

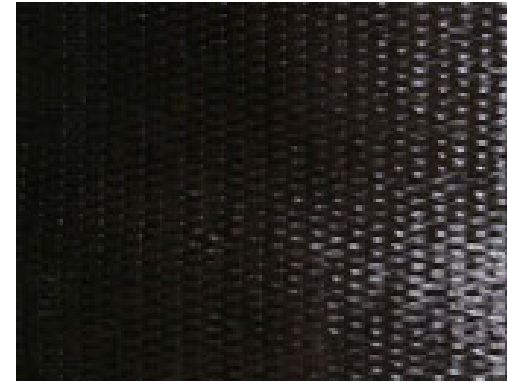
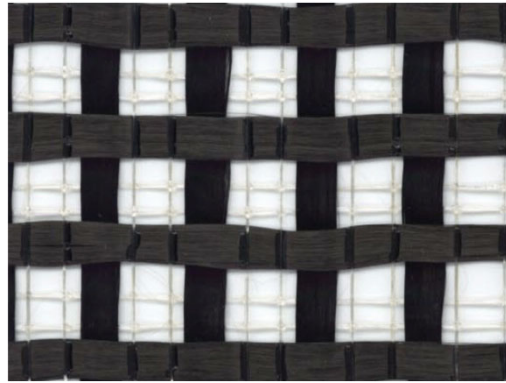
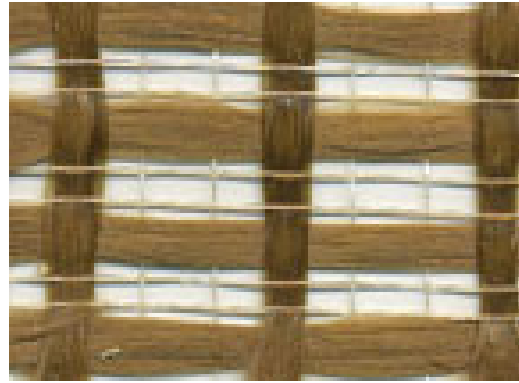


e-CAMPUS
UNIVERSITÀ

Francesco Focacci
Università Telematica E-campus

**COMPOSITI A MATRICE CEMENTIZIA
PER IL RINFORZO DI STRUTTURE E
INFRASTRUTTURE**

MATERIALI DI RINFORZO



POLIPARAFENILENBENZOBISOXAZOLO (PBO)

CARBONIO (C)

INORGANICA
(CEMENTIZIA)

FRCM

FRP

RESINA
EPOSSIDICA

FIBRE	Res. a trazione (N/mm ²)	Dil. di rottura (‰)	Modulo elastico (GPa)	Spessore nominale (mm)
Carbon net	3500	15	240	0.047 (dir. 1 and 2)
PBO net	5800	21.5	270	0.046 (dir.1) 0.022 (dir. 2)
Carbon sheet	3500	15	240	0.17

TONNARA DI FAVIGNANA (2004)

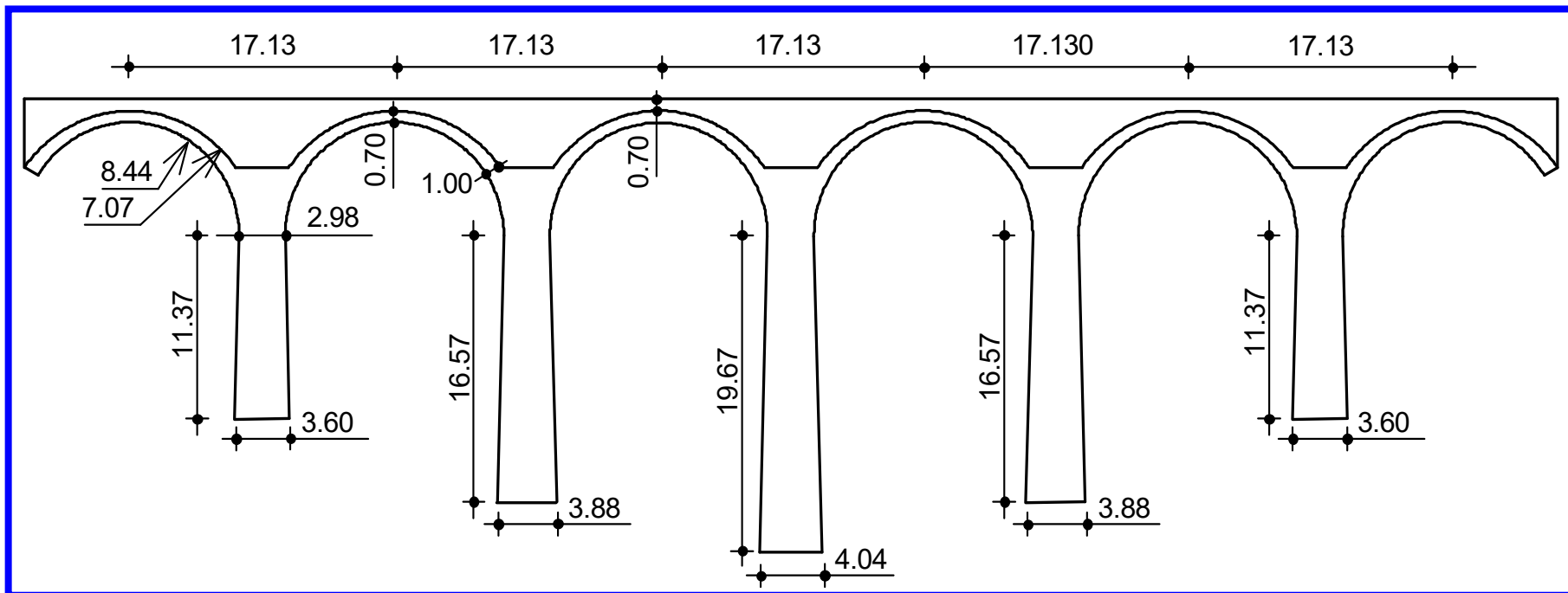


Volte nei "magazzini generali"



VIADOTTI ROMA-NAPOLI (2010-2011-2012)

- Pile di muratura
- Volte di calcestruzzo non armato





- **Quadro normativo**

ACI 549.4R-13

**Guide to Design and Construction
of Externally Bonded Fabric-
Reinforced Cementitious Matrix
(FRCM) Systems for Repair and
Strengthening Concrete and
Masonry Structures**

Reported by ACI Committee 549



American Concrete Institute®



American Concrete Institute®

Berardi, F.; Focacci, F.; Mantegazza, G.; and Miceli, G., 2011, “Rinforzo di un Viadotto Ferroviario con PBO-FRCM,” *Proceedings, 1° Convegno Nazionale Assocompositi*, Milan, Italy, May 25-26. (in Italian)

D’Ambrisi, A. D.; Feo, L.; and Focacci, F., 2012, “Bond-slip Relations for PBO-FRCM Externally Bonded to Concrete,” *Composites. Part B, Engineering*, V. 43, No. 8, pp. 2938-2949.

D’Ambrisi, A. D.; Feo, L.; and Focacci, F., 2013, “Experimental Analysis on Bond Between PBO-FRCM Strengthening Materials and Concrete,” *Composites. Part B, Engineering*, V. 44, No. 1, pp. 524-532.

D’Ambrisi, A. D., and Focacci, F., 2011, “Flexural Strengthening of RC Beams with Cement Based Composites,” *Journal of Composites for Construction*, V. 15, No. 5, pp. 707-720.



(b)

Fig. 4.1.2a—(a) Bridge structure with view of scaffolding; and (b) installation of FRCM.



Fig. 4.1.2b—Details of work in progress (second fiber mesh).

- **Quadro normativo**

CNR – Commissione di studio per la predisposizione e l'analisi di norme tecniche relative alle costruzioni

CNR DT215



CONSIGLIO NAZIONALE DELLE RICERCHE

COMMISSIONE DI STUDIO PER LA PREDISPOSIZIONE E L'ANALISI
DI NORME TECNICHE RELATIVE ALLE COSTRUZIONI

➔ Fase di **inchiesta pubblica** finita
il 31 gennaio 2019

➔ Istruzioni per la **progettazione**

**Istruzioni
per la Progettazione, l'Esecuzione ed il Controllo
di Interventi di Consolidamento Statico
mediante l'utilizzo di
Compositi Fibrorinforzati a matrice inorganica**

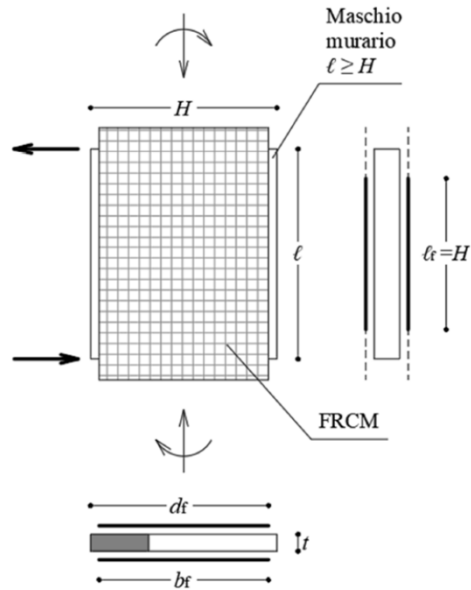


CNR-DT 215/2018

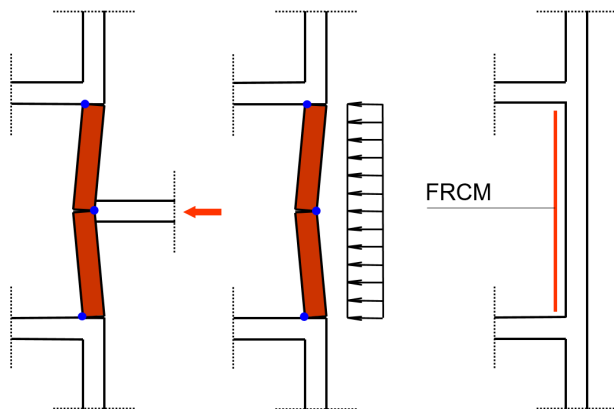
ROMA – CNR 23.10. 2018

Rinforzo di maschi murari

- pressoflessione nel piano
- taglio nel piano piano



- pressoflessione fuori piano

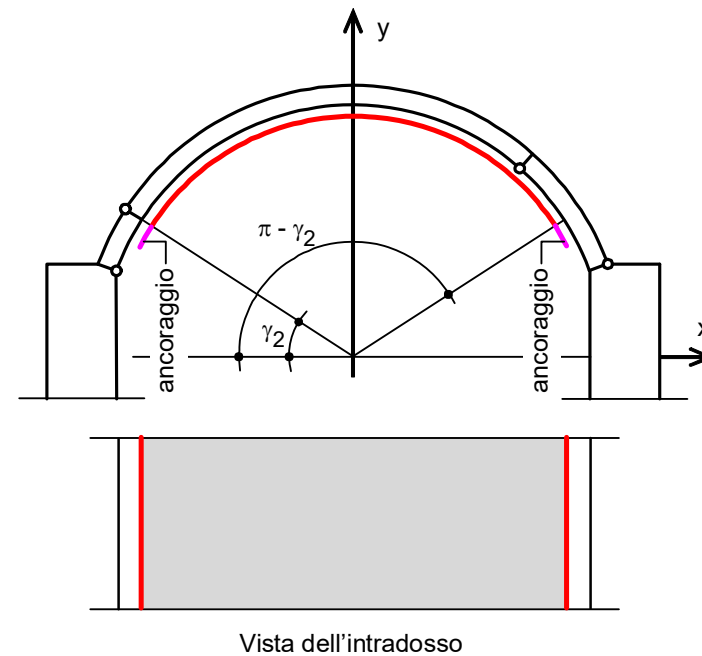


CNR DT215



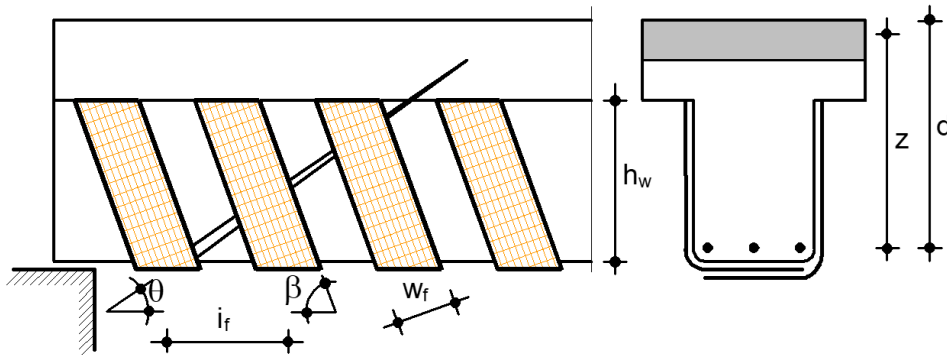
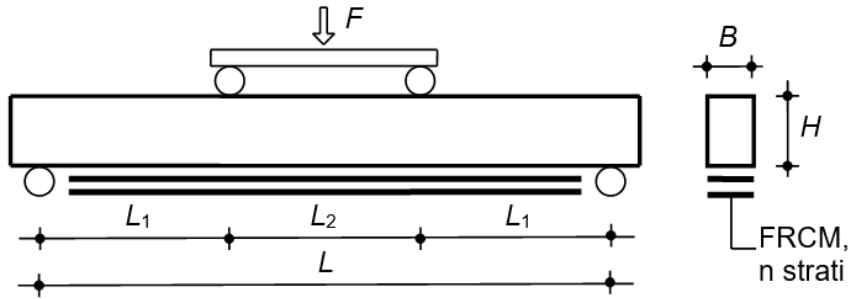
**Istruzioni
per la Progettazione, l'Esecuzione ed il Controllo
di Interventi di Consolidamento Statico
mediante l'utilizzo di
Compositi Fibrorinforzati a matrice inorganica**

Rinforzo di volte



Rinforzo cemento armato

- flessione e taglio

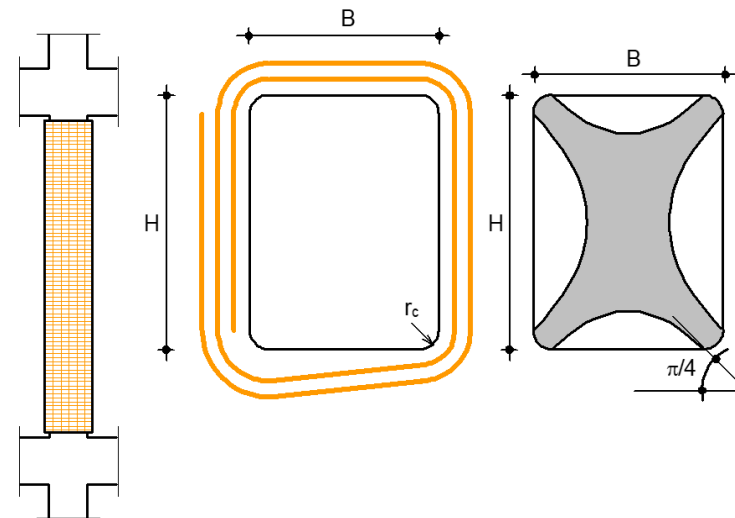


CNR DT215



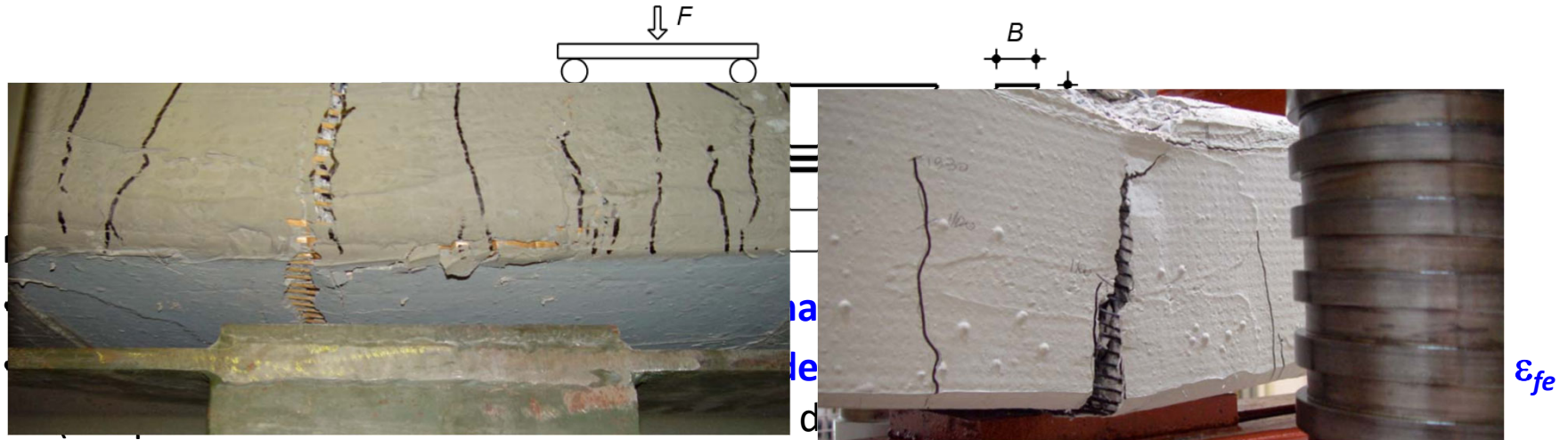
**Istruzioni
per la Progettazione, l'Esecuzione ed il Controllo
di Interventi di Consolidamento Statico
mediante l'utilizzo di
Compositi Fibrorinforzati a matrice inorganica**

- confinamento



ELEMENTI DI PROGETTAZIONE

- Rinforzo a flessione di travi di calcestruzzo armato**



→ Curvatura ultima $\chi_u = \frac{\epsilon_{fe} + \epsilon_0}{H - x_n}$

→ Asse neutro $B \cdot \int_0^{x_n} \sigma_c(\chi_u \cdot \xi) \cdot d\xi = A_s \cdot f_y + A_f E_f \cdot \epsilon_{fe}$

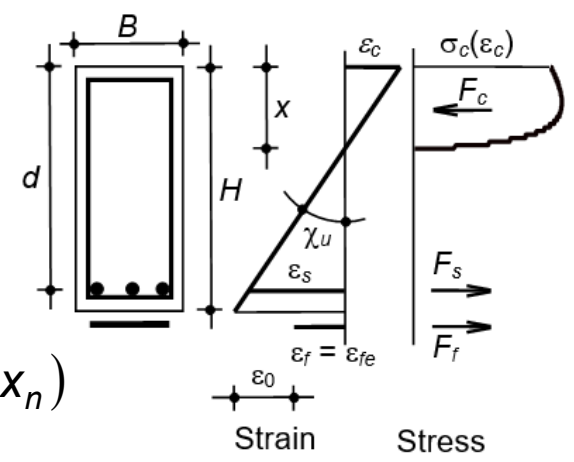
→ Momento resistente **DELLE sole FIBRE**

dilatazione di delaminazione
 dilatazione preesistente (supporto)

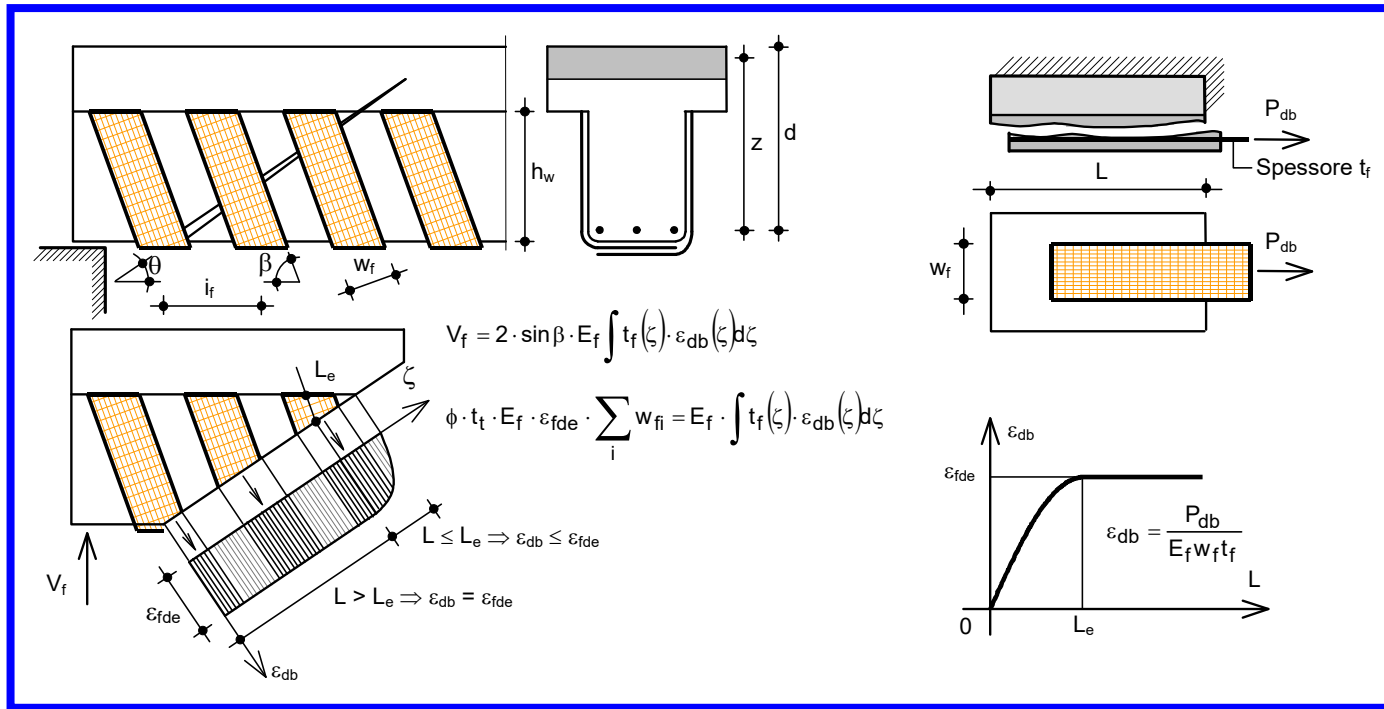
Sezione **DELLE** sole **FIBRE**

Modulo elastico **DELLE** sole **FIBRE**

$$M_R = B \cdot \int_0^{x_n} \sigma_c(\chi_u \cdot \xi) \cdot \xi d\xi + A_s \cdot f_{yd} \cdot (d - x_n) + A_f E_f \cdot \epsilon_{fe} \cdot (H - x_n)$$



Rinforzo a flessione di travi di calcestruzzo armato



External strengthening

Shear strength

$$V_{Rd} = \min \{ V_{wd} + V_{ctd} + V_{fd}, V_{cd} \}$$

V_{cd} : diagonal concrete crushing

V_{wd} : steel contribution

V_{fd} : external strengthening contribution

V_{ctd} : concrete contribution

$$V_f = \frac{1}{\gamma_{Rd}} \cdot 0.9 \cdot d \cdot \frac{2t_f w_f}{i_f} \cdot E_f \varepsilon_{fdv} \cdot \sin \beta \cdot (\cot \theta + \cot \beta)$$

$$\varepsilon_{fdv} = \phi \cdot \varepsilon_{fde}$$

$$\phi = 1 - \frac{1}{3} \cdot \frac{L_e}{h_w} \cdot \sin \beta$$

Dilatazione di delaminazione di estremità
Lunghezza di trasferimento efficace

RINFORZO A FLESSIONE

VERIFICHE

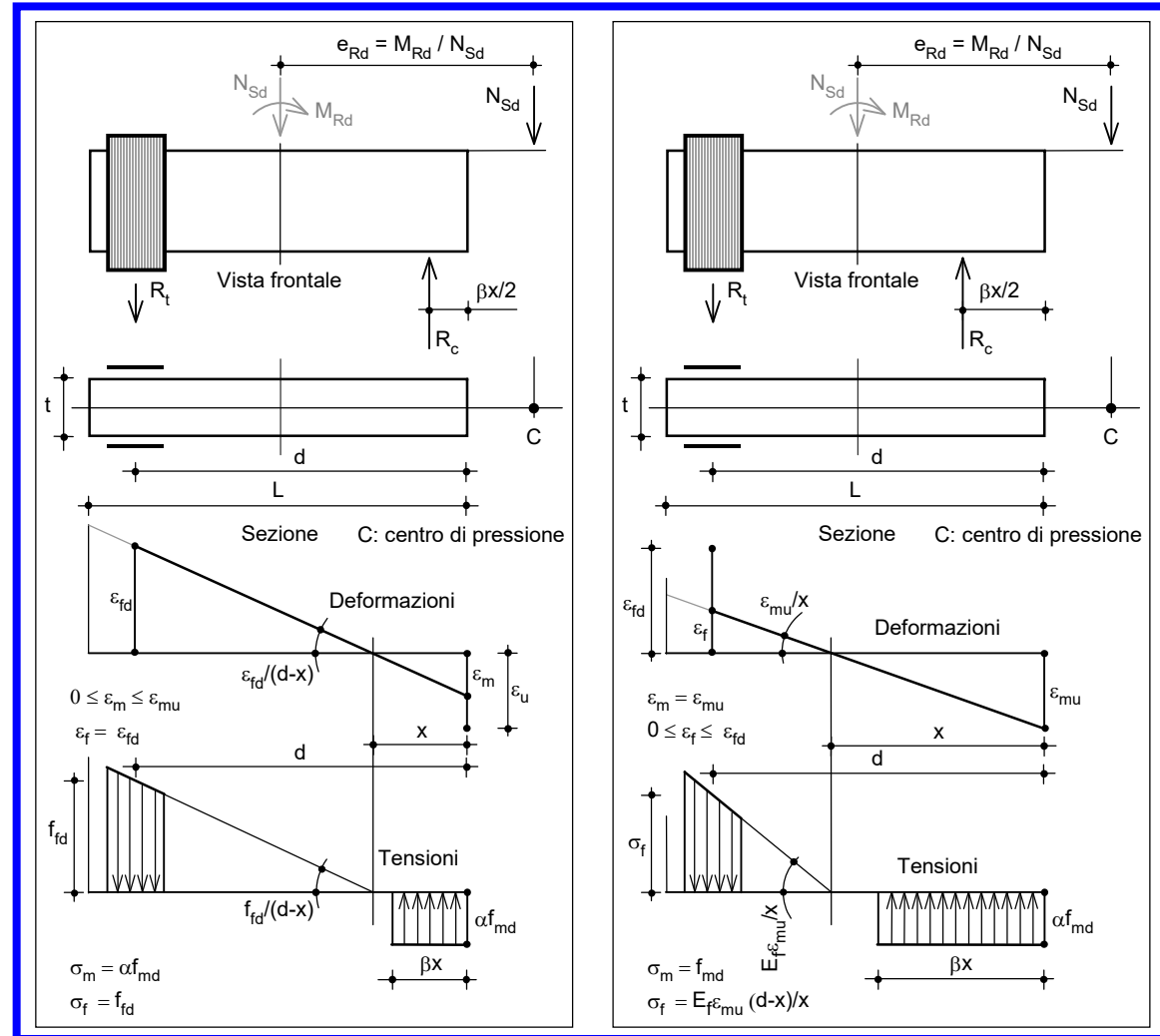
● PRESSOFLESSIONE

➔ CNR DT 200

$$f_{md} = \frac{f_{mk}}{\gamma_m} \quad \varepsilon_{mu} = 0.35\%$$

$$\alpha = 0.85 \quad \beta = 0.6 \div 0.8$$

ε_{fd} limite determinato tenendo conto della **delaminazione**



ROTTURA RINFORZO

ROTTURA MURATURA

- **Quadro normativo**

➔ Linea Guida per la identificazione, la qualificazione ed il **controllo di accettazione** di compositi fibrorinforzati a matrice inorganica (FRCM) da utilizzarsi per il consolidamento strutturale di costruzioni esistenti




Parametri meccanici di calcolo



Formulazioni di progetto



➔ **Reluis** 

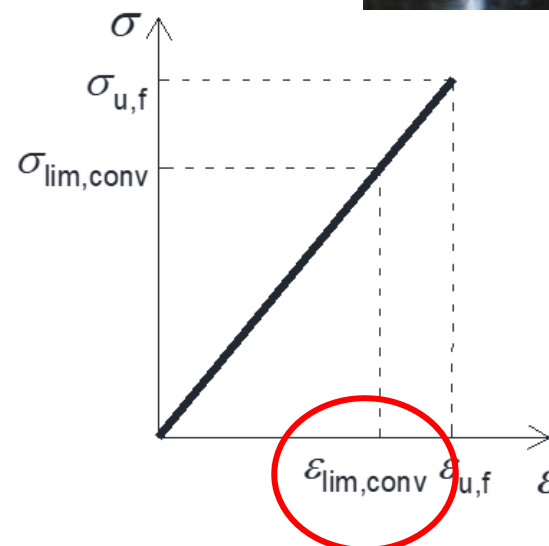
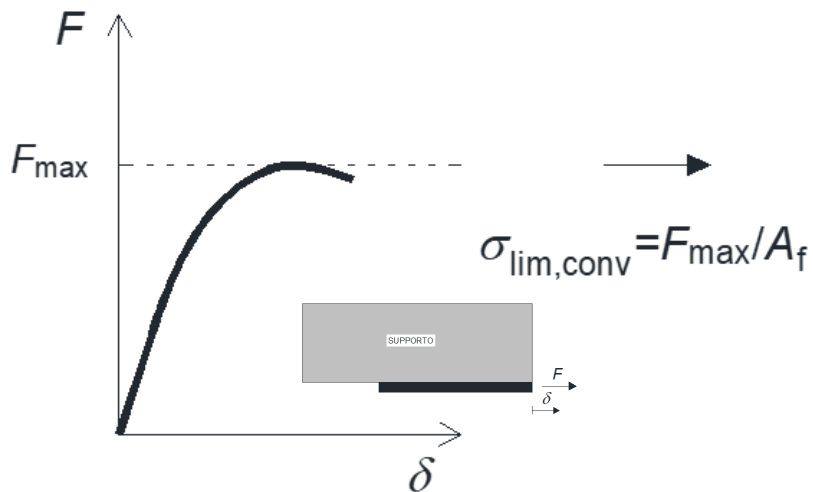
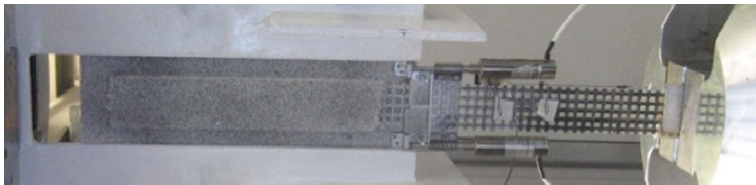
Linea: **Temi generali**, settore di ricerca: **Materiali innovativi** per interventi infrastrutturali su costruzioni esistenti.

↳ (UR29: Uniecampus)

Istruzioni
per la **Progettazione, l'Esecuzione ed il Controllo**
di **Interventi di Consolidamento Statico**
mediante l'utilizzo di
Compositi Fibrorinforzati a matrice inorganica

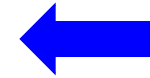


LINEA GUIDA CNR



Flessione $\longrightarrow \epsilon_{fd} = \alpha \epsilon_{lim,conf}$
 Taglio $\longrightarrow \epsilon_{fd} = \epsilon_{lim,conf}$

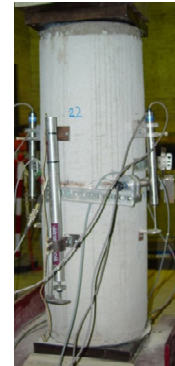
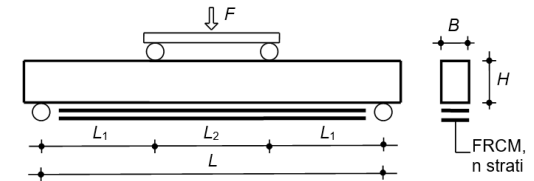
CNR DT215



- ➔ Quasi tutte le formulazioni di progetto includono la dicitura **«in mancanza di specifica sperimentazione....»**
- ➔ Questo è dovuto al fatto che diversi FRCC presentano marcate differenze sotto il profilo meccanico, in termini di
 - proprietà delle fibre
 - proprietà della matrice
 - adesione fibre-matrice
 - geometria della rete
 - modalità di delaminazione

SPERIMENTAZIONI

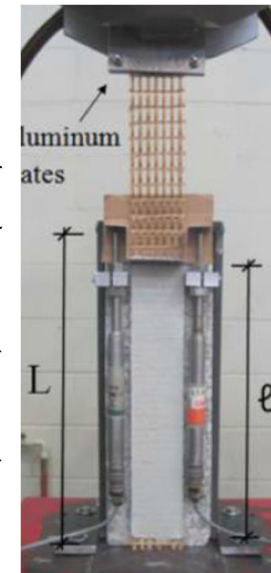
- ➔ Prove di flessione di travi e solette di calcestruzzo armato
- ➔ Prove di taglio di travi di calcestruzzo armato
- ➔ Prove confinamento su pilastri
- ➔ Prove aderenza (bond) su calcestruzzo



D'Ambrisi, Feo, Focacci (2012)

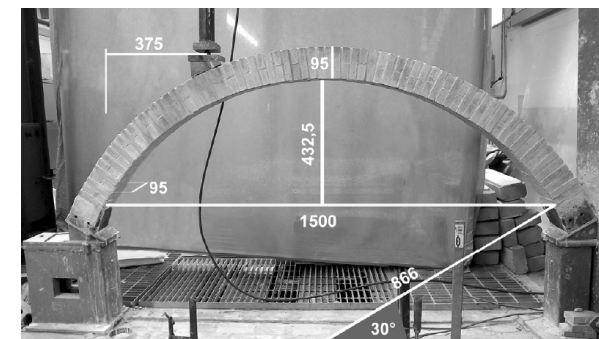


D'Antino T, Carloni C, Sneed LH (2014)



- ➔ Prove di archi e volte
- ➔ Prove di pannelli murari (compressione diagonale)
- ➔ Prove su tavola vibrante di macroelementi
- ➔ Prove aderenza (bond) su muratura

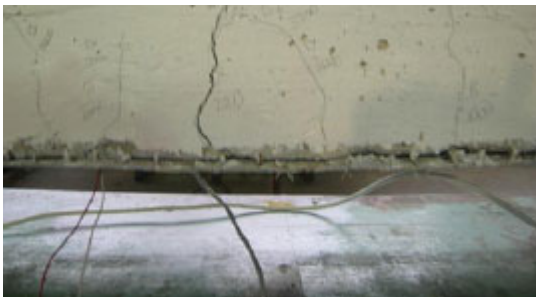
Round robin test
(Rilem Technical Committee 250-CSM)



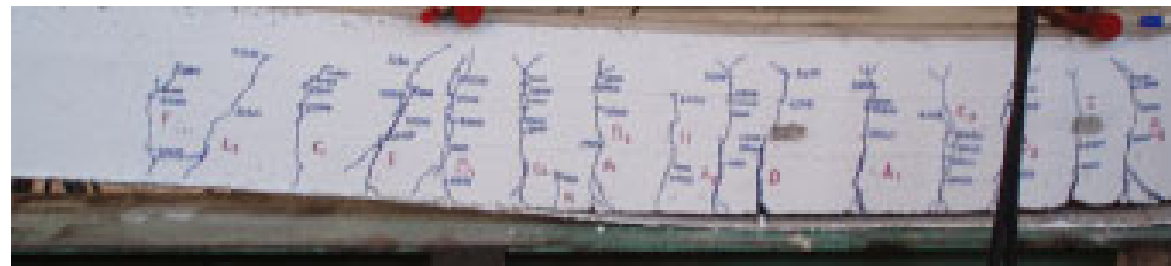
- **Osservazione:** la crisi degli elementi strutturali (calcestruzzo e muratura) rinforzati avviene per **delaminazione del rinforzo**



Täljsten, B., Blanksvärd, T. (2007). Mineral-based bonding of carbon FRP to strengthen concrete structures. *J.Composites for Construction*, 11(2),120–8.



Ombres, L. (2012). Debonding analysis of reinforced concrete beams strengthened with fibre reinforced cementitious mortar. *Engineering Fracture Mechanics*, 81, 94–109.



Ombres, L. (2011). Flexural analysis of reinforced concrete beams strengthened with a cement based high strength composite material. *Composite Structures*, 94(1), 143–155.

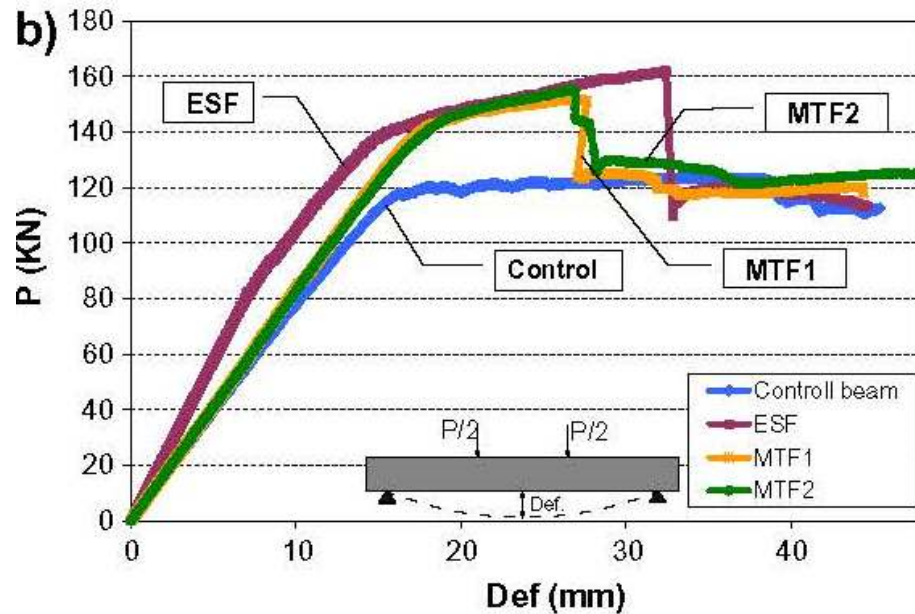
- **Osservazione preliminare:** la crisi degli elementi strutturali (calcestruzzo e muratura) rinforzati avviene per **delaminazione del rinforzo**



Napoli, A. Realfonzo, R. (2015). Reinforced concrete beams strengthened with SRP/SRG systems: experimental investigation. *Construction and Building Materials*, 93, 654–677.

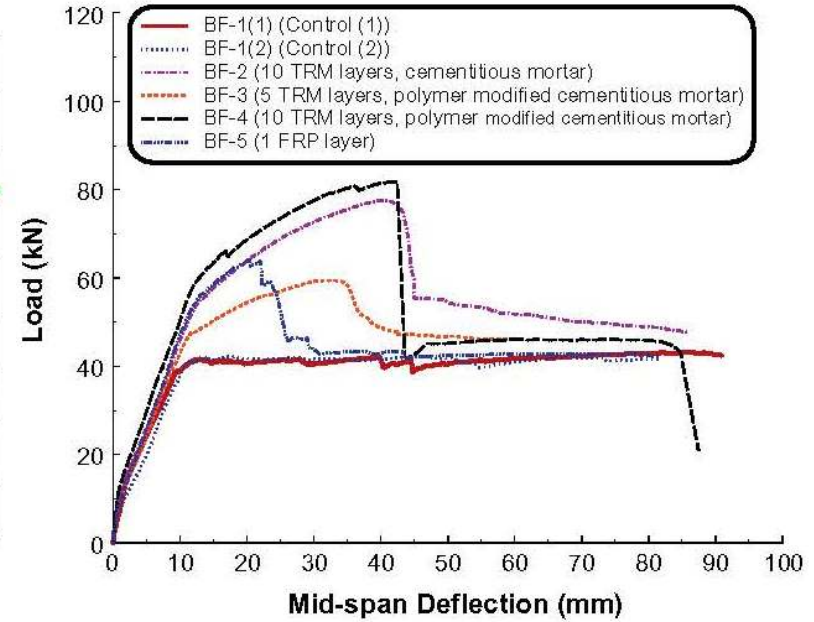
➔ Il rinforzo FRCM incrementa il **carico di collasso**

FIBRE DI CARBONIO

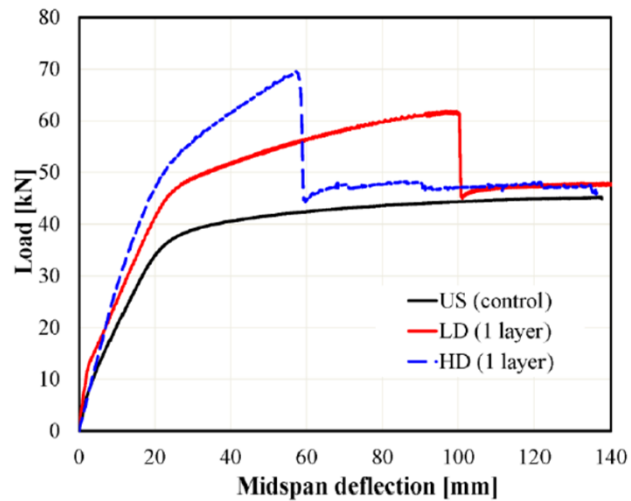


C-FRCM, Hashemi e Al-Mahaidi (2012)

FIBRE DI BASALTO



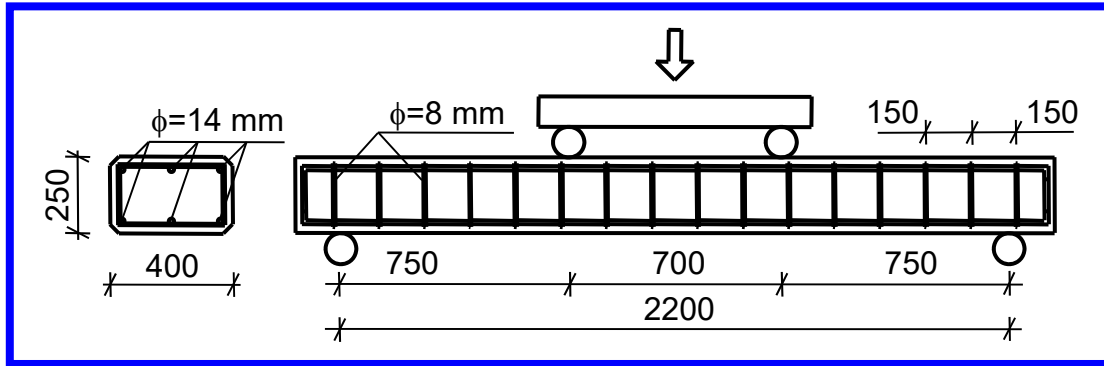
B-FRCM, Elsanadey et al. (2013)



FIBRE DI ACCIAIO

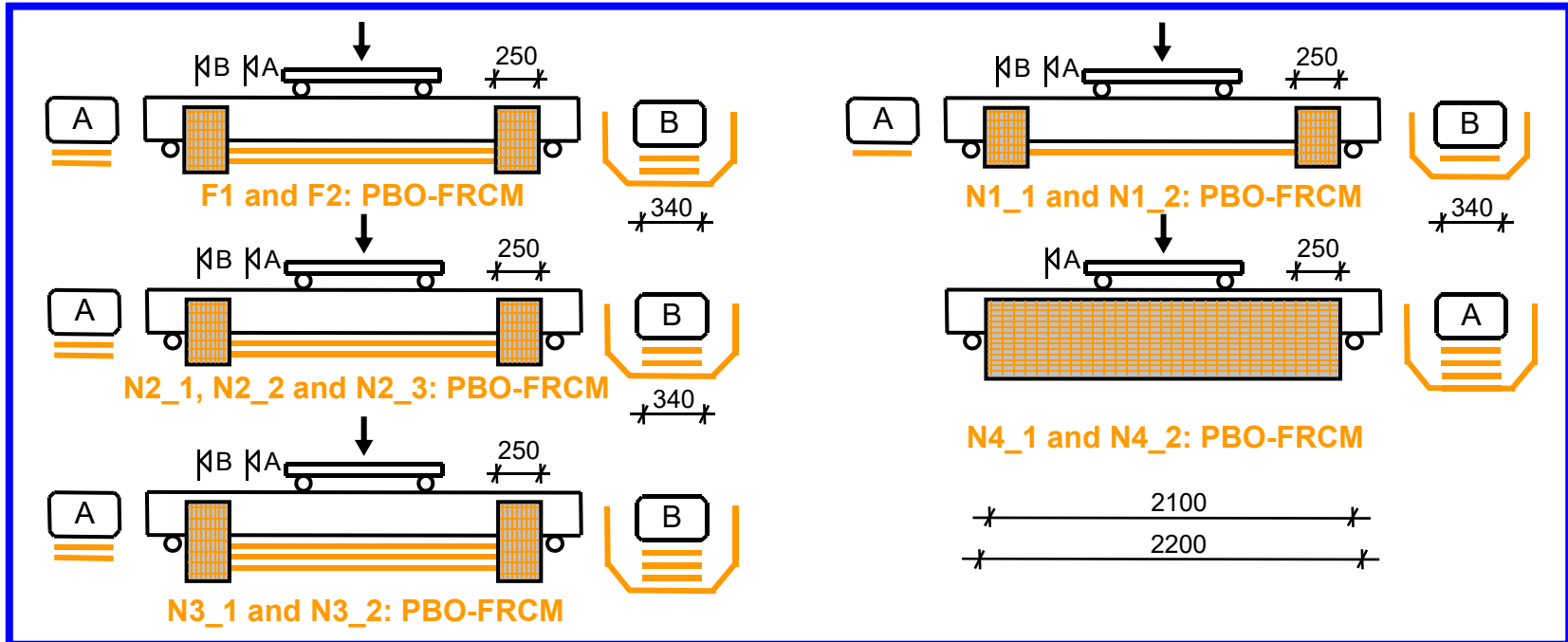
S-FRCM, Napoli, A. Realfonzo, R. (2015).

STRENGTHENING SETUP - SECOND CAMPAIGN



← SPECIMENS

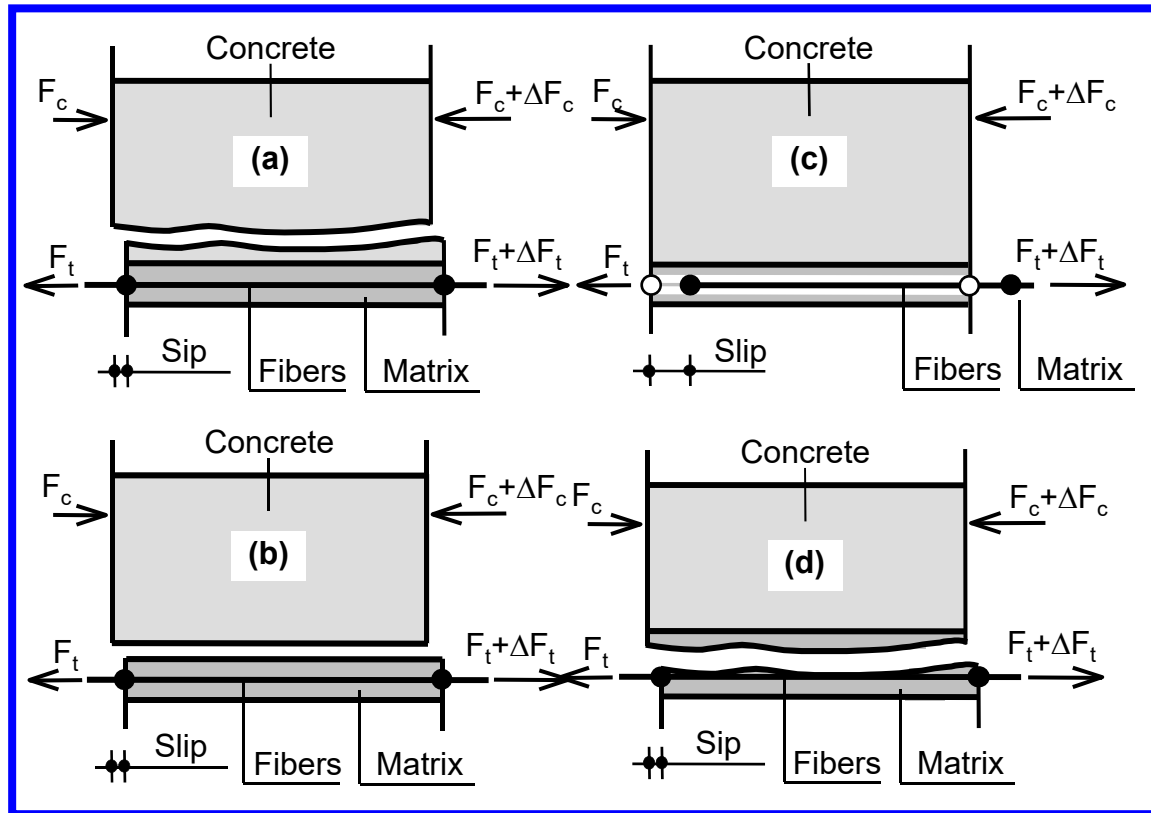
STRENGTHENING



Concrete compr. strength (cubic) (N/mm ²)	63.66
Steel yielding stress (N/mm ²)	476.17
Steel tensile strength (N/mm ²)	616.73

← MATERIALS

FAILURE MODES



(a) CFRP longer beams



(b) PBO-FRCM shorter beams
C-FRCM longer beams



(c) C-FRCM longer beams
PBO-FRCM shorter beams



(d) PBO-FRCM longer beams



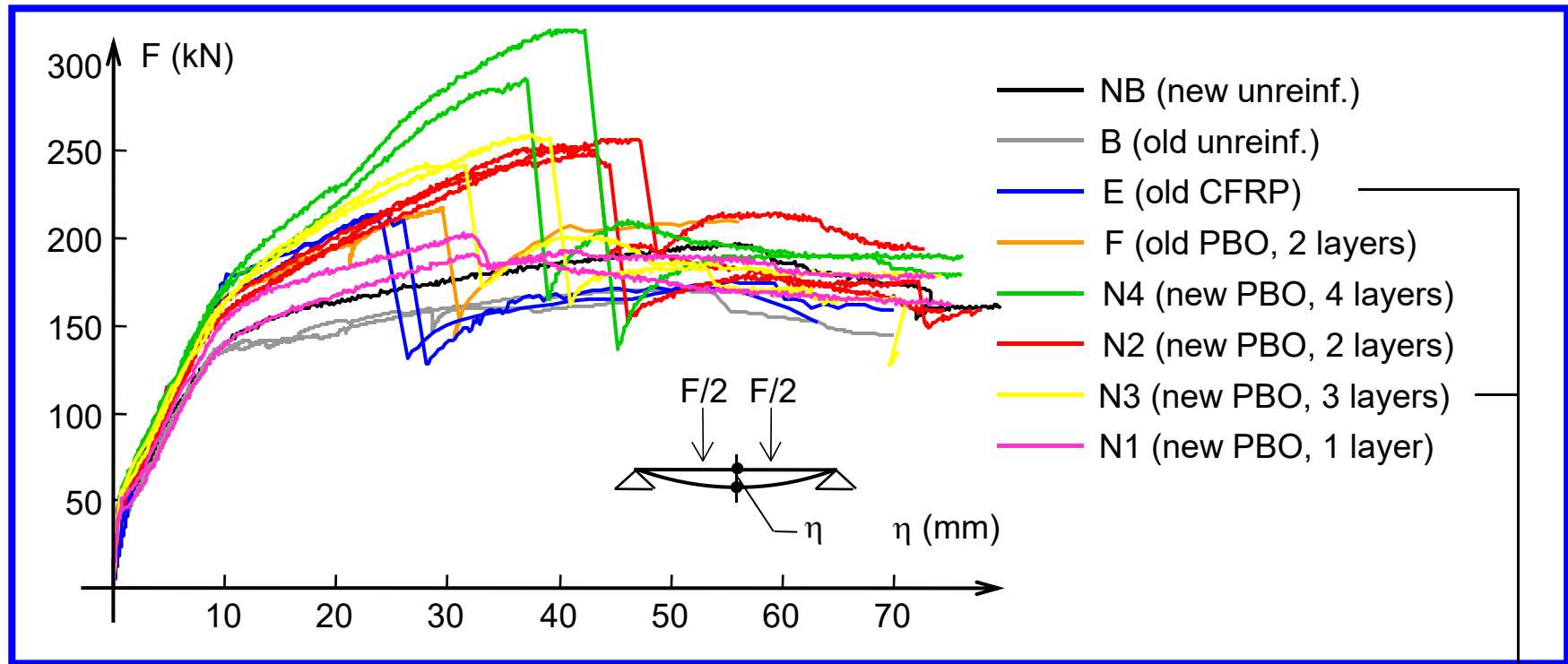
FAILURE MODES

FRCM



FRP





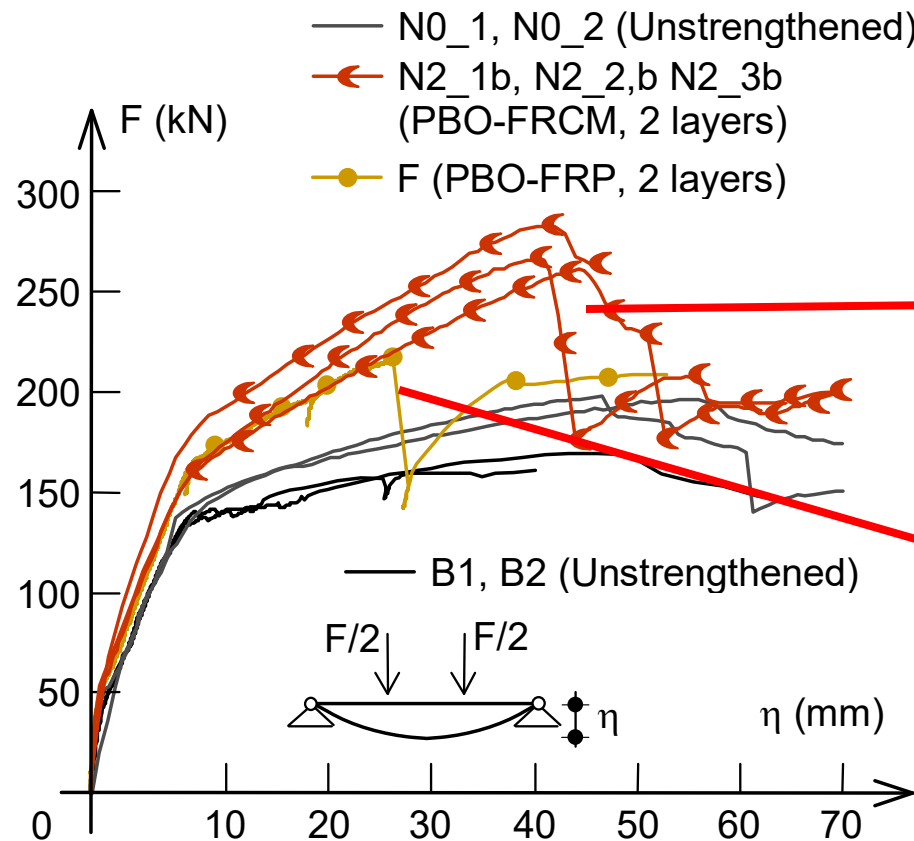
**SECOND CAMPAIGN
LOAD-DEFLECTION
CURVES**

Specimen	DESCRIPTION	FAILURE MODE	Maximum load (kN)	AVERAGE (kN)	Increasing (%)
B1	Unreinforced	Concrete crushing	163.07	166.54	--
B2			170.00		
E1	1 CFRP layer and U shaped end reinforcing	(a)	215.75	214.91	+ 29.04
E2			214.07		
F2	2 PBO-FRCM layers and U shaped end reinforcing	(b)	217.26	217.26	+ 30.45
7	Unreinforced	Concrete crushing	196.95	196.95	--
N1_1	1 PBO-FRCM layer and U shaped end reinforcing	(b)	192.60	197.73	+ 0.40
N1_2			202.86		
N2_1	2 PBO-FRCM layers and U shaped end reinforcing	(d)	256.92	253.24	+ 28.58
N2_2			253.38		
N2_3			249.43		
N3_1	3 PBO-FRCM layers and U shaped end reinforcing	(d)	243.12	251.41	+ 27.65
N3_2			259.69		
N4_1	4 PBO-FRCM layers, one shaped	(d)	319.68	305.48	+ 55.11
N4_1			291.27		

Equal fibers cross section

➔ **Gerarchia** delle resistenze di interfaccia

- Non è immediato stabilire a quale superficie sia associato il carico di collasso **più piccolo**



→ Experimental work

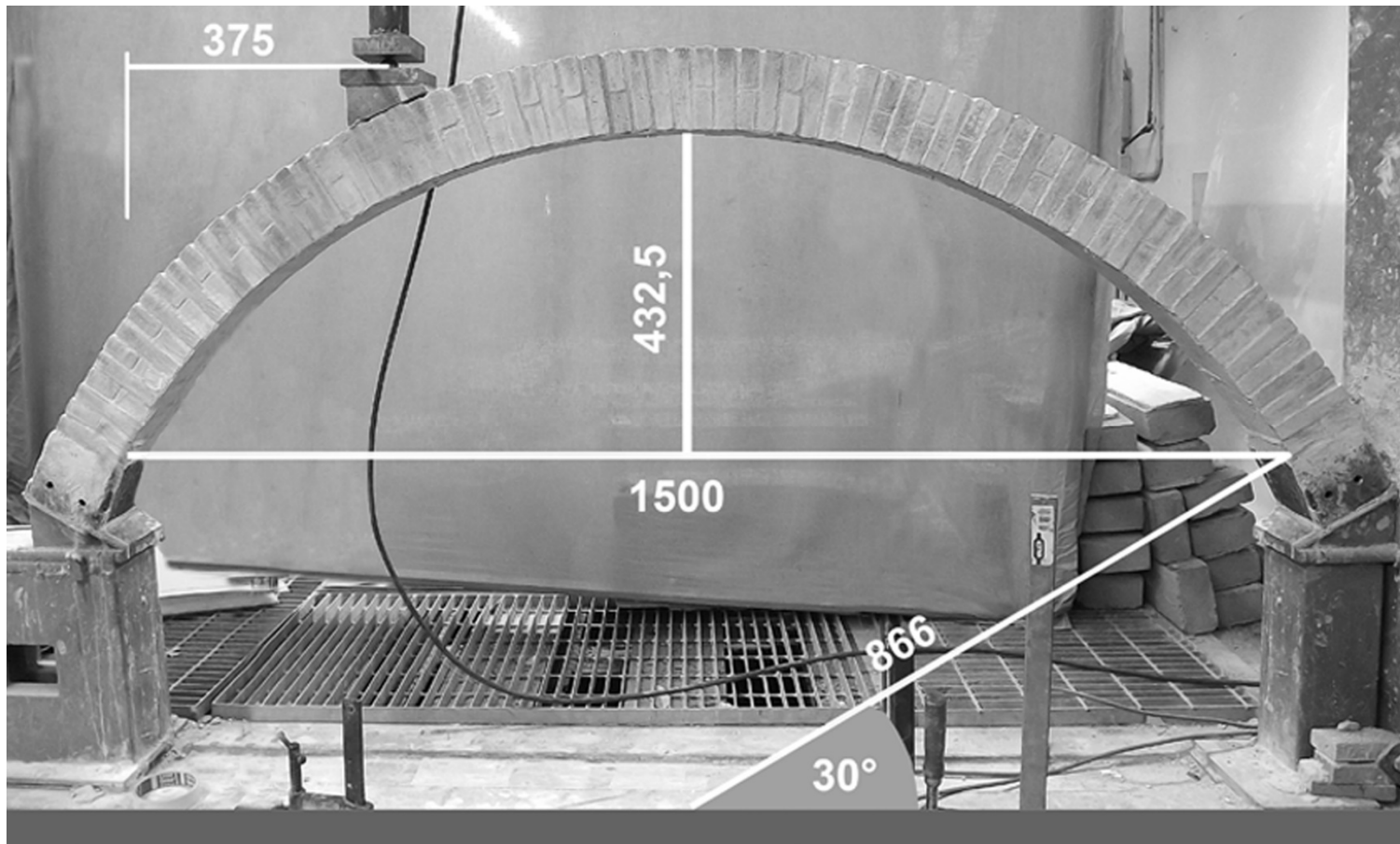
- Brick masonry arches (1/2 scaled)



eCAMPUS
UNIVERSITÀ



Ricerca in collaborazione con M. De Stefano, L. Rovero, V. Alecci, G. Stipo

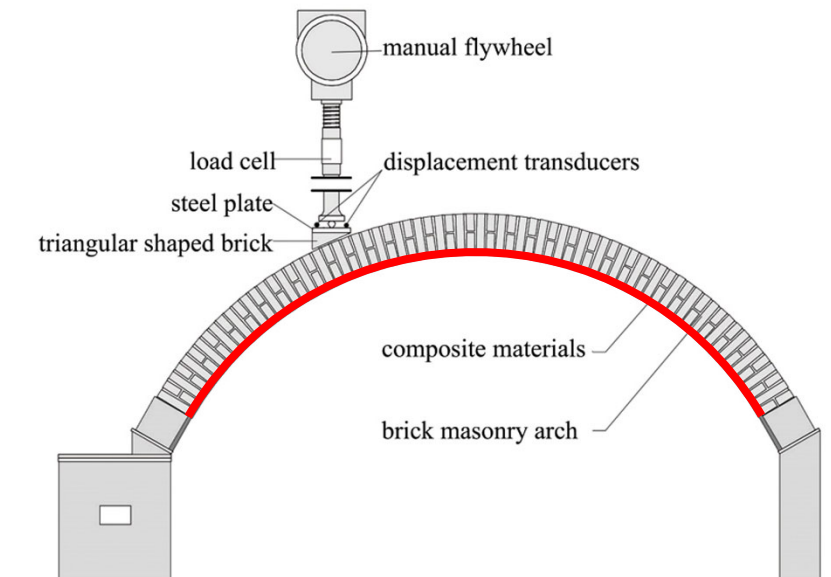


Thickness of the arches: 95 mm

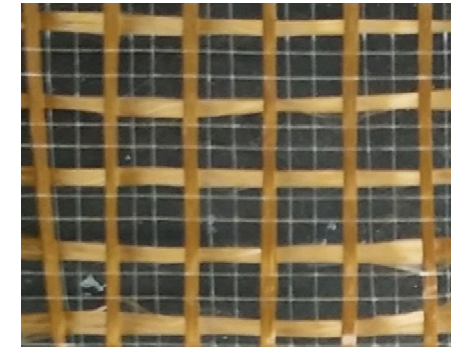
Experimental work

- Strengthening materials

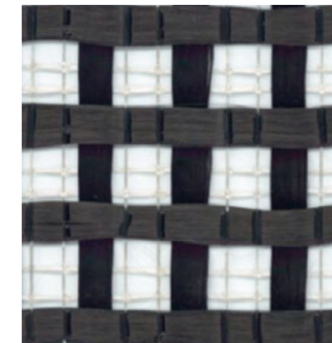
Specimen	Pos.	Str. material	t_f [mm]	A_f [mm ²]
1-US	--	--	--	--
2-US	--	--	--	--
1-ES	Extr.	PBO-FRCM	0.014	1.33
2-ES	Extr.	PBO-FRCM	0.014	1.33
1-PM	Intr.	PBO-FRCM	0.014	1.33
2-PM	Intr.	PBO-FRCM	0.014	1.33
1-CM	Intr.	C-FRCM	0.047	4.47
2-CM	Intr.	C-FRCM	0.047	4.47
1-CP	Intr.	C-FRP	0.17	16.15
2-CP	Intr.	C-FRP	0.17	16.15



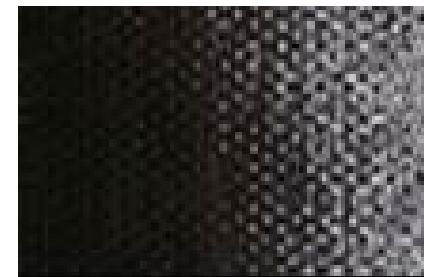
PBO-FRCM



C-FRCM

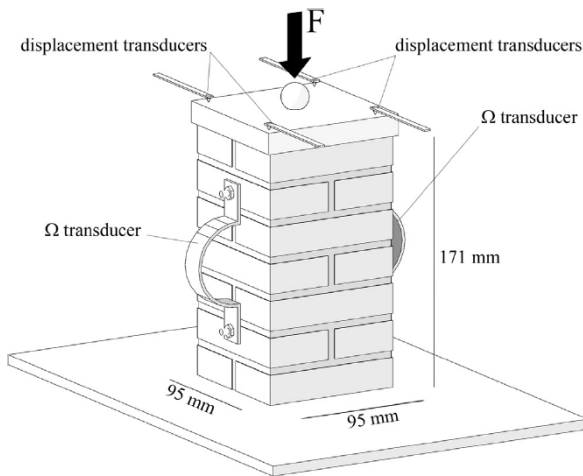
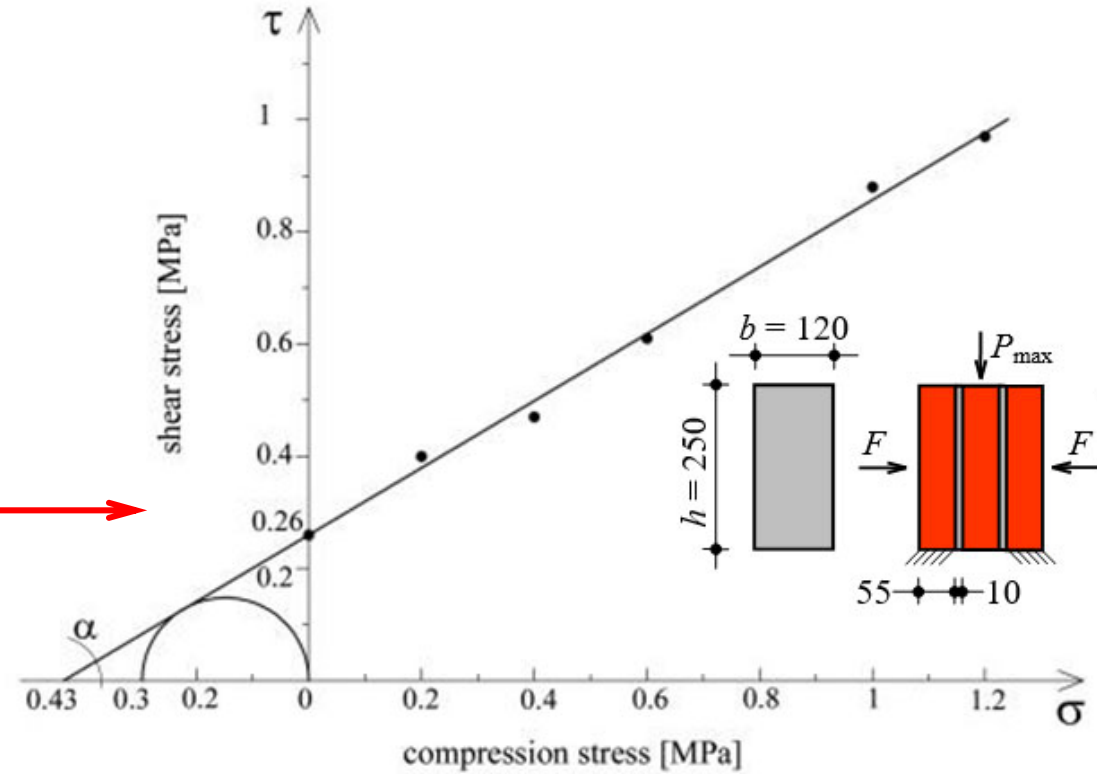
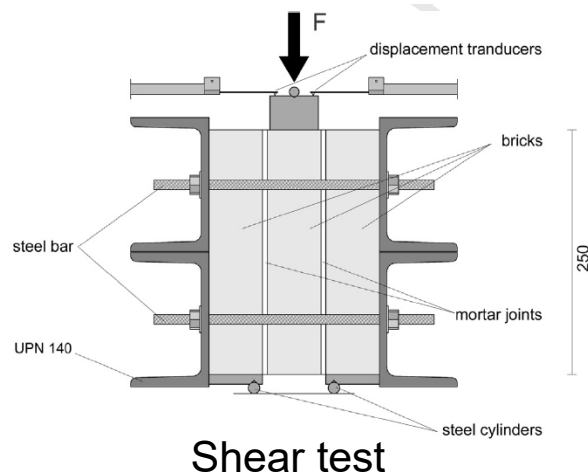


C-FRP



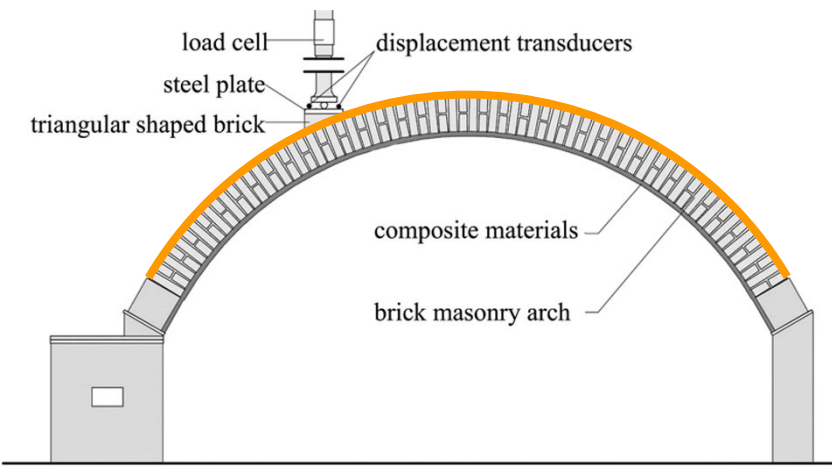
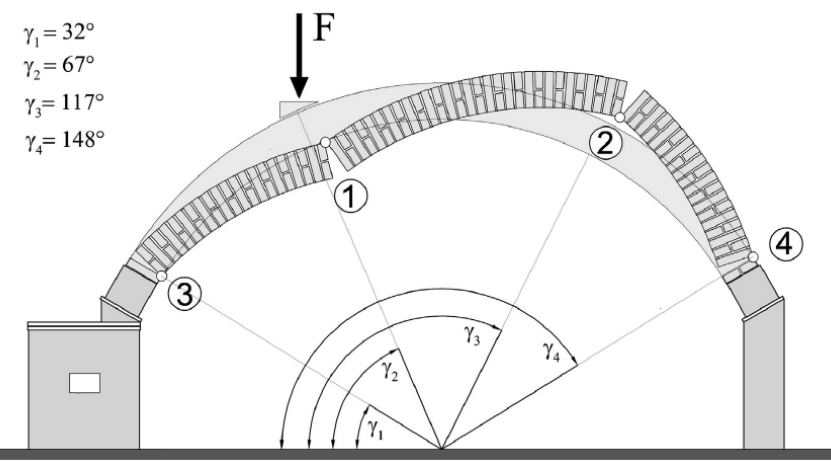
Experimental work

- Masonry characterization

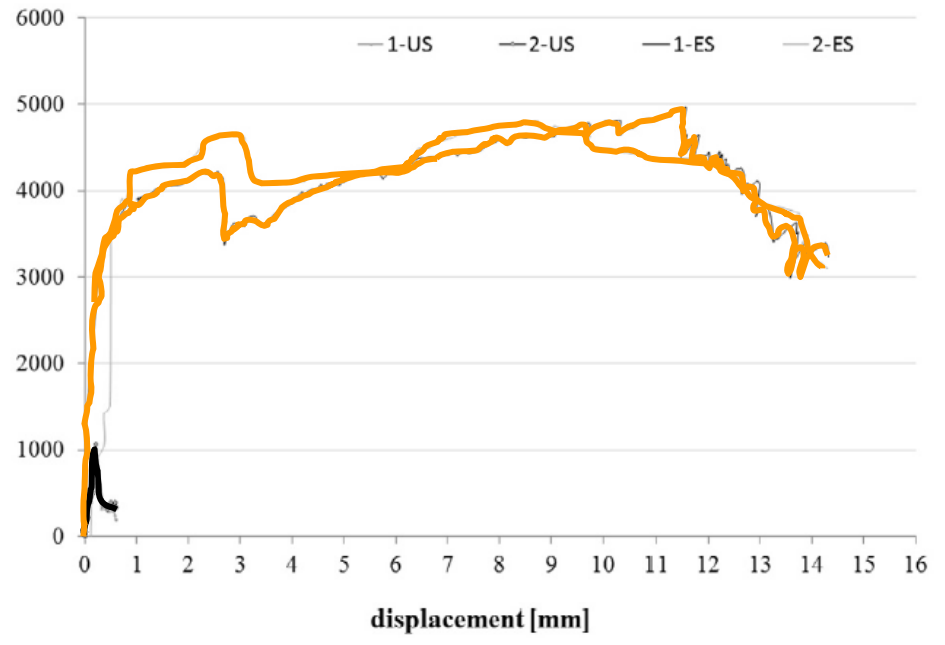
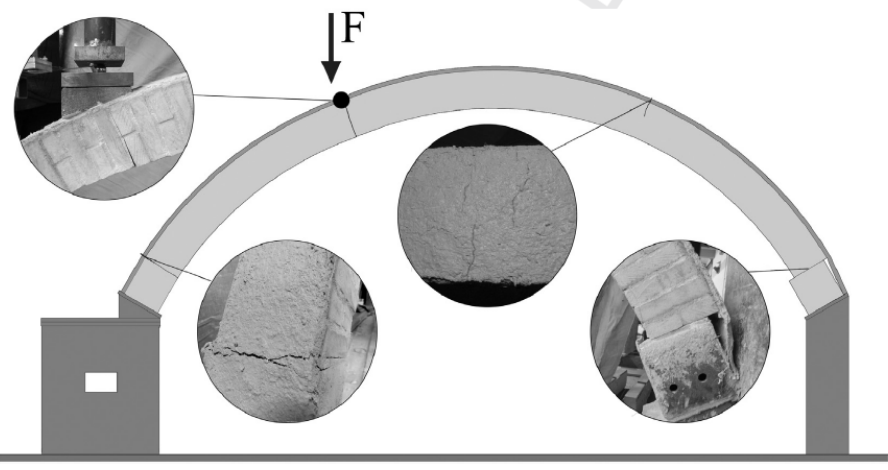


Compressive strength	f_m [MPa]	8.53
Failure strain	ε_{mu} [%]	0.76
Compressive elastic modulus	E_m [MPa]	1753.7
Cohesion	C [MPa]	0.26
Friction coefficient	μ	--
Tensile strength	f_{mt} [MPa]	0.30

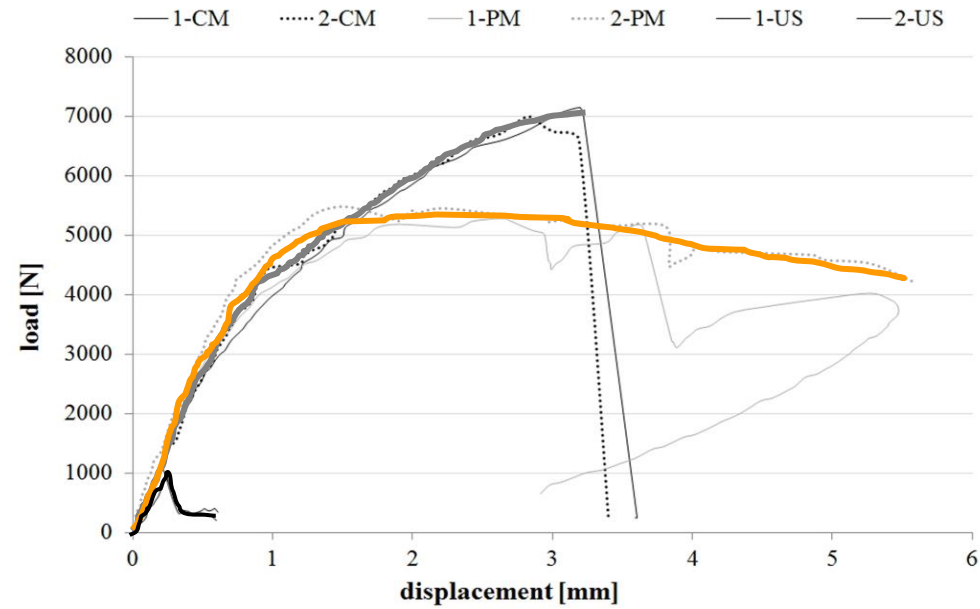
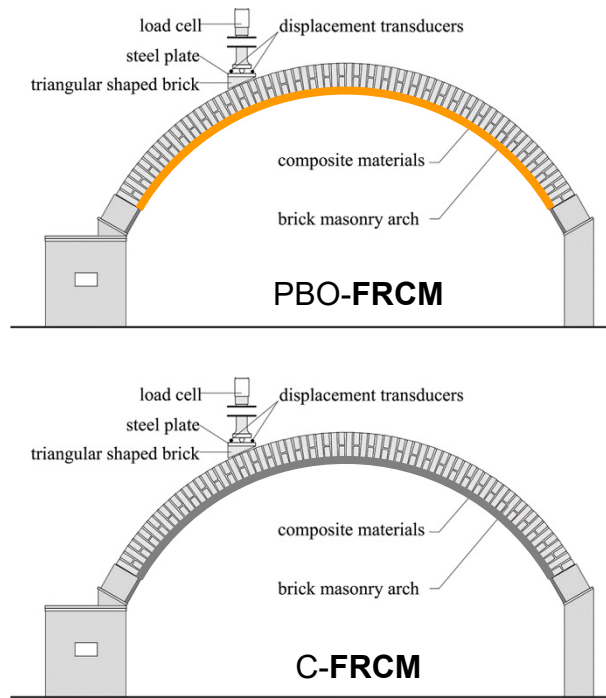
Results: unstrengthened vs. PBO-FRCM extrados strengthened



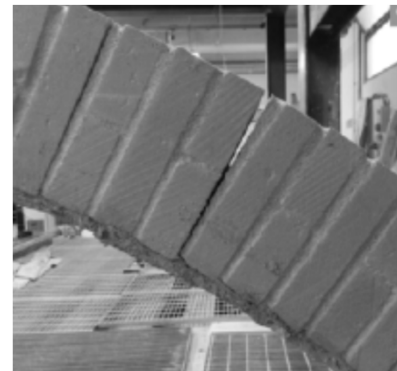
Specimen	Pos.	Str. material	t_f [mm]	F_{max} [N]	$\frac{F_{max}}{F_{max0}}$
1-US	--	--	--	910	--
2-US	--	--	--	1066	
1-ES	Estr.	PBO-FRCM	0.014	4813	4.95
2-ES	Estr.	PBO-FRCM	0.014	4968	



Results: unstrengthened vs. FRCM intrados strengthened



Specimen	Pos.	Str. material	t_f [mm]	F_{max} [N]	$\frac{F_{max}}{F_{max0}}$
1-US	--	--	--	910	--
2-US	--	--	--	1066	
1-PM	Intr.	PBO-FRCM	0.014	5280	5.49
2-PM	Intr.	PBO-FRCM	0.014	5672	
1-CM	Intr.	C-FRCM	0.047	7140	7.08
2-CM	Intr.	C-FRCM	0.047	6989	

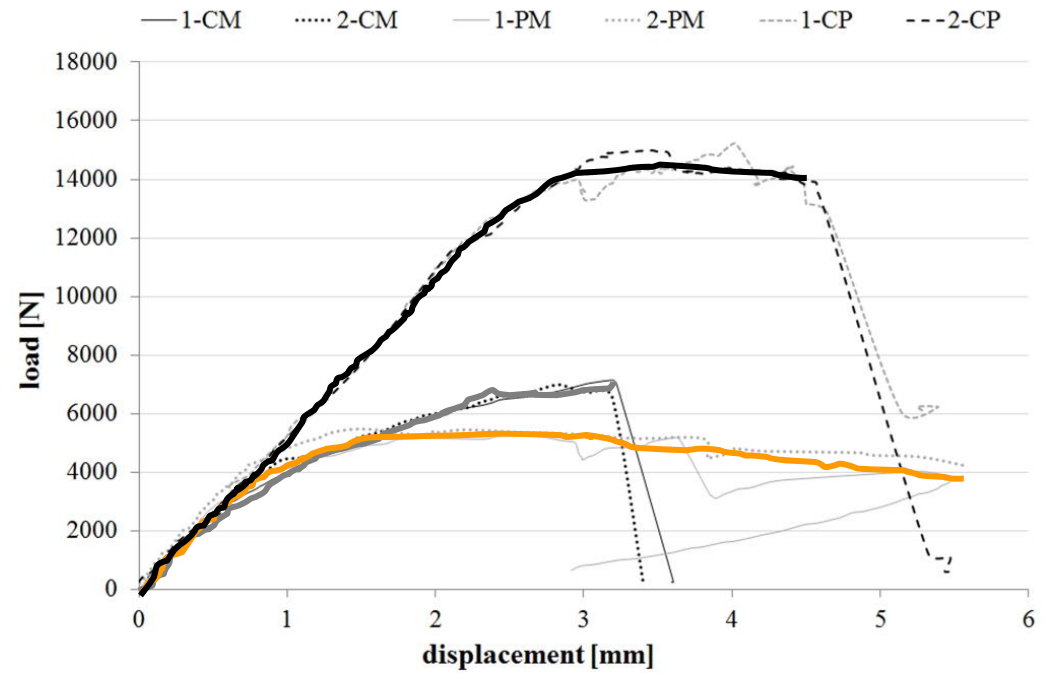
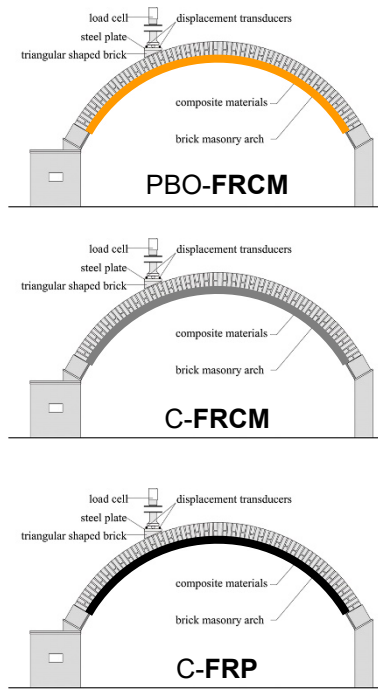


First crack
(PBO-FRCM)

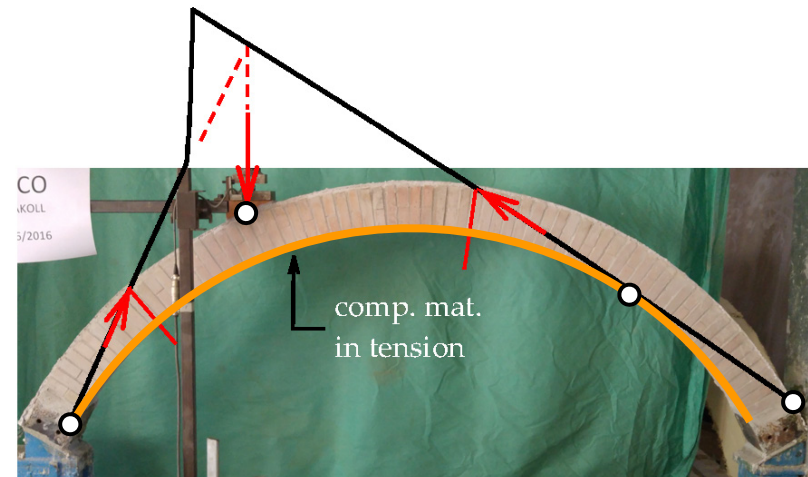


Collapse
(C-FRCM)

Results: FRCM vs. FRP intrados strengthened

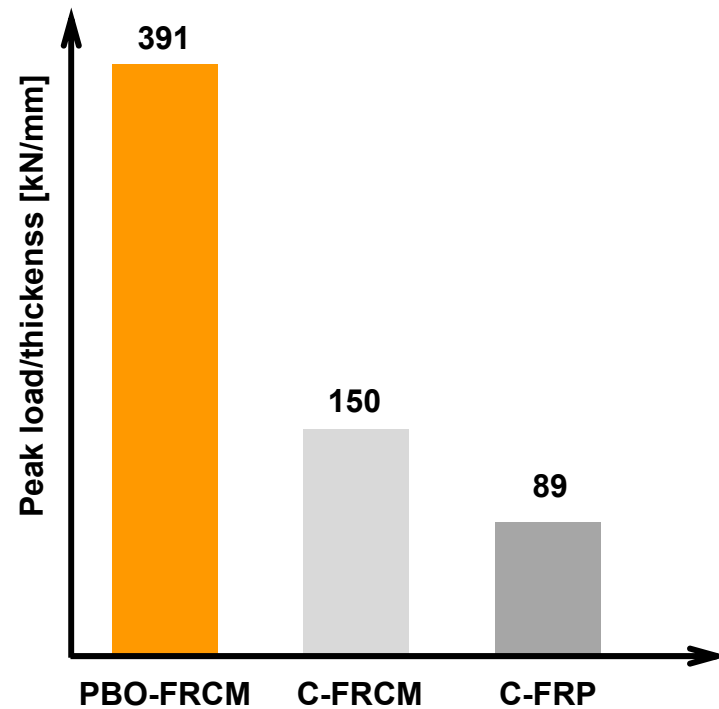
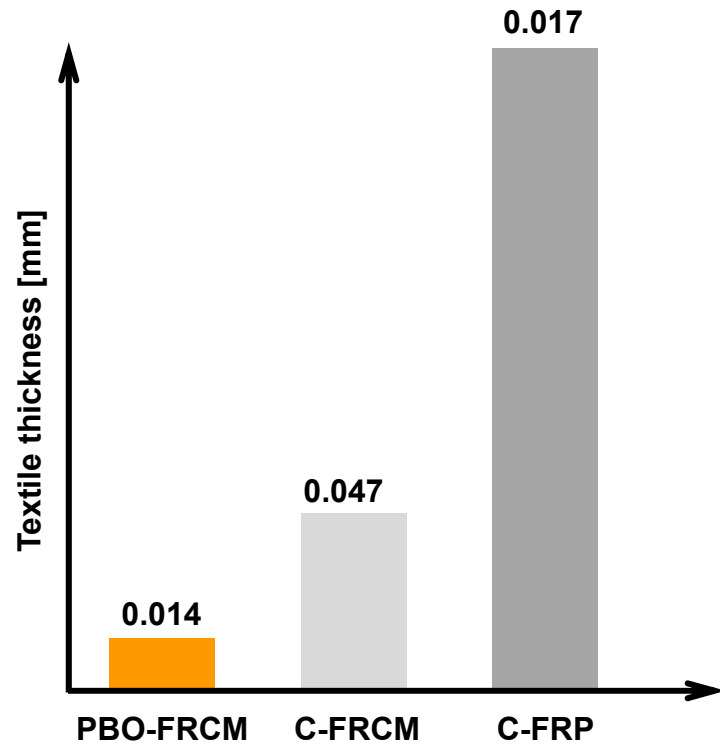
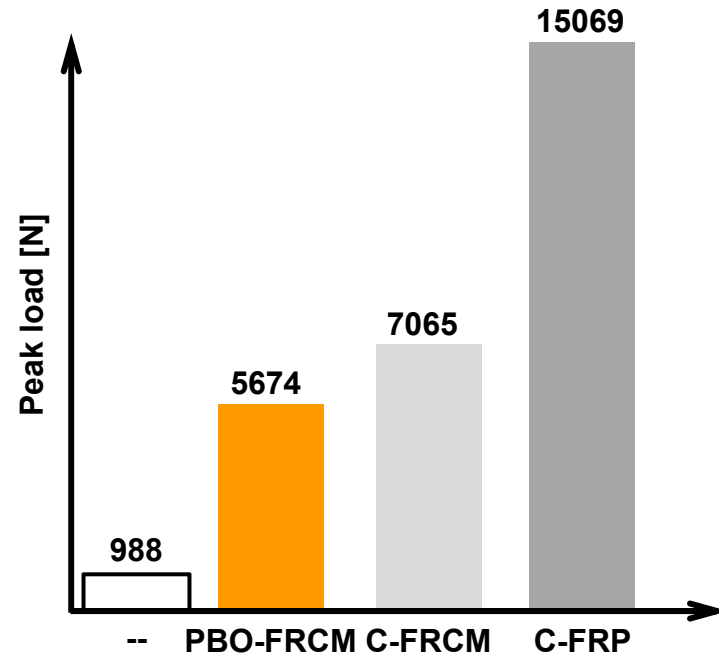


Specimen	Pos.	Str. material	t_f [mm]	F_{max} [N]	$\frac{F_{max}}{F_{max0}}$
1-US	--	--	--	910	--
2-US	--	--	--	1066	
1-PM	Intr.	PBO-FRCM	0.014	5280	5.49
2-PM	Intr.	PBO-FRCM	0.014	5672	
1-CM	Intr.	C-FRCM	0.047	7140	7.08
2-CM	Intr.	C-FRCM	0.047	6989	
1-CP	Intr.	C-FRP	0.17	15198	15.09
2-CP	Intr.	C-FRP	0.17	14940	



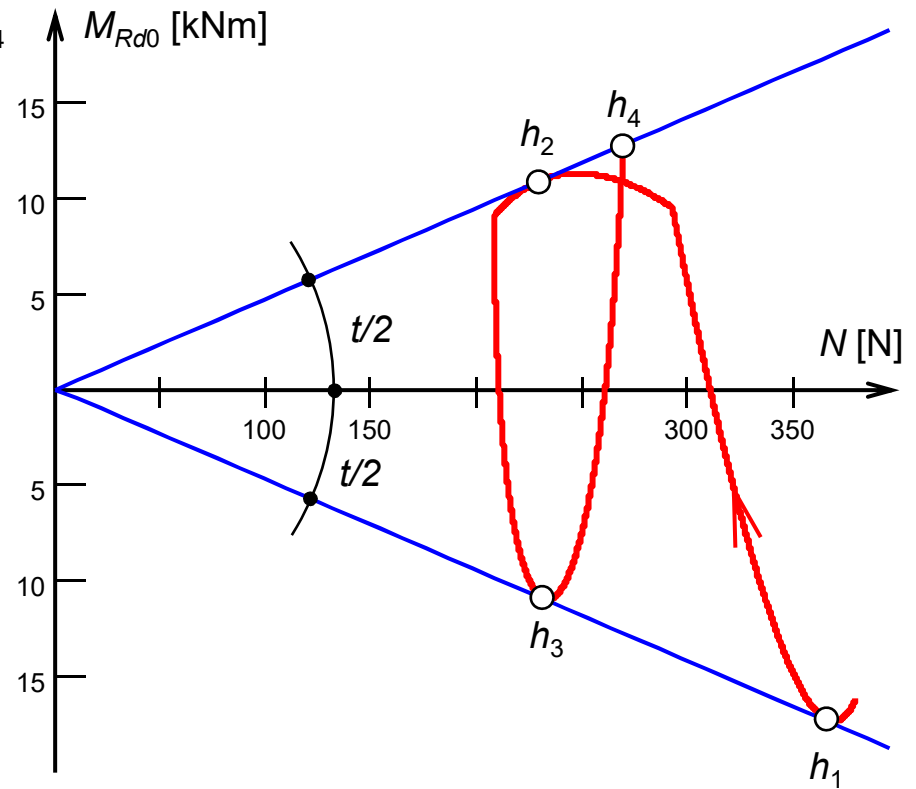
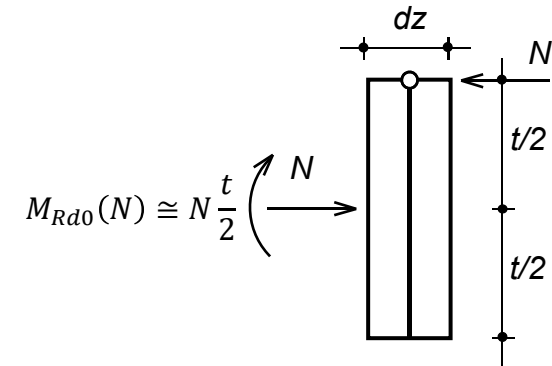
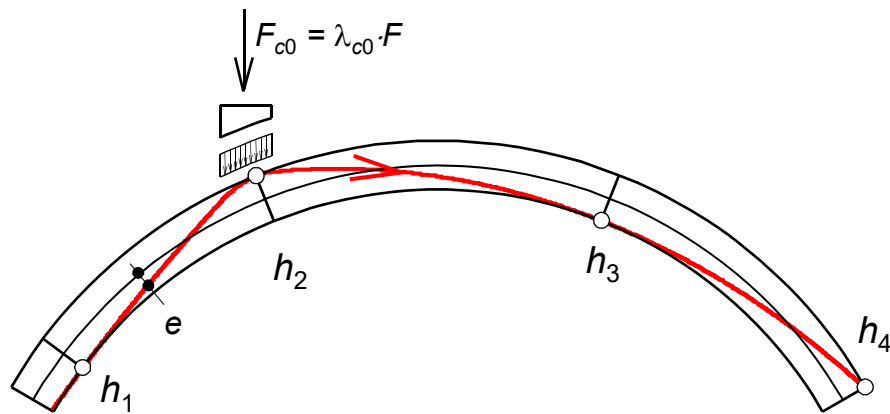
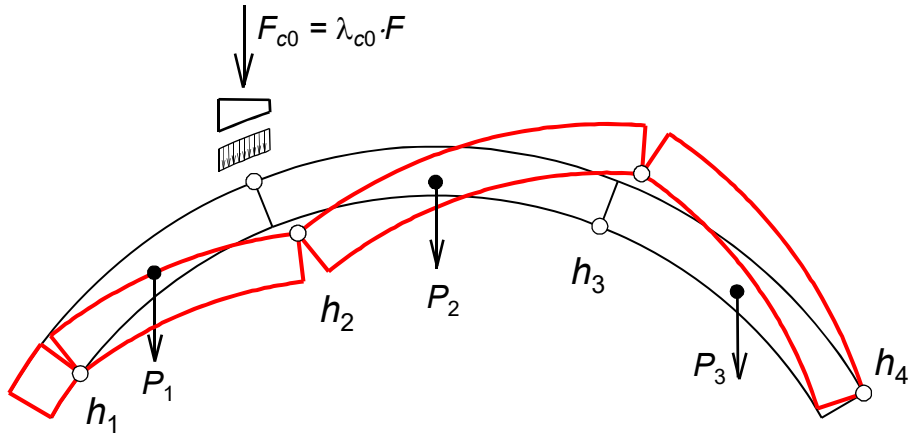
→ Comparison

Specimen	Pos.	Str. material	t_f [mm]	F_{max} [N]	$\frac{F_{max}}{F_{max0}}$
1-US	--	--	--	910	--
2-US	--	--	--	1066	
1-PM	Intr.	PBO-FRCM	0.014	5280	5.49
2-PM	Intr.	PBO-FRCM	0.014	5672	
1-CM	Intr.	C-FRCM	0.047	7140	7.08
2-CM	Intr.	C-FRCM	0.047	6989	
1-CP	Intr.	C-FRP	0.17	15198	15.09
2-CP	Intr.	C-FRP	0.17	14940	



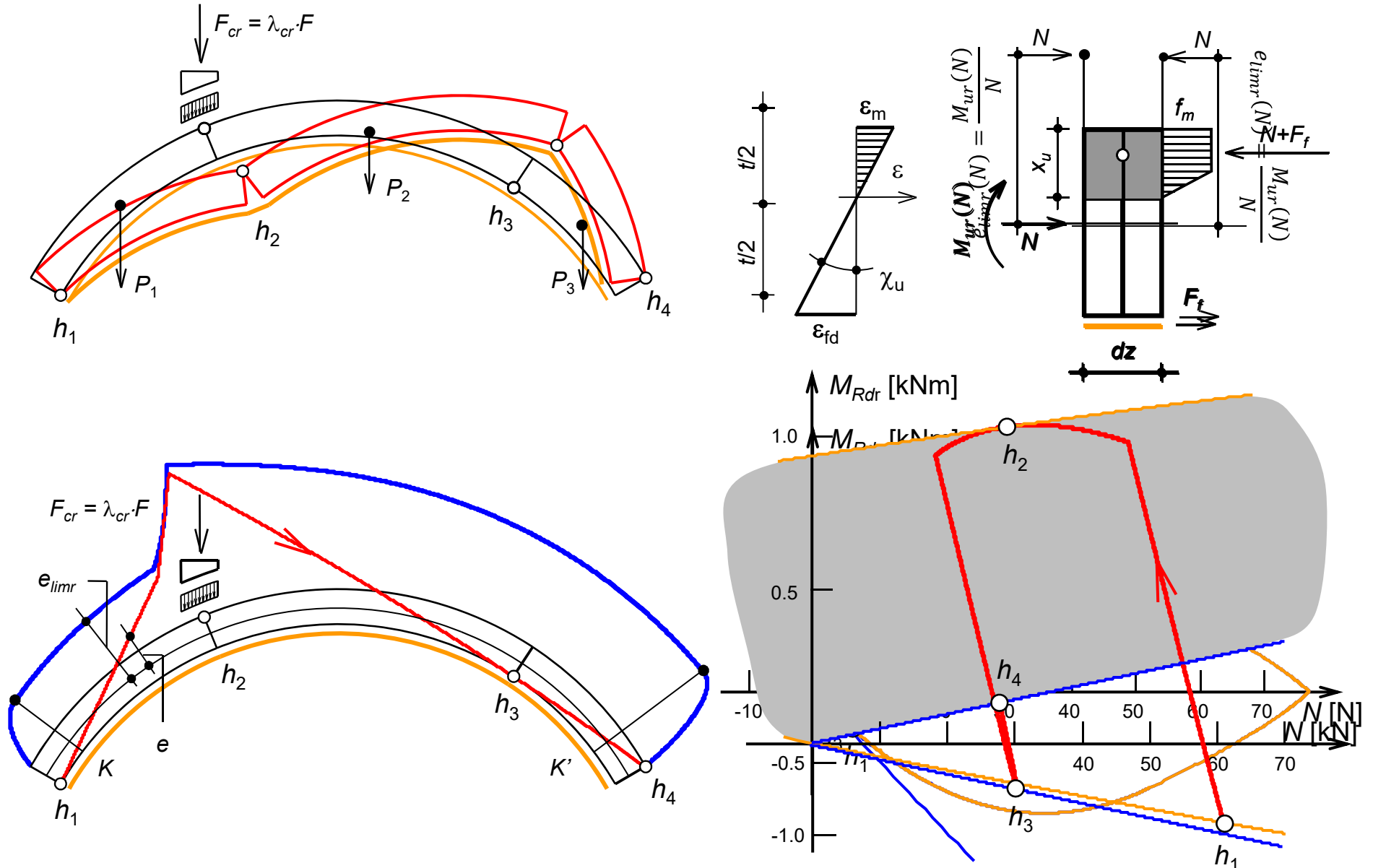
➔ Analytical evaluation of the collapse load

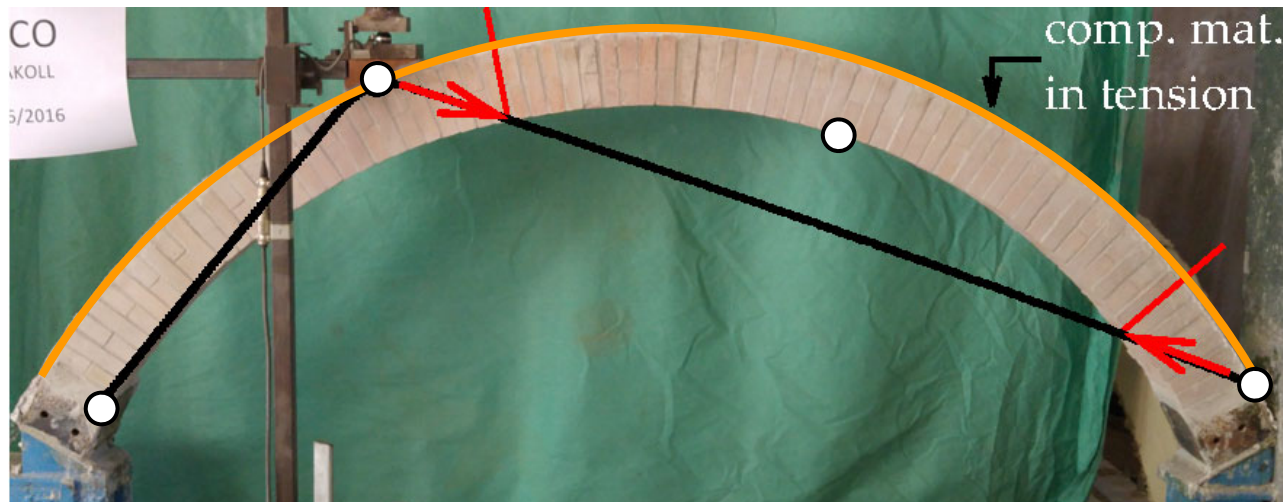
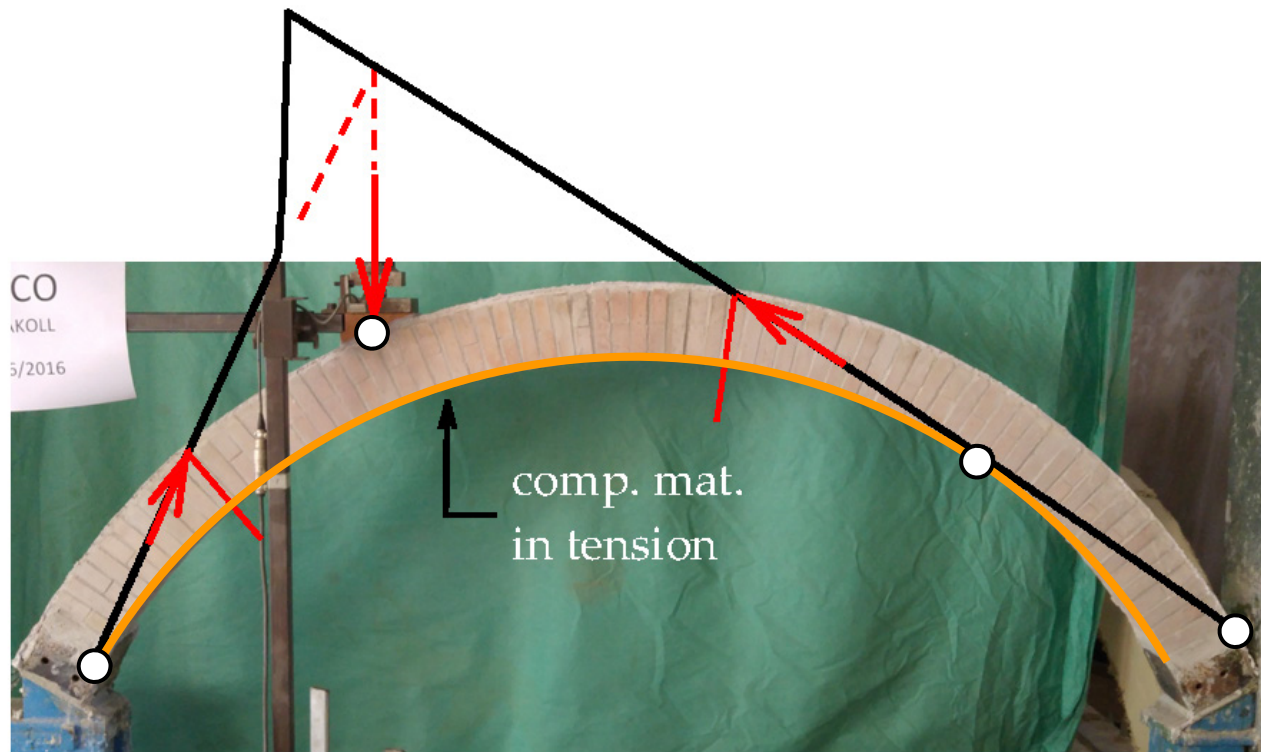
- Un-strengthened arches



➔ Analytical evaluation of the collapse load

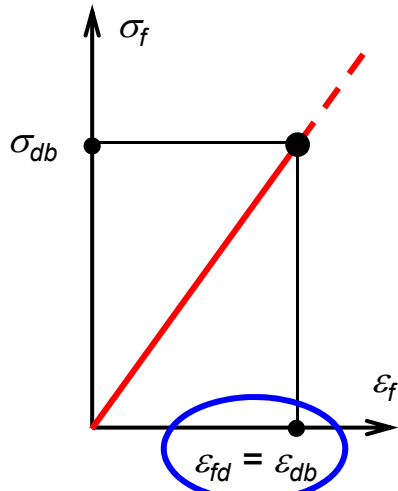
- Strengthened arches (intrados)



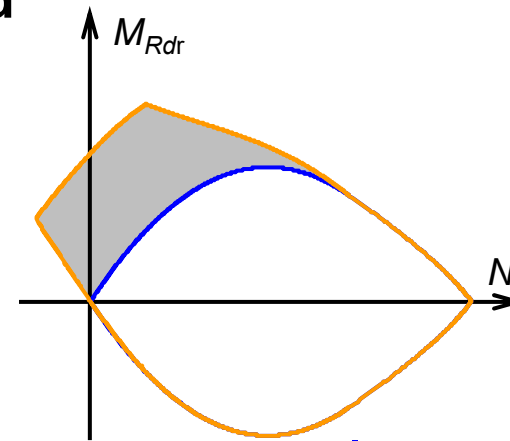


➔ Analytical evaluation of the collapse load

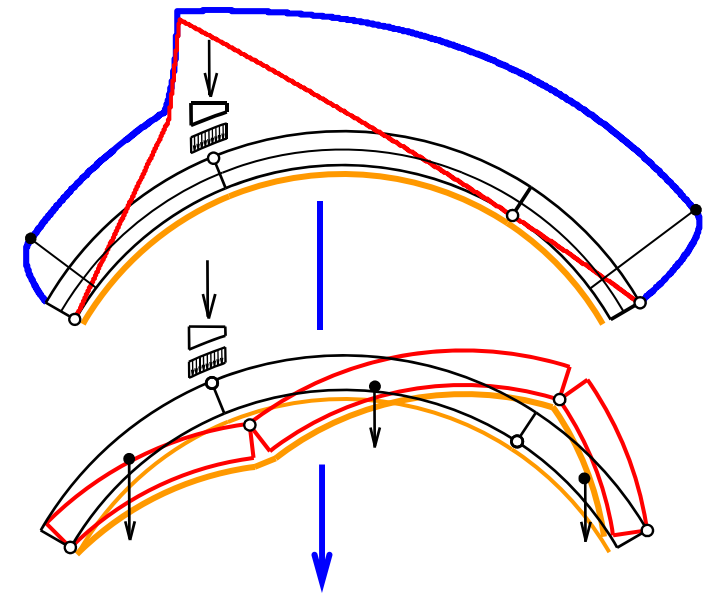
- Strengthened arches



Plane Cross-sections



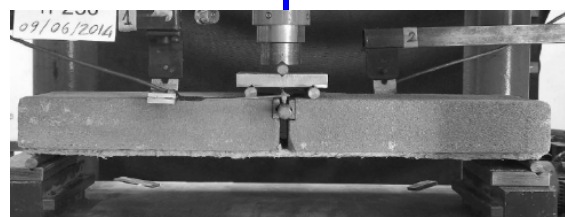
Limit analysis



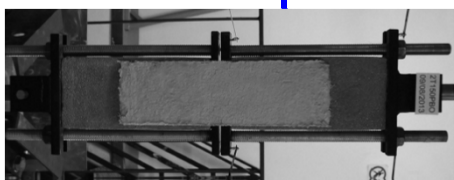
Failure load



Single-lap shear test



Beam test



Double-lap shear test

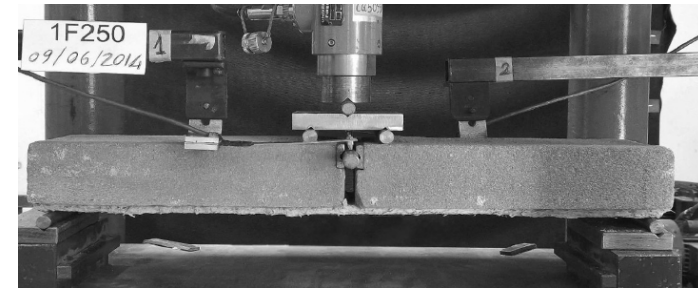
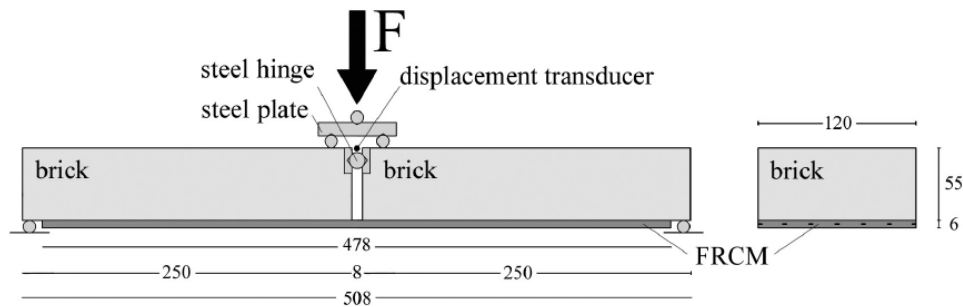


Tensile test

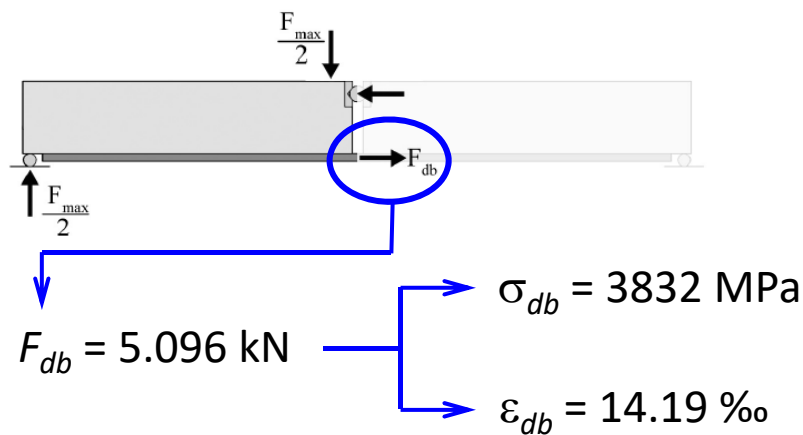
➔ Analytical evaluation of the collapse load

- Extradados strengthened arches (PBO-FRCM)
- Maximum fiber strain from **beam tests** performed by

Alecci V, De Stefano M, Luciano R, Rovero, L, Stipo G. Experimental Investigation on Bond Behavior of Cement-Matrix-Based Composites for Strengthening of Masonry Structures. J Compos Constr 2015



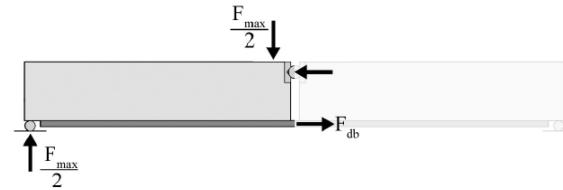
L = 250 mm



Specimen	Maximum force F_{\max} (N)	Bond capacity F_{db} (N)
1-F250	2436	5239
2-F250	2612	5618
3-F250	2265	4872
4-F250	2279	4901
5-F250	2143	4609
6-F250	2483	5339
7-F250	2369	5096
8-F250	2419	5202
9-F250	2382	5123
10-F250	2346	5045
11-F250	2382	5123
12-F250	2420	4989

➔ Analytical evaluation of the collapse load

- Extrados strengthened arches (PBO-FRCM)
- Maximum fiber strain from **beam tests**



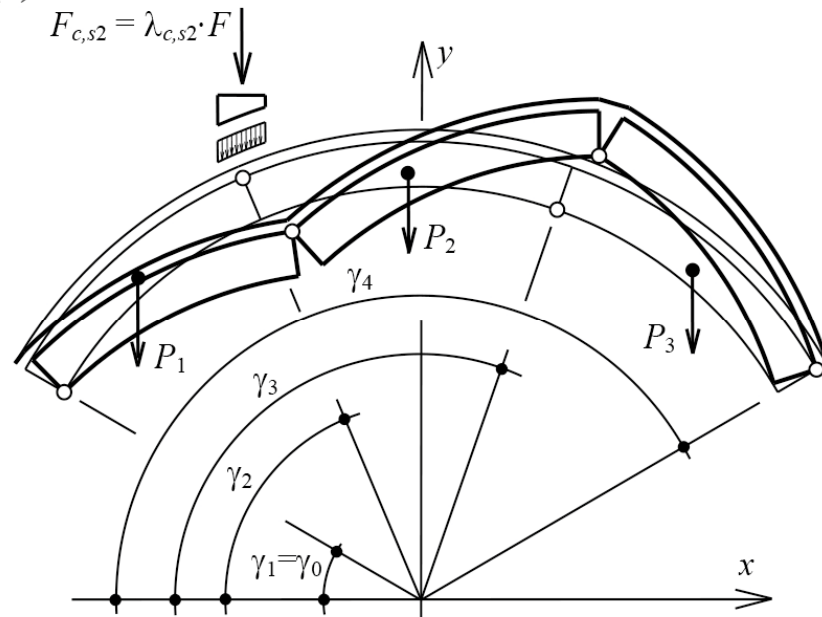
$$F_c = 4.709 \text{ kN}$$



$$F_{exp} = 4.891 \text{ kN}$$

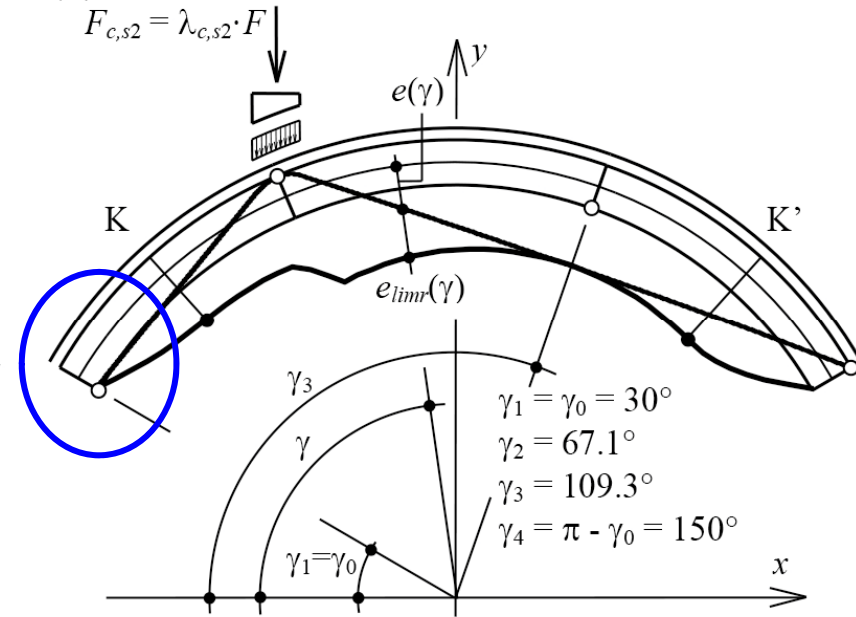
Underestimate 3.7%

(a)



Collapse mechanism

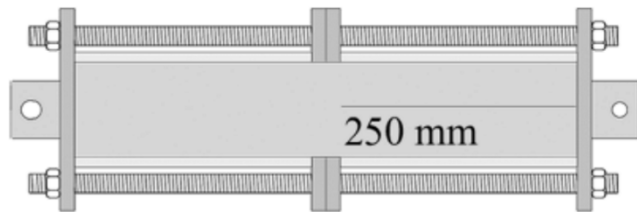
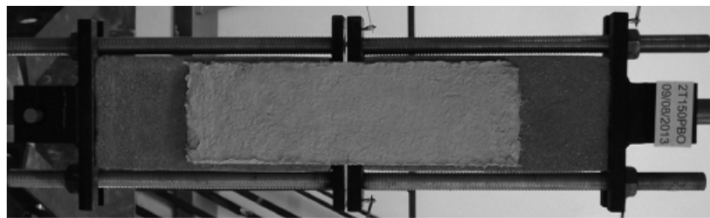
(b)



Thrust line

➔ Analytical evaluation of the collapse load

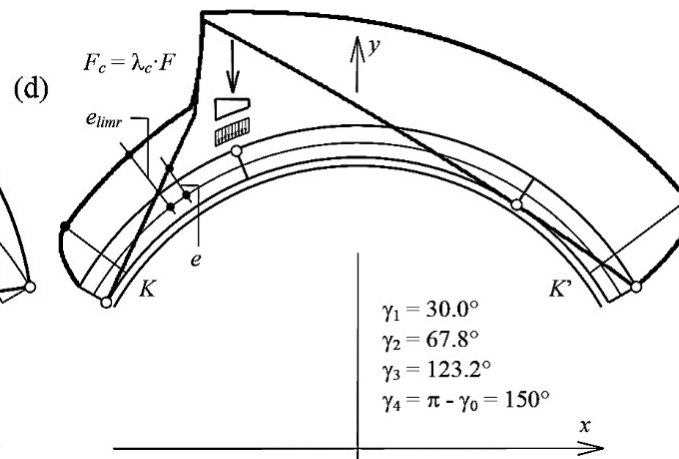
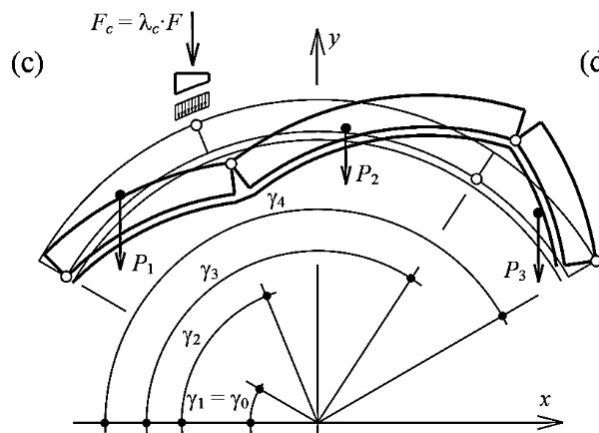
- Intradados strengthened arches (PBO-FRCM and C-FRCM)
- Maximum fiber strain from **double-lap shear tests** performed by Alecci V, De Stefano M, Luciano R, Rovero, L, Stipo G. Experimental Investigation on Bond Behavior of Cement-Matrix-Based Composites for Strengthening of Masonry Structures. J Compos Constr 2015



C-FRCM: $\epsilon_{db} = 3.84\%$
PBO-FRCM: $\epsilon_{db} = 9.30\%$

C-FRCM:
 $F_c = 3.1 \text{ kN} (\cong 0.44 F_{exp})$
 $F_{exp} = 7.1 \text{ kN}$

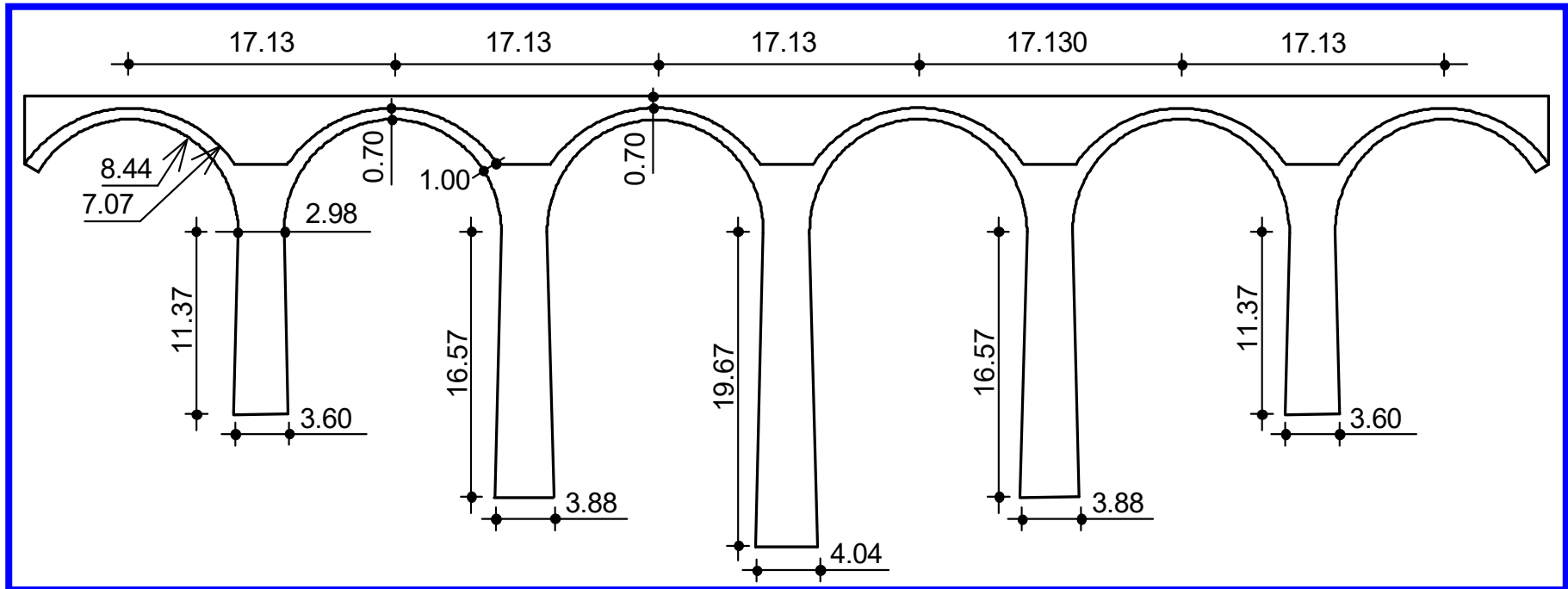
PBO-FRCM:
 $F_c = 2.6 \text{ kN} (\cong 0.47 F_{exp})$
 $F_{exp} = 5.5 \text{ kN}$



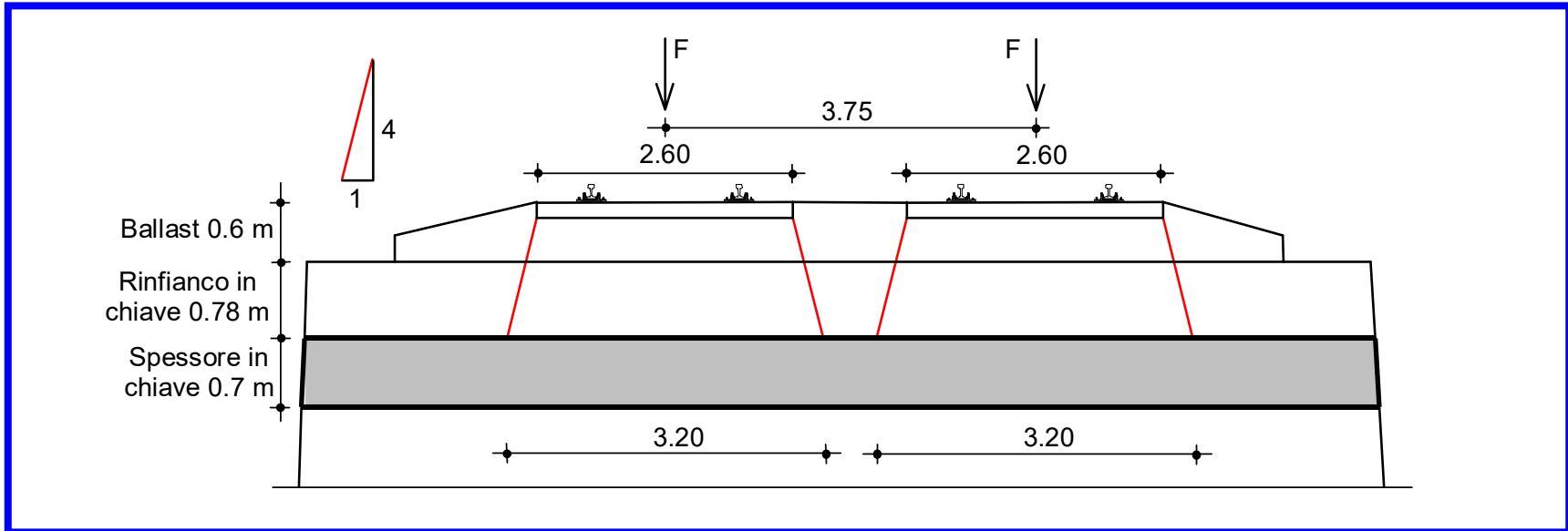
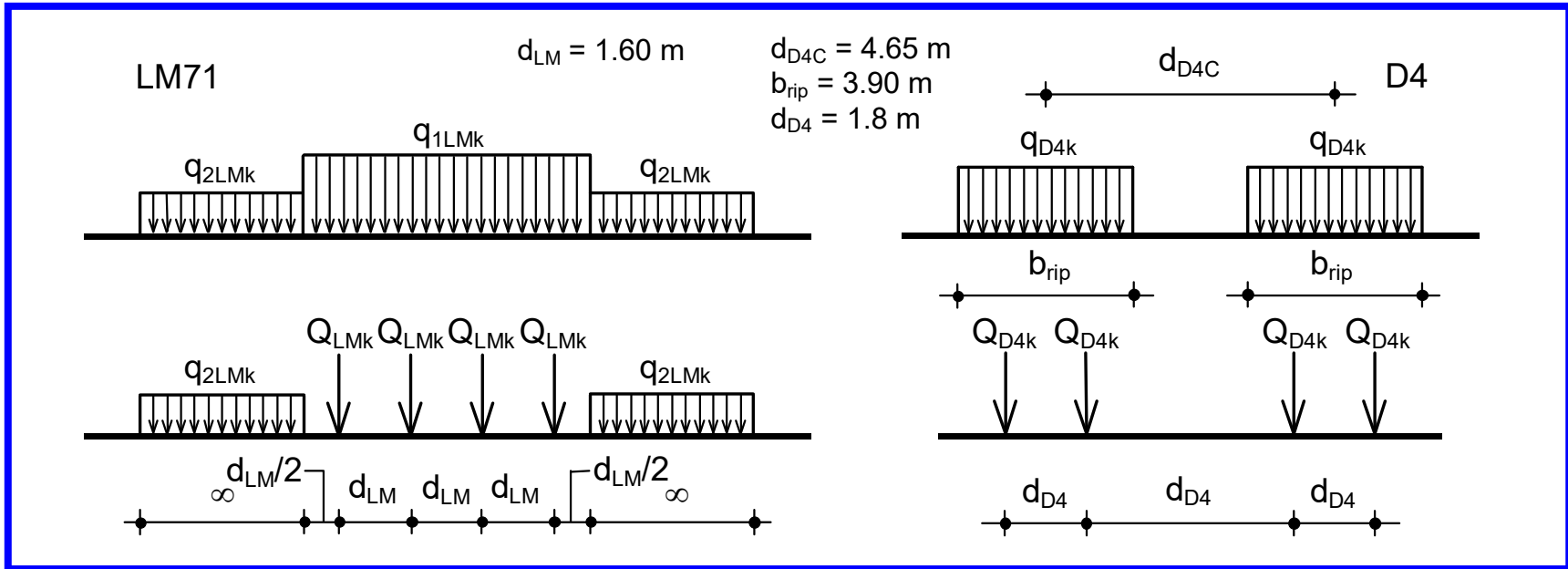
VIADOTTO km 32+926, Roma-Formia Rinforzo con FRCM



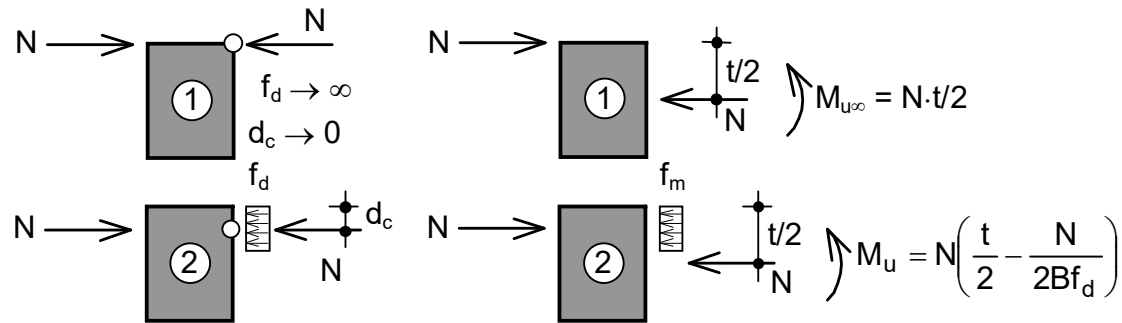
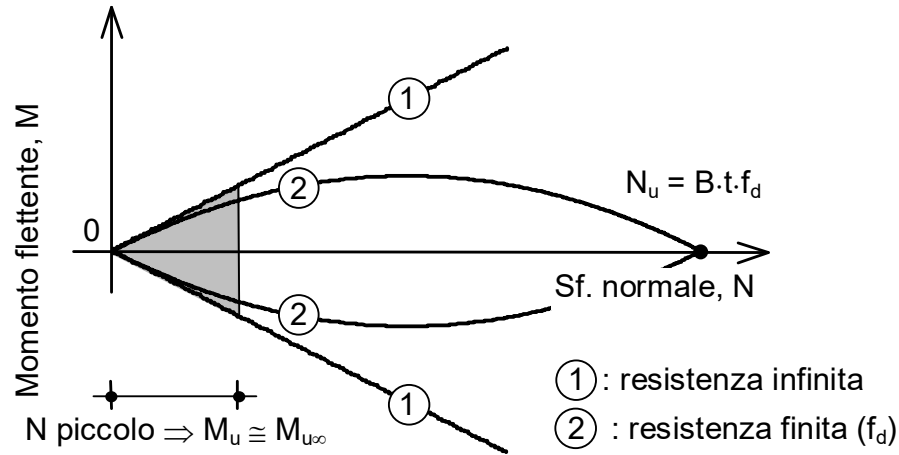
- Pile di muratura
- Volte di calcestruzzo non armato



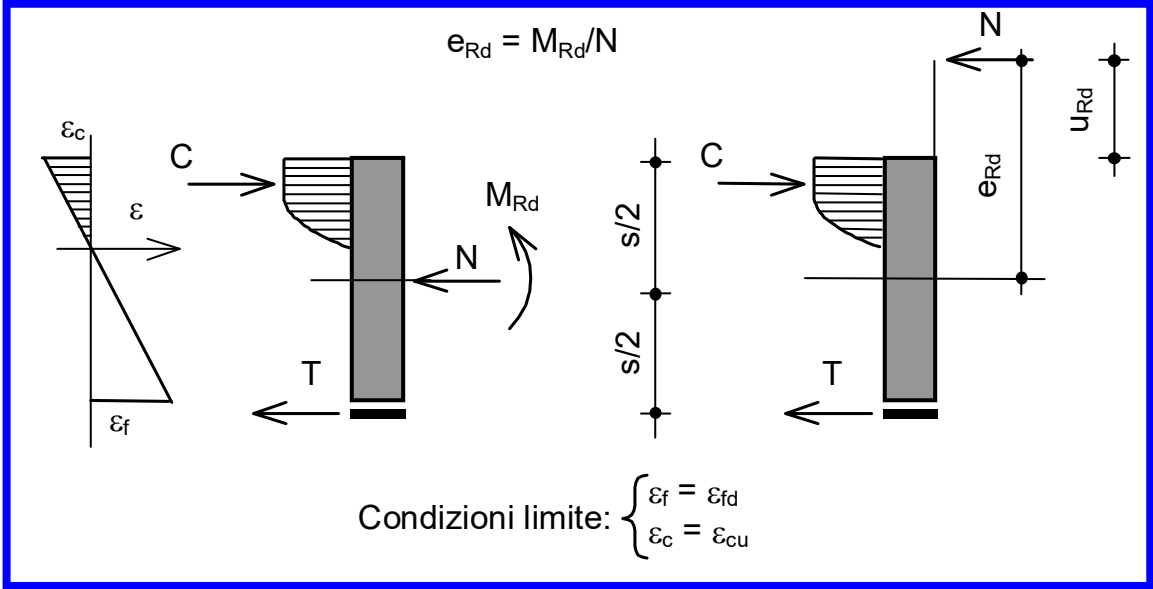
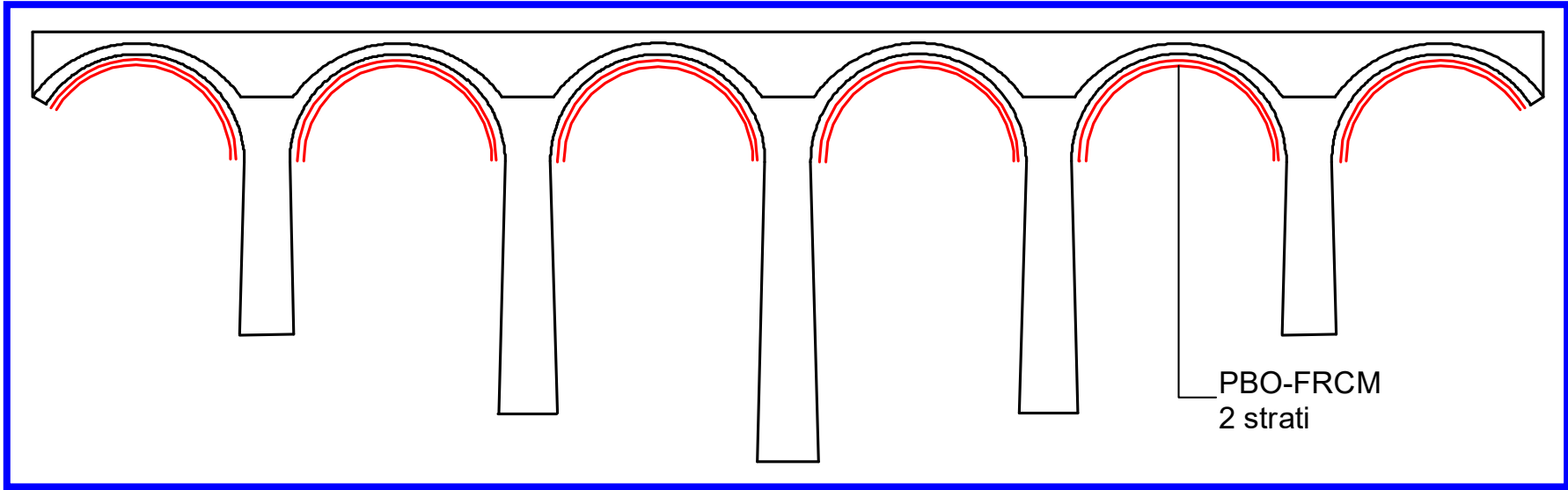
CARICHI VERTICALI



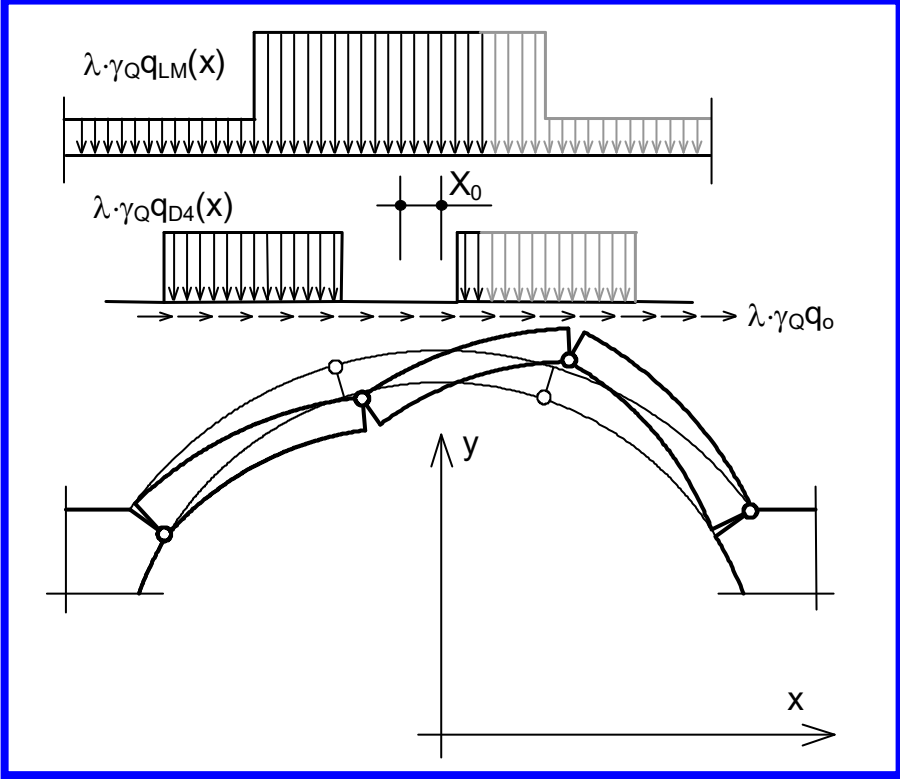
RESISTENZA A COMPRESSIONE FINITA



CONFIGURAZIONE DI RINFORZO

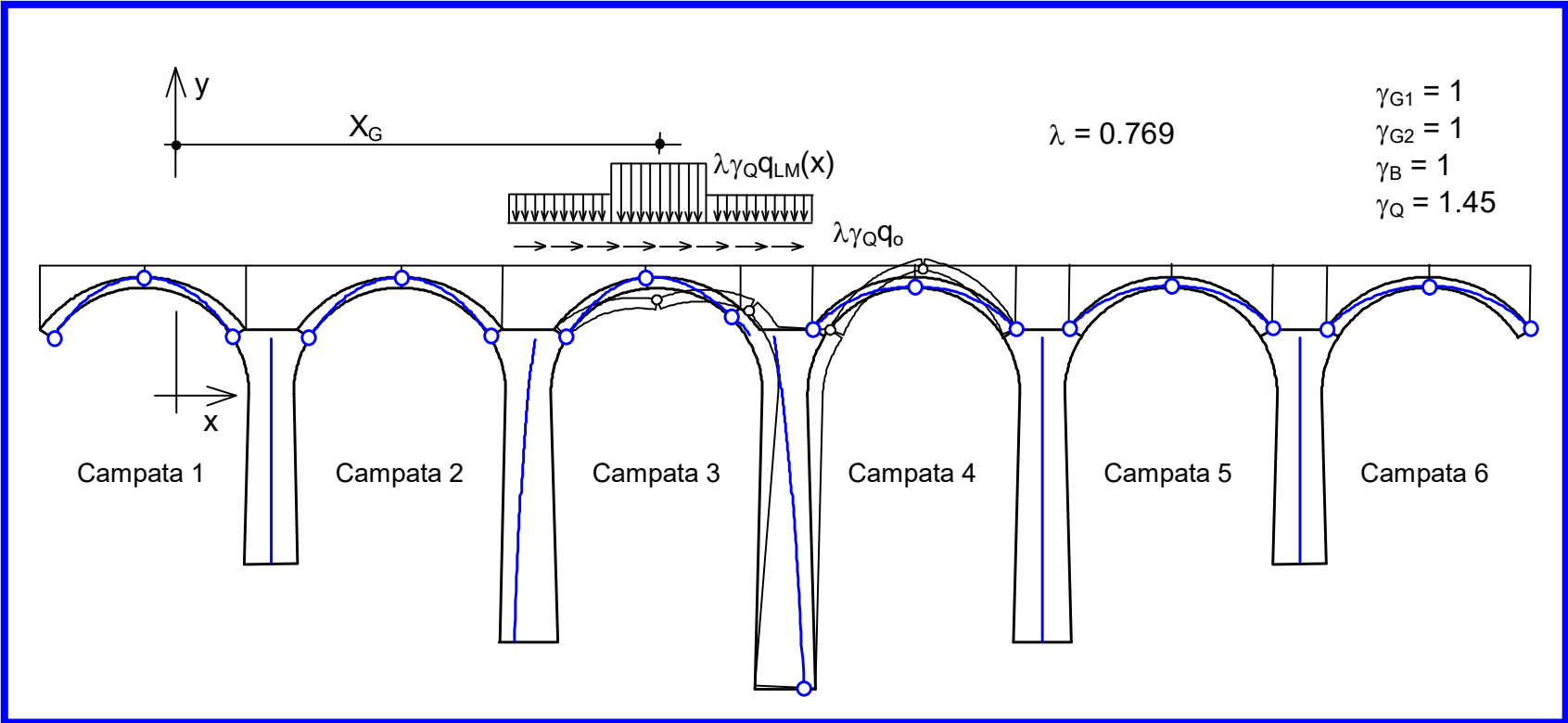


POSSIBILI MECCANISMI DI COLLASSO



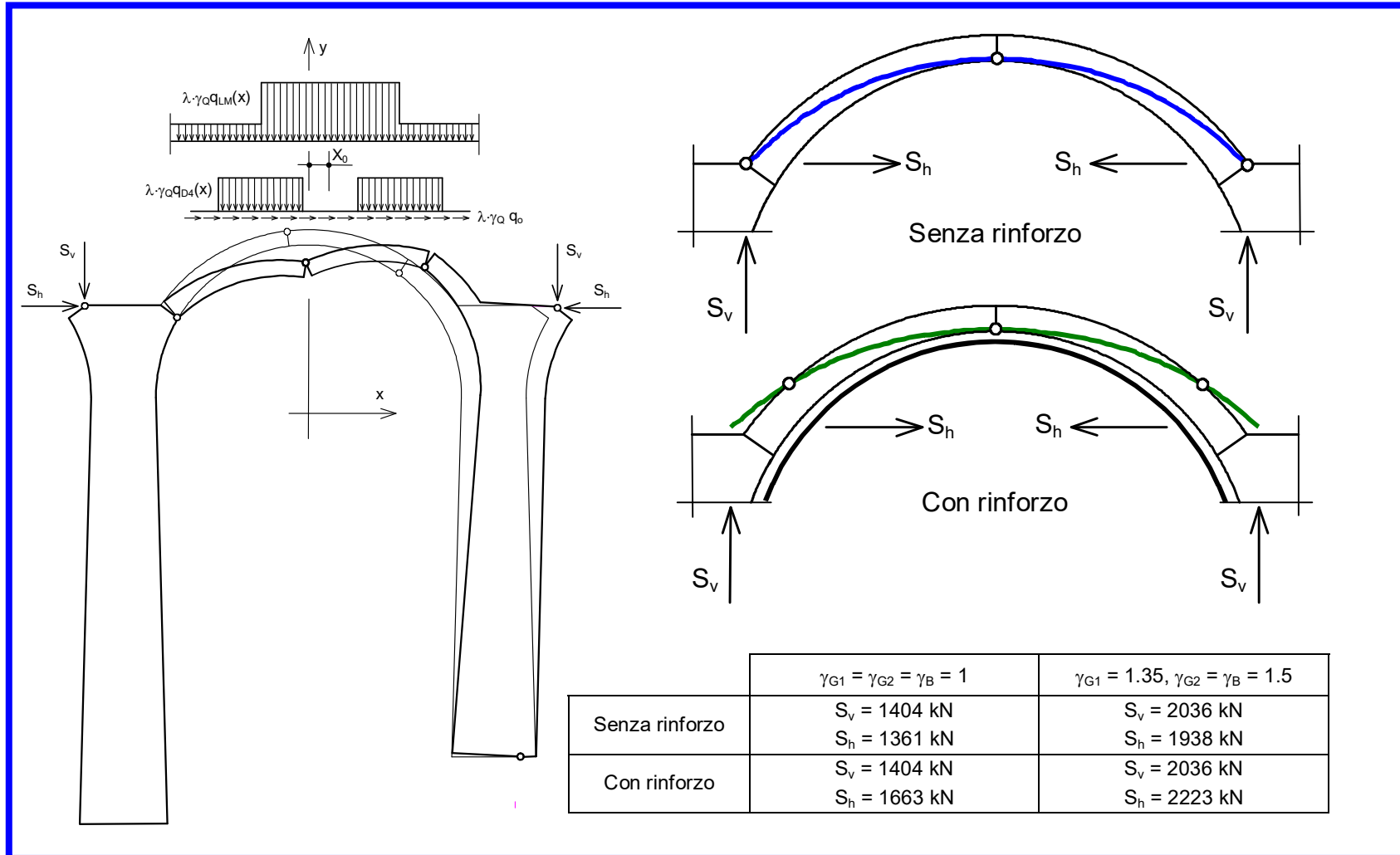
- **MECCANISMO 1: Carichi verticali/Azione sismica**

POSSIBILI MECCANISMI DI COLLASSO

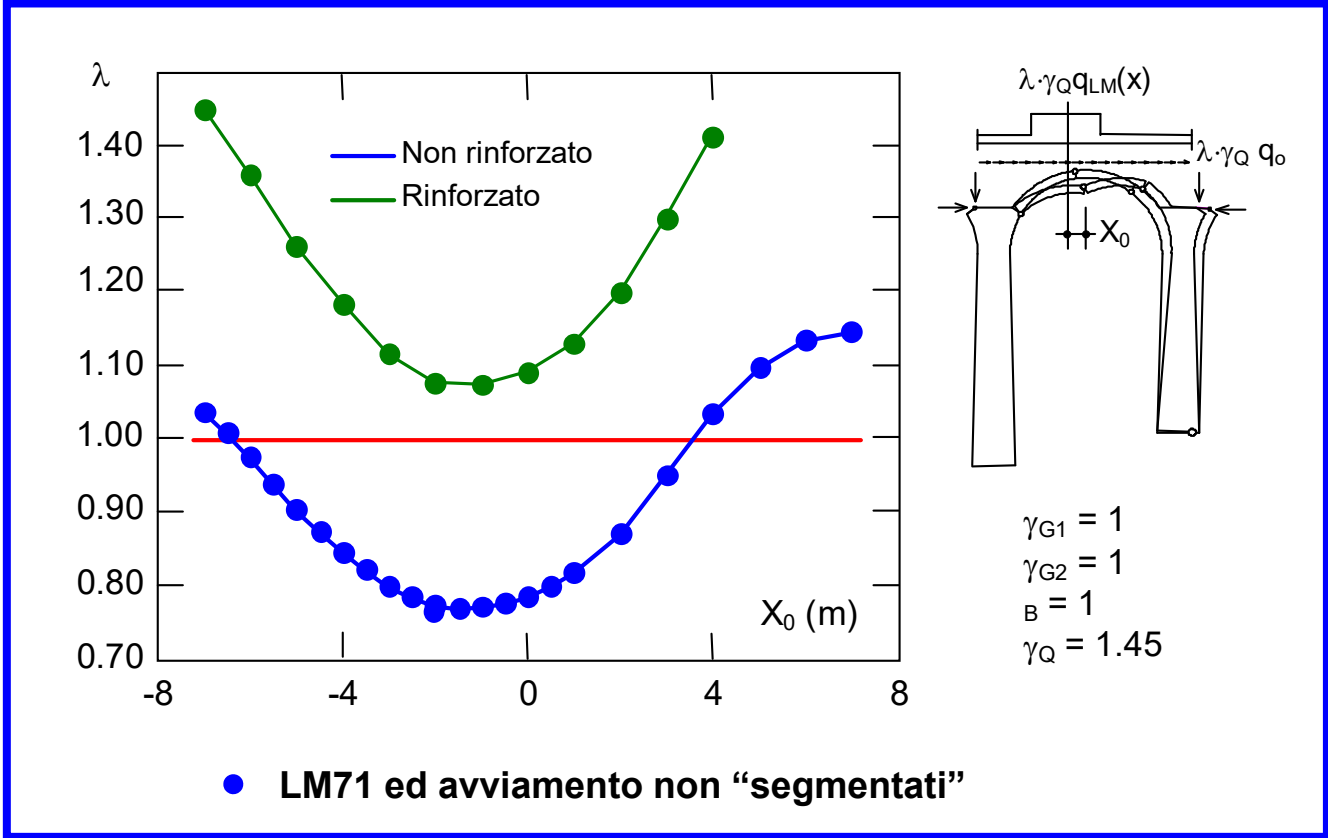


- **MECCANISMO 2: Carichi verticali**

- MECCANISMO 2: Sistemi singoli



RISULTATI: Meccanismo 2, senza sisma







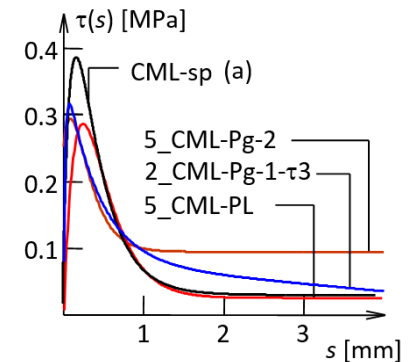
- **CONCLUSIONI: Cosa differenzia i diversi materiali FRCM?**

- **Parametri geometrici** → **Spessore nominale** (o equivalente)

- **Parametri meccanici delle fibre** → **Modulo elastico** (delle fibre)

- Modalità di trasferimento delle forze all'interfaccia per mezzo di tensioni tangenziali

- Diverse possibili superfici di rottura di interfaccia
- Diverse leggi aderenza-scorrimento



Informazioni di grande dettaglio dai produttori di FRCM

Parametri di calcolo per flessione, taglio, confinamento, ecc