debonding	0.0086	482.9	verified
2	intermediate debonding	0.0086	469.4	verified
3	intermediate debonding	0.0086	455.8	verified
3	intermediate debonding	0.0086	342.7	verified
4	intermediate debonding	0.0086	332.2	verified
5	intermediate debonding	0.0086	321.6	verified
6	intermediate debonding	0.0086	310.9	verified
6	intermediate debonding	0.0086	202.4	verified
7	intermediate debonding	0.0086	194.9	verified
8	intermediate debonding	0.0086	187.3	verified
9	end debonding	0.0043	121.3	verified

Numerical example (Appendix H)

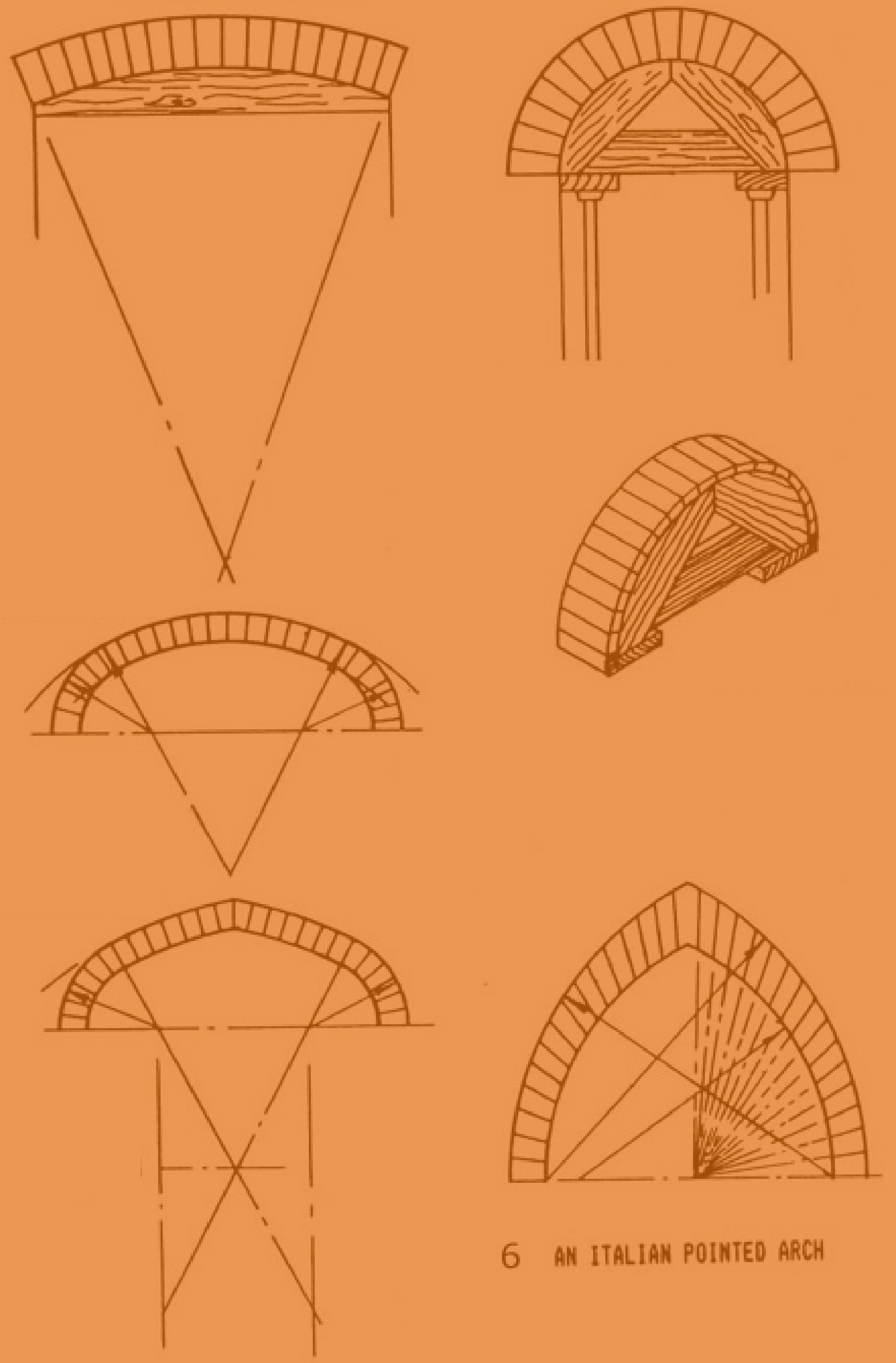
Table 14-18– Shear capacity of panel 1.

Level [m]	Factored shear V_{Sd} [kN]	Masonry contribution $V_{Rd,m}$ [kN]	FRP contri-bution $V_{Rd,f}$ [kN]	$V_{Rd,max}$ [kN]	Shear capaci-ty V_{Rd} [kN]	$V_{Rd} \geq V_{Sd}$	Failure
0	76.58	57.7	124.02	1140	181.7	satisfied	FRP failure
1	76.58	45.8	124.02	1140	169.8	satisfied	FRP failure
2	76.58	40.0	124.02	1140	164.1	satisfied	FRP failure
3	76.58	34.3	124.02	1140	158.3	satisfied	FRP failure
3	46.48	35.5	124.02	855	159.5	satisfied	FRP failure
4	46.48	31.2	124.02	855	155.2	satisfied	FRP failure
5	46.48	26.9	124.02	855	150.9	satisfied	FRP failure
6	46.48	22.6	124.02	855	146.6	satisfied	FRP failure
6	21.85	25.3	124.02	570	149.3	satisfied	FRP failure
7	21.85	22.4	124.02	570	146.4	satisfied	FRP failure
8	21.85	19.6	124.02	570	143.6	satisfied	FRP failure
9	21.85	12.6	124.02	570	136.6	satisfied	FRP failure

Numerical example (Appendix H)

Table 14-19 – Shear capacity of panel 2.

Level [m]	Factored shear V_{Sd} [kN]	Masonry contribution $V_{Rd,m}$ [kN]	FRP contribution $V_{Rd,f}$ [kN]	$V_{Rd,max}$ [kN]	Shear capacity V_{Rd} [kN]	$V_{Rd} \geq V_{Sd}$	Failure
0	95.43	155.61	124.02	1140.0	279.6	satisfied	FRP failure
1	95.43	143.70	124.02	1140.0	267.7	satisfied	FRP failure
2	95.43	137.96	124.02	1140.0	262.0	satisfied	FRP failure
3	95.43	132.22	124.02	1140.0	256.2	satisfied	FRP failure
3	72.51	90.17	124.02	855.0	214.2	satisfied	FRP failure
4	72.51	85.86	124.02	855.0	209.9	satisfied	FRP failure
5	72.51	81.56	124.02	855.0	205.6	satisfied	FRP failure
6	72.51	77.25	124.02	855.0	201.3	satisfied	FRP failure
6	45.1	37.57	124.02	570.0	161.6	satisfied	FRP failure
7	45.1	34.70	124.02	570.0	158.7	satisfied	FRP failure
8	45.1	31.83	124.02	570.0	155.9	satisfied	FRP failure
9	45.1	24.88	124.02	570.0	148.9	satisfied	FRP failure



Thanks for your attention

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