Experimental efficiency of FRP bars as injected anchors for masonry structures

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INTRODUCTION

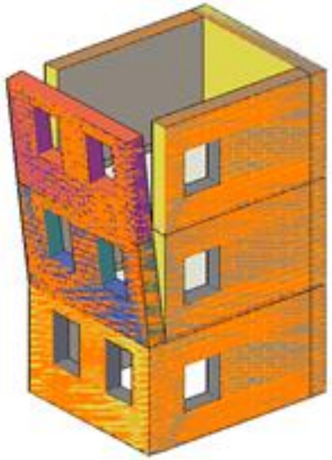
➢ Seismic Vulnerability of existing masonry buildings

MASONRY STRUCTURES

➢ *Damage assessment*

SIMPLE OVERTURNING

Mechanism I



COMPOUND OVERTURNING

Mechanism II

- The seismic vulnerability of masonry buildings to out-of-plane failure mechanisms is frequently related to poor connections between orthogonal walls and between walls and horizontal diaphragms (lack of box behavior);

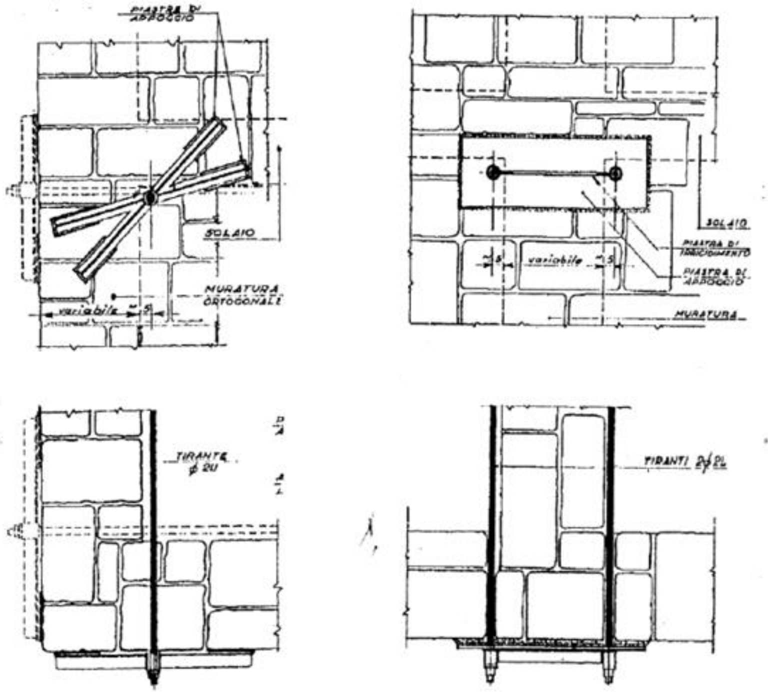
- Experimental program goal: to validate the effectiveness of innovative injected anchors based on the use of composite systems (grouted anchors made by hollow CFRP pultruded carbon tubes wrapped with longitudinal and spiral stainless steel fabrics)

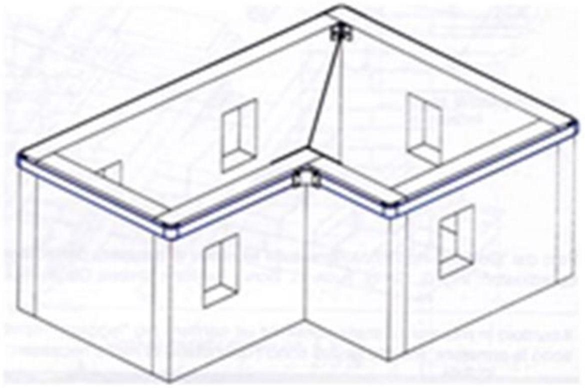
INTRODUCTION

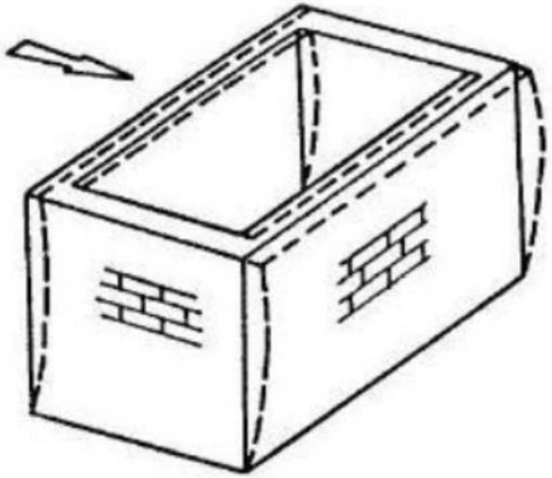
➢ Seismic Vulnerability of existing masonry buildings

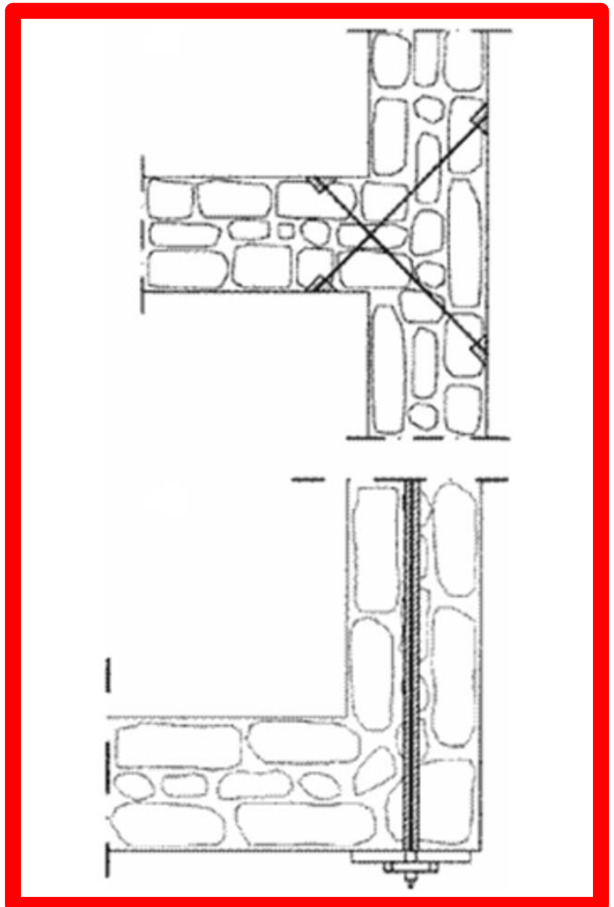
➢ *Seismic Upgrade: Traditional interventions to avoid out-of-plane mechanisms*

- *Steel Ties*
- *RC/Steel confining elements*
- *Injected anchors*









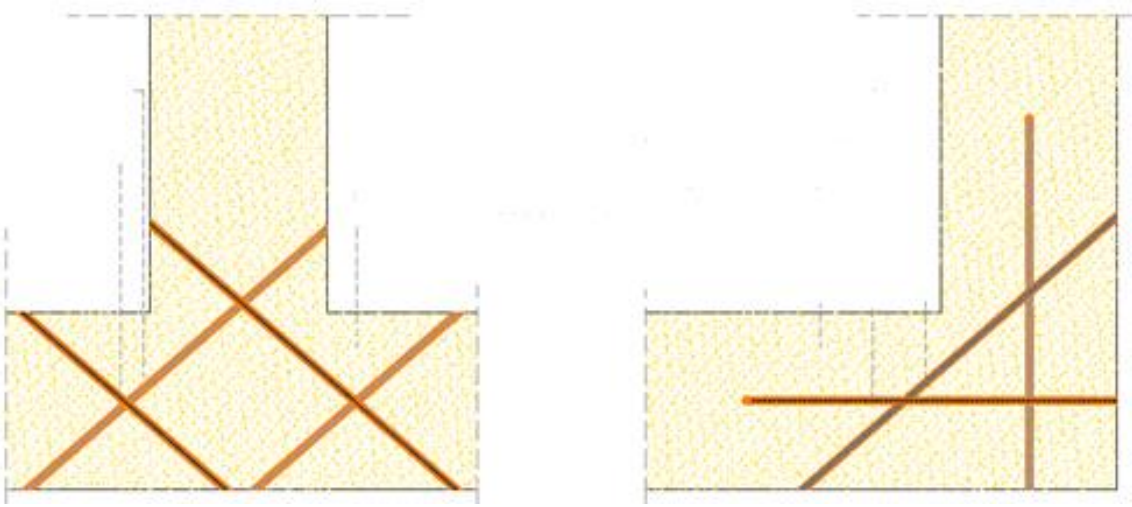
INTRODUCTION

- **Seismic Vulnerability of existing masonry buildings**
  - ***Seismic Upgrade: Injected anchors, field case example***

Caserma dell’arma , Amatrice 2016

INTRODUCTION

- **Seismic Vulnerability of existing masonry buildings**
  - ***Seismic Upgrade: Traditional vs. Innovative solutions***



Advantages
- Reduced invasiveness
- Installation from exterior
- Easy and fast execution
- No mass increase

Problem reated to the use of steel rebars:
- Corrosion

FRP rebars

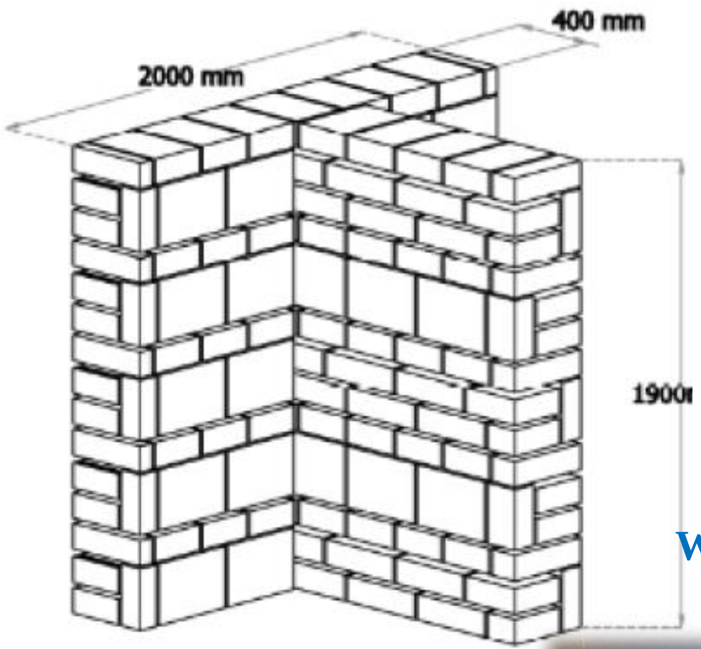
- High corrosion resistance
- Low maintenance

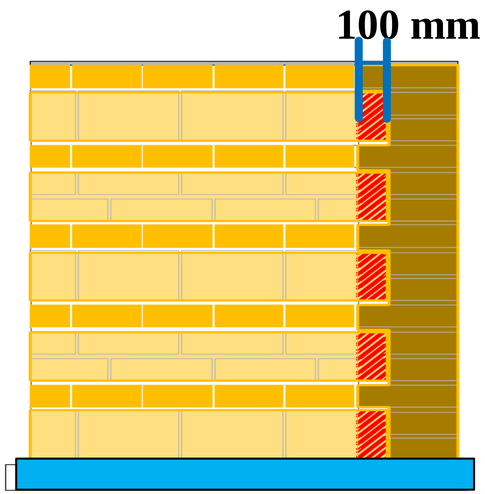
ADVANCED MATERIAL FOR SEISMIC STRENGTH.

➢ Experimental Program : Full scale element

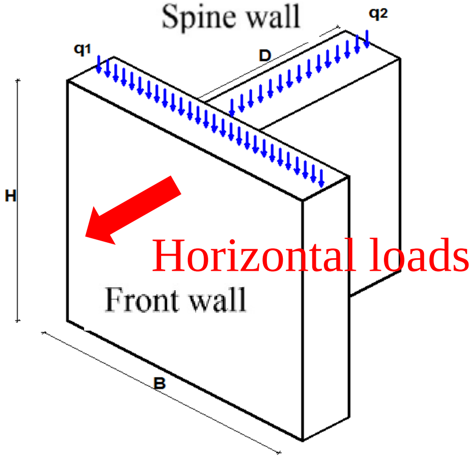
➢ *Seismic Upgrade & Exp. Validation*

Full Scale Experimental tests on T-Shape masonry specimen





Weak connection between orthogonal walls



Yellow tuff blocks & lime-based mortar

Contents lists available at ScienceDirect
Composites Part B
journal homepage: www.elsevier.com/locate/compositesb

Out-of-plane experimental behaviour of T-shaped full scale masonry wall strengthened with composite connections

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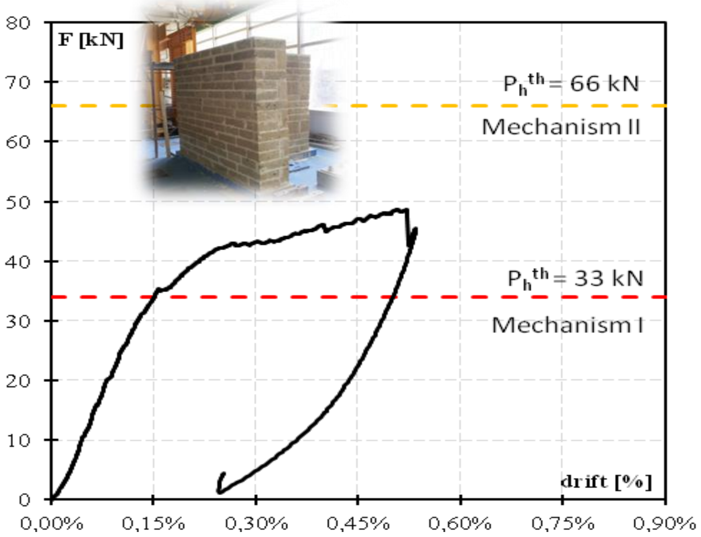
Comp. Part B: 2016

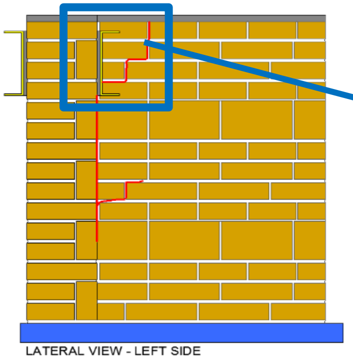
ADVANCED MATERIAL FOR SEISMIC STRENGTH.

➢ Experimental Program: Full scale element

➢ *Seismic Upgrade & Exp. Validation*

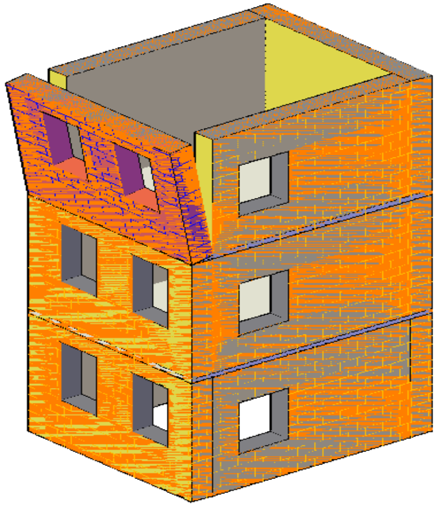
Monotonic test on "As Built" Specimen

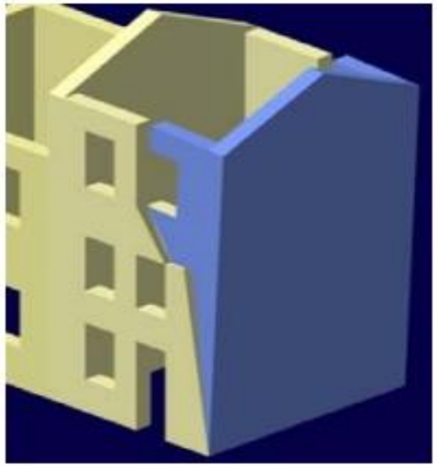




Intermediate failure mechanism

Mechanism I





Mechanism II

ADVANCED MATERIAL FOR SEISMIC STRENGTH.

➢ Experimental Program: Full scale element

➢ *Seismic Upgrade & Exp. Validation*

Injected anchors: innovative solution to overcome typical problems of corrosion due to the use of steel bars as a connection system of masonry orthogonal walls

Hollow pultruded carbon fibre tubes (Carbotube)

Diameter 10 mm	
Tensile Strength	3100 Mpa
Elastic Modulus	170 Gpa
Ultimate Strain	1,6%

+

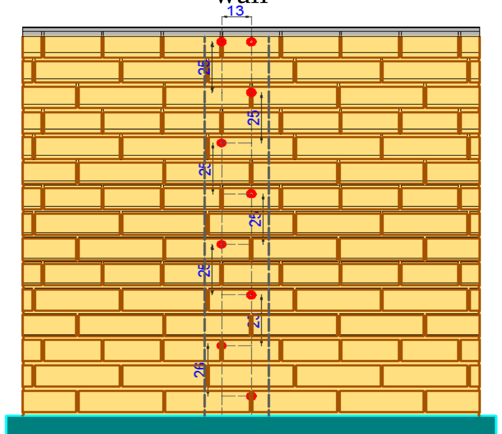
Stainless steel fabrics

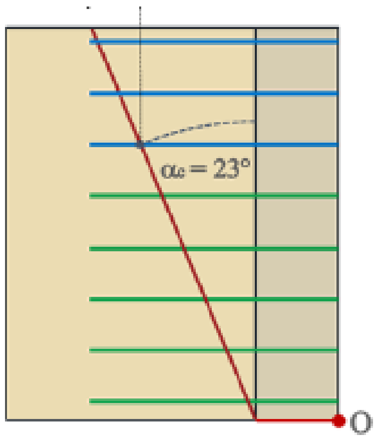
Average tensile strength 3600 N

=

Injected Anchor

$L_{tube} = 3 \times t_{wall} = 120$ cm



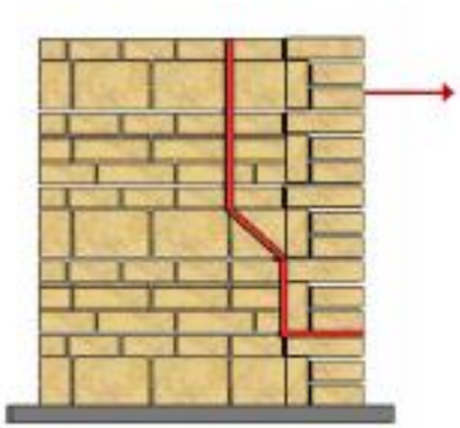


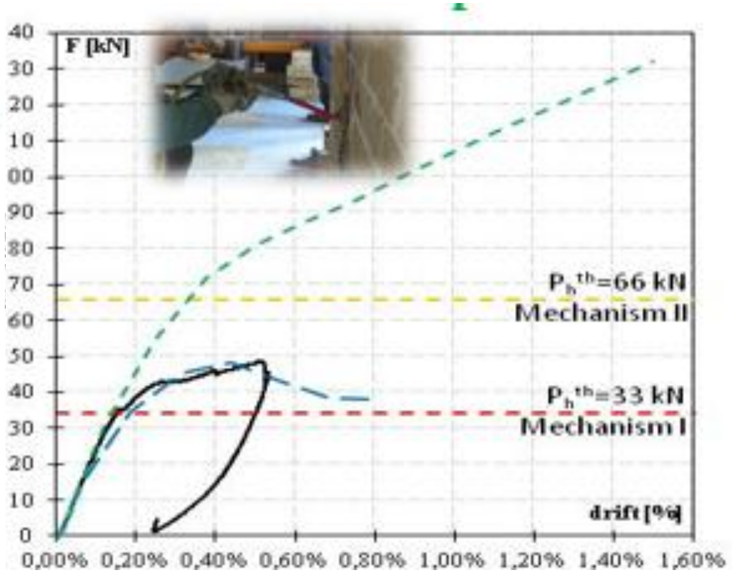
Injection of superfluid, cement free, binder (based on lime and Eco-Pozzolan)

➢ Experimental Program: Full scale element

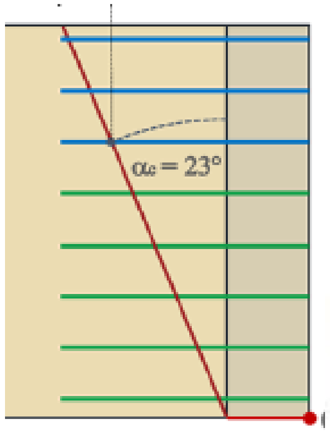
➢ *Seismic Upgrade & Exp. Validation*

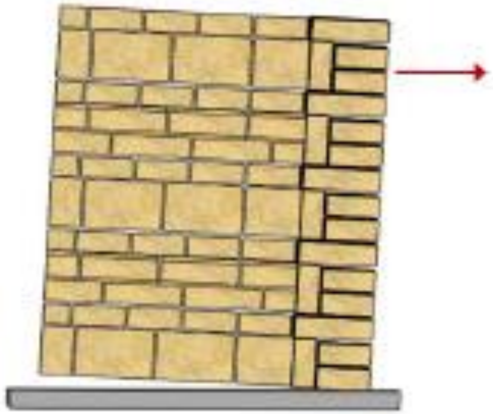
"As Built"





"Reinforced with composite connections"



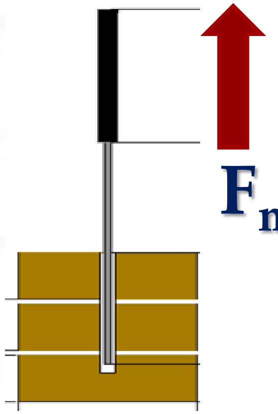


- ➢Out of plane capacity increase: +175% the horizontal force
- ➢Ultimate drift and the energy dissipation capacity increase:78% and 250%
- ➢The strengthening technique is a sound alternative to traditional steel based connections
- ➢It is a non-invasive technique and the use of cement-free mortar injections make the system suitable also in the case of historical buildings.

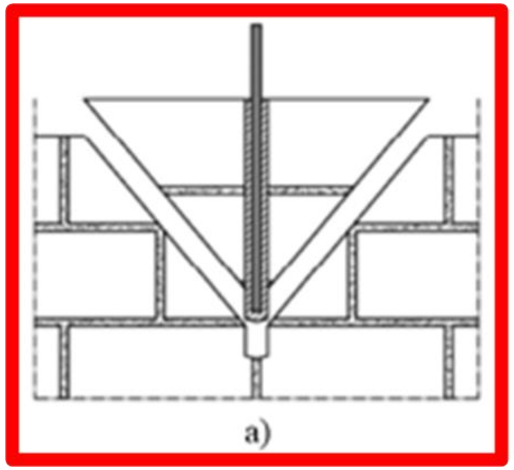
ADVANCED MATERIAL FOR SEISMIC STRENGTH.

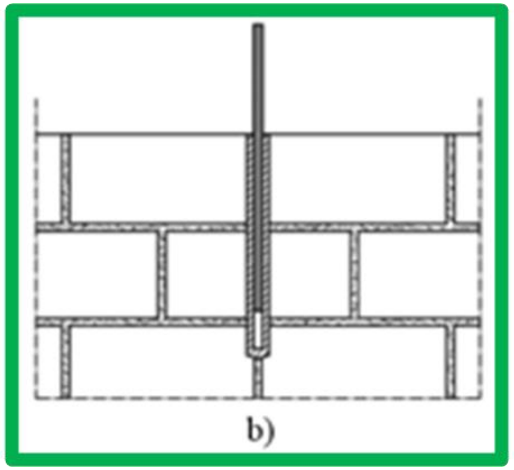
➢ Experimental Program: Pull out tests

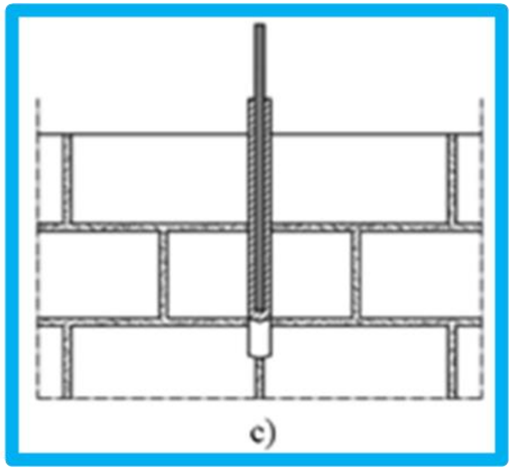
➢ *Seismic Upgrade: Design formulations*



Mostly related to steel rebars!!!







Mixed (MIX) cone detachment & slippage

Cone Masonry Detachment failure (CMD)

MSJC, 2013
ACI 318, 2011 ; fib 58, 2011
CEB, 1994
F. Arifponic & M.P. Nielsen, 2006

Slippage at bar/grout interface (SBG)

B. Gigla & F. Wenzel, 2000
ACI 318, 2011 ;

Slippage at grout/masonry interface (SGM)

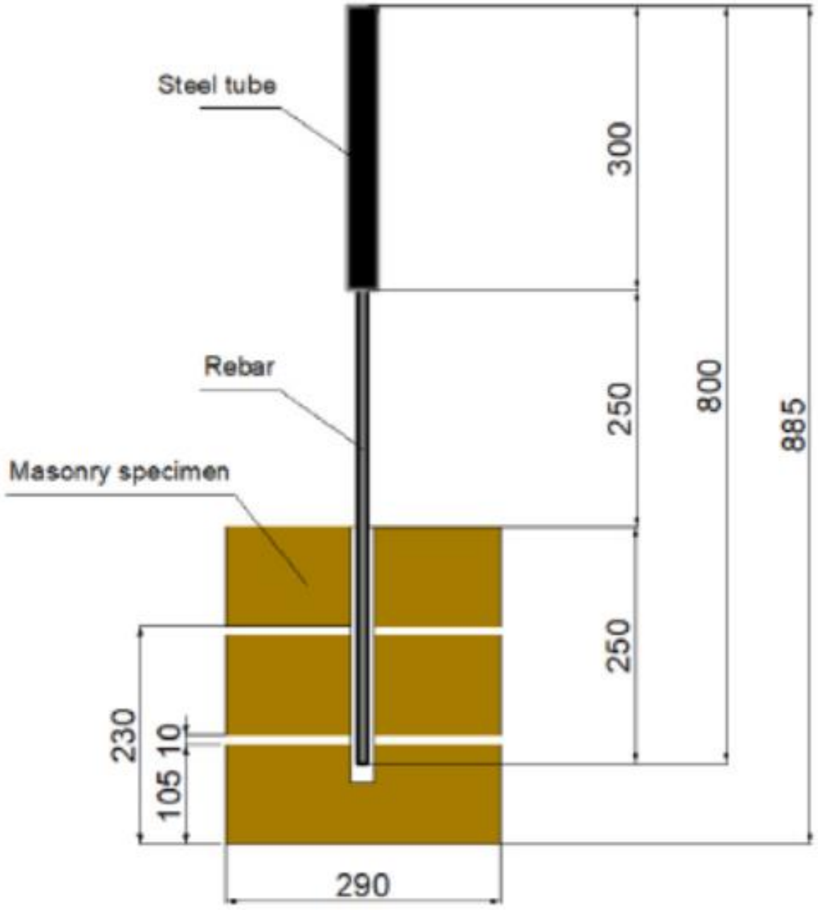
F. Arifponic & M.P. Nielsen, 2006
CEB, 1994

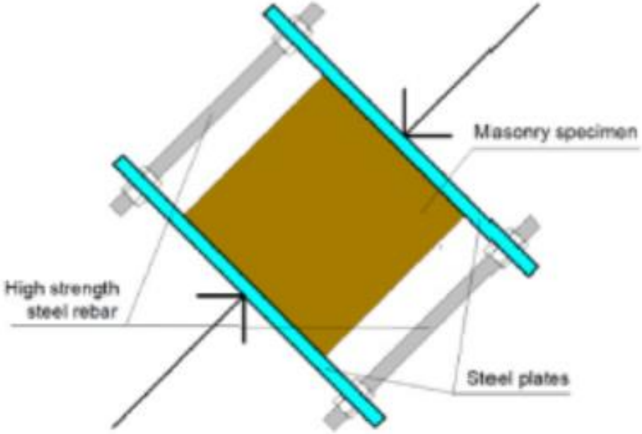
PULL OUT TESTS

➢ Experimental Program: Pull out tests

➢ *Test Setup*

- Anchors embedded 250 mm, holes diameter 25 mm.
- Displ. Control 0.5 mm/min
- Confinement pressure 0.4 MPa





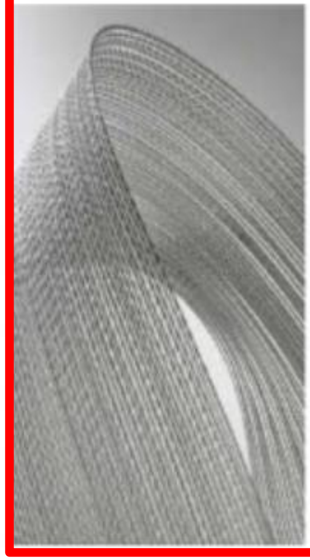
(c)

ADVANCED MATERIAL FOR SEISMIC STRENGTH.

➢ Experimental Program: Pull out tests – Round #1

➢ *Test results: Summary*




Tests on 15 masonry prisms (5 types of anchors):
1) steel ribbed bars 10 mm diameter;
2) sanded glass FRP (GFRP) bars 12 mm diameter w and w/o surface treatment;
3) hollow pultruded smooth carbon FRP (CFRP) tubes (outside/inside diameter 10/8 mm) w and w/o surface treatment

Ribbed STEEL 10 mm bars

sanded GFRP 12 mm bars

smooth CFRP 10 mm tubes;

Surface treatment: wrapping the FRP bars with a stainless steel fabrics (SRP) embedded in a putty

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Traditional and innovative systems for injected anchors in masonry elements: Experimental behavior and theoretical formulations

Check for updates

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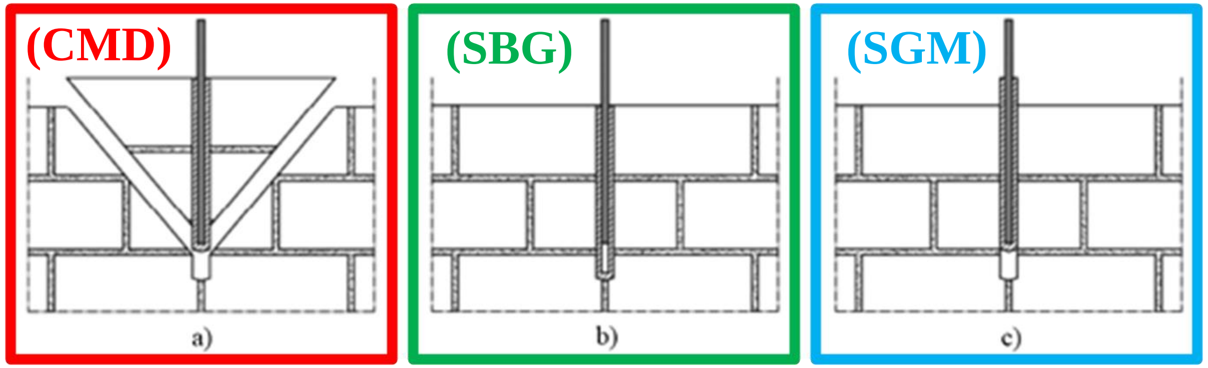
Constr. Build. Mat.: 2020

PULL OUT TESTS

- **Experimental Program: Pull out tests #1**
  - ***Test results: Summary***



FAILURE MODE

a) Sliding at bar-grout (SBG) interface for the ribbed steel bars;
b) Sliding at bar-grout (SBG) interface on GFRP bars;
c) Sliding at bar-grout (SBG) for CFRP tubes (MC10u-2);
d) Sliding at grout-masonry (SGM) interface for treated GFRP bars;
e) Mixed failure (SGM + CMD) for treated CFRP tubes

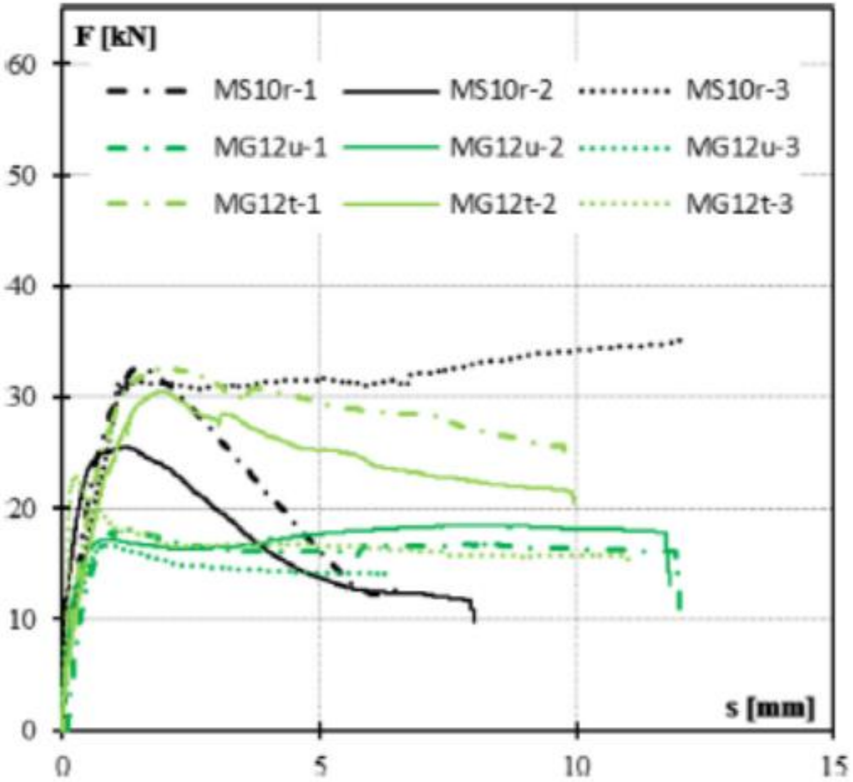
PULL OUT TESTS

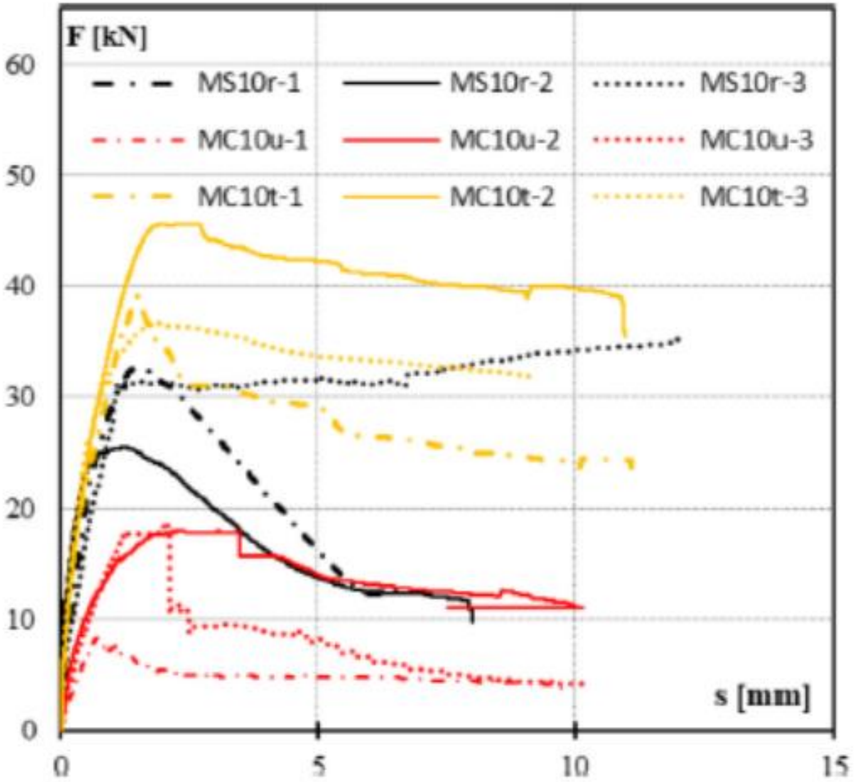
➢ Experimental Program: Pull out tests #1

➢ *Test results: Summary*

specimens' labels: XY_j_k_n,

- X: material (M = masonry))
- Y: bar material type (S = steel, G = GFRP, C = CFRP),
- j: diameter (10 or 12 mm),
- k: surface treatment (r = ribbed, t = treated, u = untreated)
- n: repetition 1, 2, or 3





STEEL
GFRP untr.
GFRP tr.
CFRP untr.
CFRP tr.

➢ The tests showed that FRP systems are able to provide performance comparable or higher in comparison with the steel bars <u>only by increasing their bond behaviour by means of a surface treatment</u>.

PULL OUT TESTS

➢ Experimental Program: Pull out tests #1

➢ *Test results: Summary*

- **specimens' labels: XY_j_k_n,**
  - X: material (M = masonry))
  - Y: bar material type (S = steel, G = GFRP, C = CFRP),
  - j: diameter (10 or 12 mm)
  - k: surface treatment (r = ribbed, t = treated, u = untreated)
  - n: repetition 1, 2, or 3

Label [-]	Failure mode [-]	F_{max} [kN]	$F_{max,mean}$ [kN]	Δ_x [%]
MS10r-1	SBG + CMD	32.7	30.1	
MS10r-2	SBG + CMD	25.5		–
MS10r-3	SBG + CMD + SY	36.9		
MG12u-1	SBG	18.1		
MG12u-2	SBG	18.4	17.7	−41.2%
MG12u-3	SBG	16.7		
MC10u-1	–*	8.36*	18.3	−39.2%
MC10u-2	SBG	17.9		
MC10u-3	SBG + SGM	18.7		
MG12t-1	SGM	32.5	31.5	+4.7%
MG12t-2	SGM	30.5		
MG12t-3	-*	22.9*		
MC10t-1	MIX (SGM + CMD)	39.1		
MC10t-2	MIX (SGM + CMD)	45.6	40.5	+34.9%
MC10t-3	MIX (SGM + CMD)	36.7		

PULL OUT TESTS

➢ Experimental Program: Pull out tests – Round #2

➢ *Test results: Summary*

Anchor type	min diameter [mm]	Surface treatment
Basalt bar – B8	8	helicoidal ribbed wrapping
Carbon bar – C10	10	Smooth
Glass bar – G10	10	helicoidal wrapping
Glass bar – G12	12	helicoidal wrapping
Glass spike anchor - Gspike	10	Sand coating

helicoidally ribbed basalt bar (B 8)

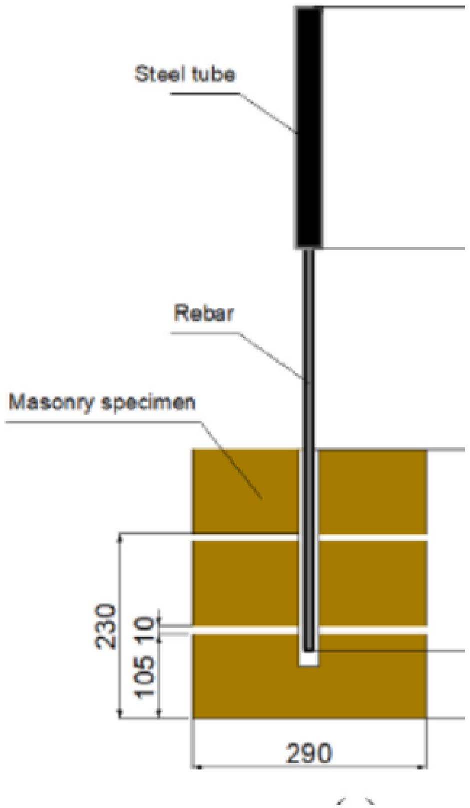
smooth carbon bar (C10)

helicoidally wrapped glass bar (G10 and G12)

sanded glass spike (Gspike)

Experimental Program: Pull out tests

Material Mechanical properties



- **Masonry**
  - **Compression tests**
    30 tuff cubes (side 100 mm, EN 1926:2007)
    Av. strength f_{mcm} = 3.3 MPa
    SD = 1.1 Mpa; CoV = 33%
  - **Compressive tests**
    prismatic tuff samples (EN 14580:2005)
    Av. Young's modulus E_m = 1920 MPa
    SD =212 Mpa; CoV = 11%
  - **Flexural tests**
    prismatic tuff samples (EN 12372:2022)
    Av. tensile strength flexure f_{mfm} = 0.84 MPa
    SD = 0.21 Mpa; CoV = 26%
    Actual tensile strength, f_{mtm}, / 1.2 , f_{mtm} = 0.7 MPa

- **Mortar Joints (M 2.5)**
  - (EN 1015- 11:2007).
    f_{jcm} = 2.8 MPa
    CoV = 10.3%
  - (EN 1015- 11:2007).
    f_{jfm} = 0.8 MPa
    CoV = 6%

- **Injection Grout**
  - f_{gcm} = 8.7 MPa
    SD = 0.3 Mpa;CoV = 3.7%
  - (EN 1015- 11:2007).
    f_{gfm} = 1.23 MPa
    SD = 0.18 Mpa; CoV = 14.3%

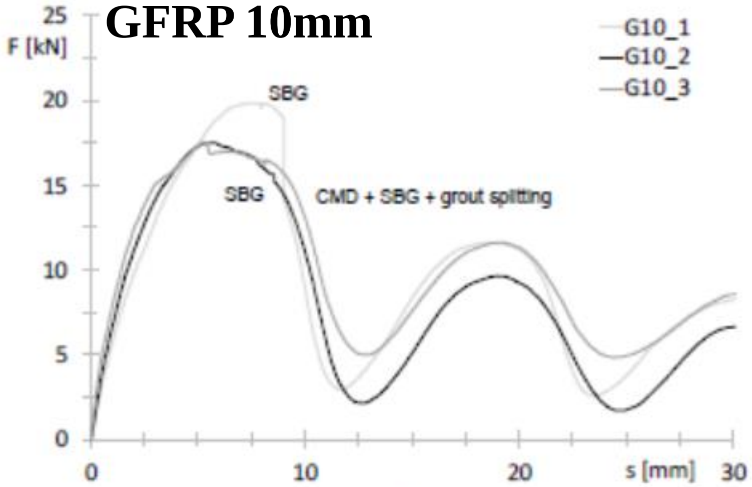
PULL OUT TESTS

➢ Experimental Program: Pull out tests – Round #2

➢ *Test results: Summary*

helicoidally wrapped glass bar (G10 and G12)

GFRP 10mm

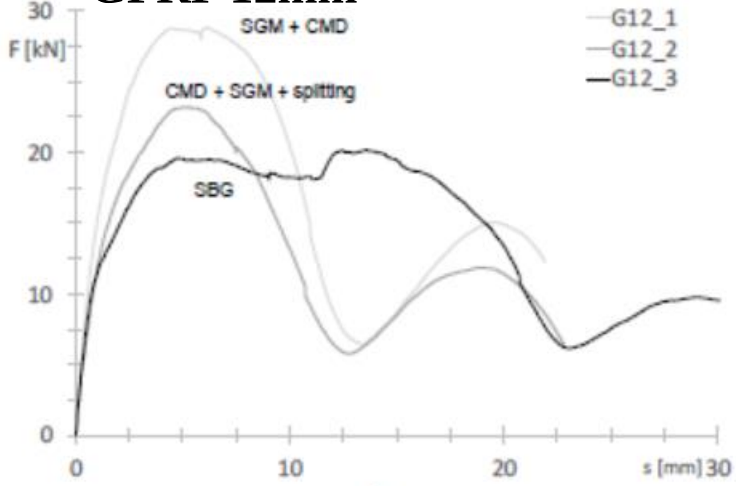


a)

G10_1: SBG G10_2: SBG G10_3: CMD+SBG+SG

b)

GFRP 12mm



c)

G12_1: SGM+CMD G12_2: CMD+SGM+SM G12_3: SBG

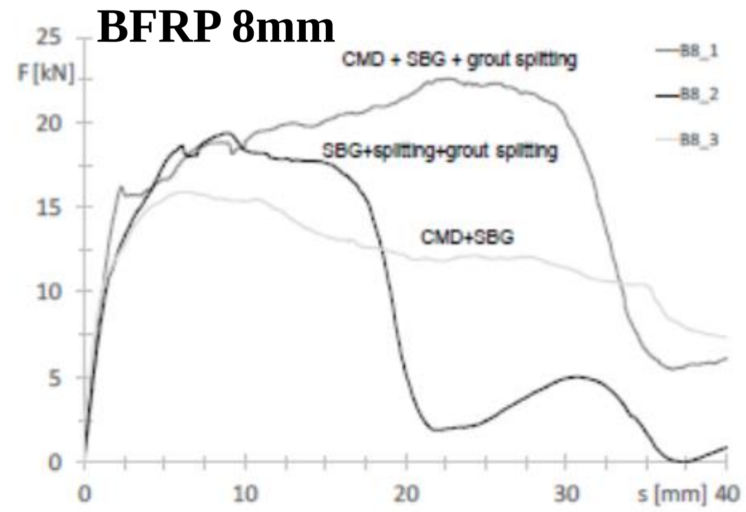
d)

- ➢ In most cases mixed failure modes were observed, (two or three failure mechanisms)
- ➢ After peak, a sinusoidal trend was observed due to the progressive slippage of the bar/grout system from the surrounding masonry and, relevant reduction of the embedded length.
- ➢ For the glass bars, the load increase was only 16% when the diameter changed from 10 mm to 12 mm, which corresponds to an increase of 59% in terms of anchor's area.

PULL OUT TESTS

➢ Experimental Program: Pull out tests – Round #2

➢ *Test results: Summary*



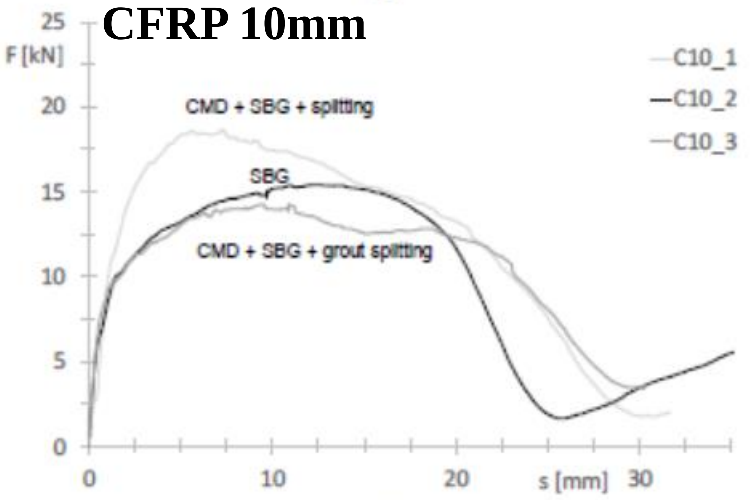
e)


B8_1: CMD+SG B8_2: SBG+SM+SG B8_3: CMD+SBG

f)


helicoidally ribbed basalt bar (B 8)

- ➢ In most cases mixed failure modes were observed,
- ➢ The basalt bars attained the highest values of tensile stress and a very ductile post-peak behaviour characterized by residual bond strengths and large displacements



g)


C10_1: CMD+SBG+SM C10_2: SBG C10_3: CMD+SBG+SG

h)


smooth carbon bar (C10)

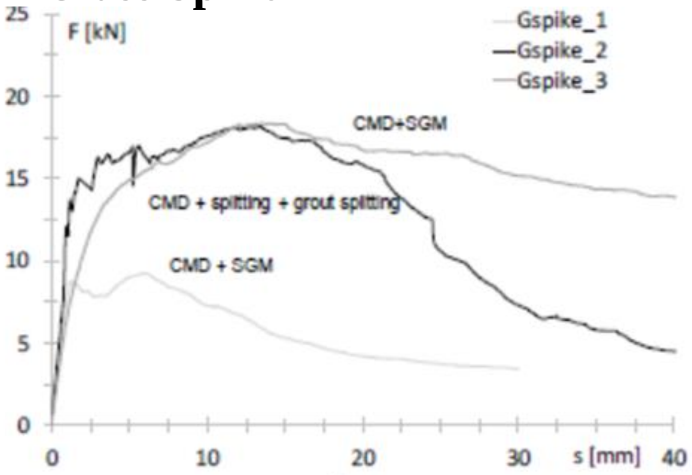
- ➢ The lowest pull-out forces were attained by the carbon bars with diameter 10 mm (16.15 kN in average) characterized by a smooth lateral surface.

PULL OUT TESTS

➢ Experimental Program: Pull out tests – Round #2

➢ *Test results: Summary*

Glass Spike



i)

Gspike_1: CMD+SGM Gspike_2: CMD+SM+SG Gspike_3: CMD+SGM

l)

sanded glass spike (Gspike)

- The pull-out loads on glass bars diameter 10 mm, basalt bars diameter 8 mm and glass spike anchors were very similar (18.1 – 18.7 kN) and in average with the results of the other bars

- The highest ratio $\eta = \sigma_{max,av}/f_{atm}$ was attained by the glass spike anchor, even if this system was the most sensitive to detailing, because the curing of the resin incorporating the glass fibres and the sand coating were realized in laboratory and not by the producer

PULL OUT TESTS

➤ **Experimental Program: Pull out tests – Round #2**

➤ ***Test results: Summary***

$\eta = \sigma_{max,av}/f_{atm}$. average exploitation ratio

Specimen	A_{nom}	$F_{max,exp}$	$F_{max,av}$	$\sigma_{max,exp}$	$\sigma_{max,av}$	Failure mode	η
	[mm^2]	[kN]	[kN]	[MPa]	[MPa]	-	-
G10_1	78.5	19.80	18.68 1.59 (8.5%)	252.2	233.0	SBG	0.21
G10_2		17.51		223.1		SBG	
G10_3		17.56		223.6		CMD+SBG + SG	
G12_1	113	28.82	21.69 2.18 (10.0%)	255.0	193.5	CMD+SGM	0.19
G12_2		20.15		178.3		CMD+SGM+SM	
G12_3		23.23		205.5		SBG	
B8_1	50.2	15.93	18.13 3.85 (21.2%)	317.1	305.8	SBG+CMD	0.23
B8_2		15.89		316.3		SBG + SM + SG	
B8_3		22.58		449.4		SBG+CMD+SG	
C10_1	78.5	18.69	16.15 2.28 (14.1%)	238.1	202.6	CMD+SBG +SM	0.11
C10_2		15.47		197.1		SBG	
C10_3		14.28		181.9		CMD + SBG + SG	
Gspike_1	64	9.26*	18.26 0.14 (0.8%)	144.7*	285.3	CMD+SGM	0.40
Gspike_2		18.16		283.8		CMD + SM + SG	
Gspike_3		18.36		286.9		CMD+SGM	

**not considered in the average value*

Tensile strength f_{atm} [MPa] = 1092 (G10), 1012 (G12)

helicoidally wrapped glass bar (G10 and G12)

f_{atm} [MPa] = 1306 (B8)

helicoidally ribbed basalt bar (B 8)

f_{atm} [MPa] = 1822 (C10)

smooth carbon bar (C10)

f_{atm} [MPa] = 724 (Gspike)

sanded glass spike (Gspike)

Experimental Program: Pull out tests – Round #2

Conclusive remarks

- In most specimens, the slippage at the bar-grout or at the grout/masonry interface occurred

- After the maximum load is attained, the softening behaviour of the load-slip curves is characterized by a sinusoidal trend that give high ductility to this failure mode. This behaviour is due to the progressive slippage of the bar/grout system from the surrounding masonry and, consequently, to the progressive reduction of the embedded length where the interlocking is effective, until the full slippage of the bar occurs;

- The experimental program showed that the basalt bars with diameter 8 mm and the glass spike anchors resulted the most efficient systems for the following reasons:
  1) they both attained comparable pull-out loads, in average with the results of the other bars,
  2) the basalt bars attained the highest values of tensile stress and a very ductile post-peak behaviour characterized by residual bond strengths and large displacements,
  3) the glass spike anchors attained the maximum efficiency coefficient and, probably thanks to their rough surface, the failure never occurred at the bar/grout interface.

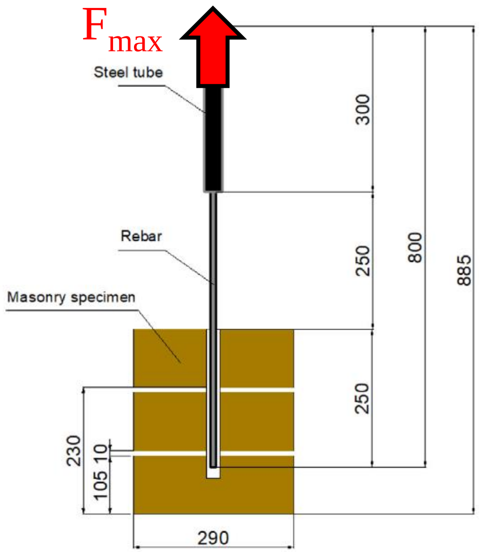
- Some scattering in the results, both in terms of failure loads and modes, is ascribable to the high heterogeneity of the tuff stones used in the tests since they were characterized by a diffuse presence of voids and inclusions.

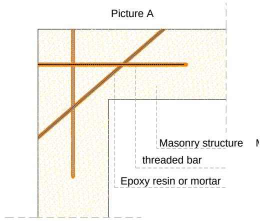
ADVANCED MATERIAL FOR SEISMIC STRENGTH.

➢ Work in progress……

➢ ***Modelling and code provisions***

Original tests + analysis of literature results on injected anchors in masonry elements + calibration of new design formulations to predict the maximum pull-out force (for predicting the pull-out strength in case of whatever failure mode)





Pull-out tests by authors: 15 tests (Steel, GFRP ,CFRP)

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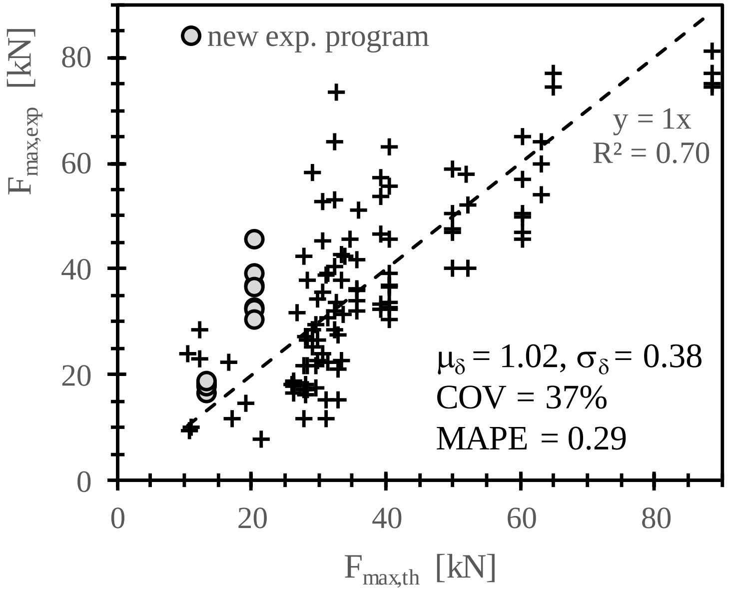
New design formulation: Steel & FRP bars



Multivariate Regression Analysis (**111 tests**)

$\alpha = 191059$, $\beta = 1.41$, $\gamma = 0.38$

$\delta = -0.37$, $\varepsilon = 2.11$, $\eta = -0.49$, $\theta = 0.50$.

$$F_{max,th} = k \cdot \left[\alpha \cdot \frac{(0.67 f_t + 0.4\sigma_c)^{\beta}}{f_{c,m}^{\ \theta}} + \gamma \cdot d_{hole}^{\ \delta} \cdot l_e^{\ \varepsilon} \cdot (0.67 f_t + 0.4\sigma_c)^{\eta} \right]$$

Design by testing procedure (EN 1990 Annex D) - 5th perc.le predicton

$$F_{max,th,k} = k_{lognorm} \cdot F_{max,th} \quad ; \quad k_{lognorm} = 0.51$$

Thank you!

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