DISCONTINUOUS FRCM-CONFINEMENT OF MASONRY COLUMNS

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DISCONTINUOUS FRCM-CONFINEMENT OF MASONRY COLUMNS

L. Ombres

The structural response of FRCM-partially confined masonry columns has been investigated by the results of studies and research conducted from the Authors . They refers mainly to experimental analyses conducted on clay brick masonry columns confined with FRCM jackets; results of theoretical analyses are also available.

This presentation summarizes the main results of these investigations according to the mechanical and geometrical parameters that were considered during the above analyses.

The initial part describes the results of the experimentations that enabled the subsequent theoretical analyses to be developed, the results of which are presented in the second part of the presentation.

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THE CONFINEMENT OF MASONRY COLUMNS

Column confinement with FRCM is a well-established reinforcement technique that provides significant increases in strength and deformation capacity.

Masonry columns are usually confined with fiber-reinforced composite jackets along their entire height (fully wrapped columns); alternatively, they can be wrapped with longitudinally discrete (i.e. spaced) jackets (partially wrapped columns).
Partial confinement represents an optimal design solution in masonry columns that require a limited increase of strength and deformation but also in historical constructions where the breathability of masonry is needed.

The effectiveness of fully confinement of masonry columns has been the subject of numerous studies and research conducted on columns under both concentric and eccentric or eccentric axial loads, varying geometric and mechanical parameters such as the amount of reinforcement (i.e., the number of fabric layers), the mortar grade, column geometry (the corner radius), the load eccentricity values.

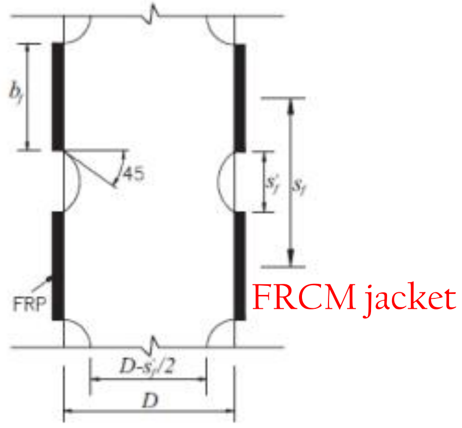
Limited information are available on the structural response of partially FRCM confined masonry columns. At the same time, no provisions are given in the main guidelines and codes.
In this context, the analysis of the mechanical response of masonry columns partially confined with FRCM is of parti cular interest.

EXPERIMENTAL INVESTIGATIONS

Four series of experimental tests were run on small size clay brick masonry columns in order to investigate on the effectiveness of the partial confinement made with FRCM jackets.

Parameters variable were:

- the amount of the textile (i.e. the number of confining layers),
- the FRCM system (textile and mortar) and,
- the confining configuration defined by the vertical spacing ratio $\zeta = s'_f/s_f$ being s'_f the centre-to-centre spacing to adjacent FRCM strips and s_f the net spacing between two strips.



Masonry columns were tested under compression load.

SERIES I

The series refers to clay brick masonry columns with square cross section, 250 x 250 mm, and overall height 770 mm. Columns had rounded edges (radius of curvature r_c=20 mm)

The PBO-FRCM confining system was adopted; the variable parameter was the confining layers (1, 2 and 3 textile layers) and the confining configuration (continuos and discontinuous).
For each discontinuous configuration the width of the FRCM strip was set to b_f= 150 mm and the ***vertical spacing ratio*** was set to 0,50 (s'_f=b_f= 150 mm; s_f= 300 mm).

Tests were performed on 7 columns; one un-confined (reference column), three fully confined and three partially confined with PBO-FRCM strips.

M.A: Aiello, A. Cascardi, L. Ombres, S. Verre (2020) «*Confinement of masonry columns with the FRCM-system: theoretical and experimental investigation*», Infrastructures, MDPI, , Vol. 5, 101; doi:10,3390/infrastructures5110101

DISCONTINUOUS FRCM-CONFINEMENT OF MASONRY COLUMNS

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SERIES I

MATERIALS

Commercial clay brick units with dimensions 250x120x55 mm were used to built columns. The compression strength of clay brick, determined by tests on 5 units, was 56,80 MPa (C.o.V.=0,02); compression and flexural strength of the mortar used to bind the clay units, determined by standard tests were 12,85 MPa (C.o.V.=0,15) and 2,65 MPa (C.o.V.=0,05), respectively.

The strengthening system was made of a PBO unbalanced textile emebedded into a cement –based mortar; in the longitudinal direction (principal direction) the textile has an equivalent thickness of 0,046 mm while in the transversal direction the equivalent thickness was 0,012 mm.
The average values of the compressive and flexural strength of the mortar, determined by standard tests, were: 36,16 MPa and 5,50 MPa, respectively.

The mechanical properties of the PBO textile and the PBO-FRCM systems, reported in the Table , were determined by tensile tests carried out on 5 specimens according to the Italian guidelines.

Textile	Elastic modulus (GPa) (C.o.V.)	Tensile strength (MPa)(C.o.V.)	Ultimate strain (mm) (C.o.V.)
PBO	211,40 (0,041)	3400(0,029)	0,025 (0,08)
FRCM	**Elastic cracked modulus** (GPa) (C.o.V.)	**Tensile strength** (MPa)(C.o.V.)	**Ultimate strain** (mm) (C.o.V.)
PBO FRCM	94,0 (0,09)	1598 (0,17)	0,0125 (0,024)

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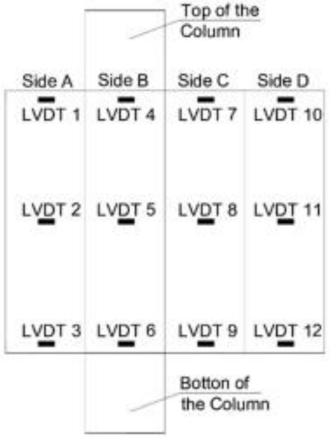
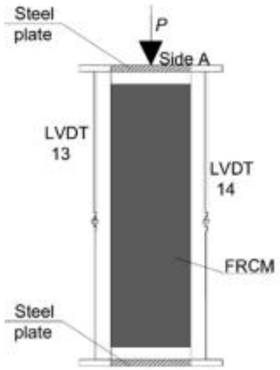
SERIES I

SET UP





Tests were conducted by the loading control method with a load rate of 40 N/sec.

The vertical displacements were measured by four LVDTs installed at the corners of the columns.

A total of twelve horizontal LVDTs were positioned along the height of the columns to measure the lateral displacements (three horizontal LVDTs for each face of the column, at the top, at the mid-height and at the bottom)

TEST RESULTS

E_{el}, elastic modulus
σ_p, peak axial stress
ε_p peak axial strain
ξ, confinement ratio
μ, ductility

Label	E_{el} (MPa)	σ_p (MPa)	ε_p (mm/mm)	ε_{lu} (mm/mm)	ξ (-)	μ (-)	$\beta = \varepsilon_{lu}/\varepsilon_{fu}$ (-)
UCS	1510	5.19	0.0025	0.003	-	0.84	-
C-C-P-1L	3181	10.59	0.0026	0.047	2.04	3.38	1.88
C-C-P-2L	2608	13.60	0.0259	0.015	2.62	3.32	0.60
C-C-P-3L	3184	15.23	0.0279	0.023	2.93	3.65	0.92
C-D-P-1L	2321	6.97	0.0077	0.024	1.34	1.56	0.96
C-D-P-2L	1909	7.41	0.0081	0.025	1.42	1.70	1.00
C-D-P-3L	1443	10.02	0.0128	0.011	1.93	2.10	0.44

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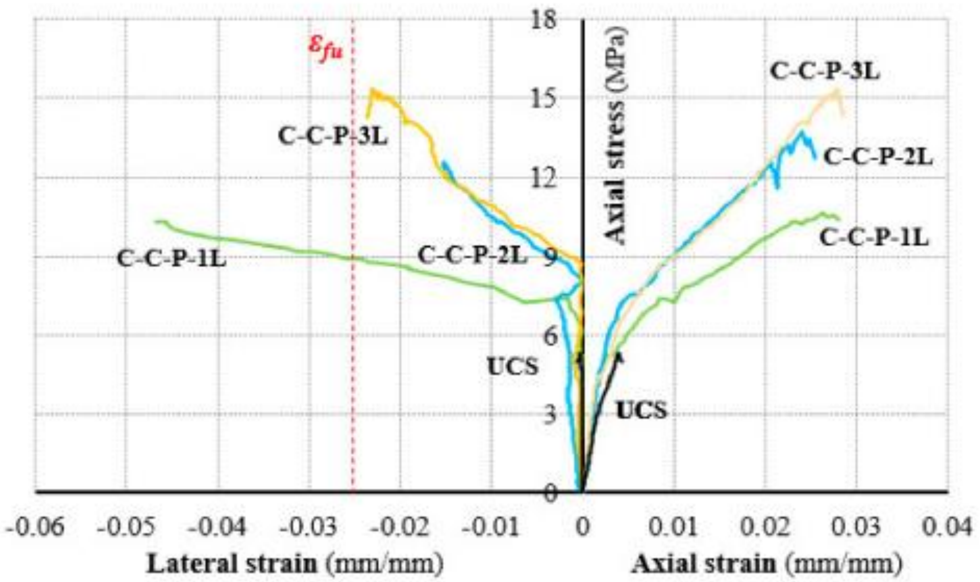
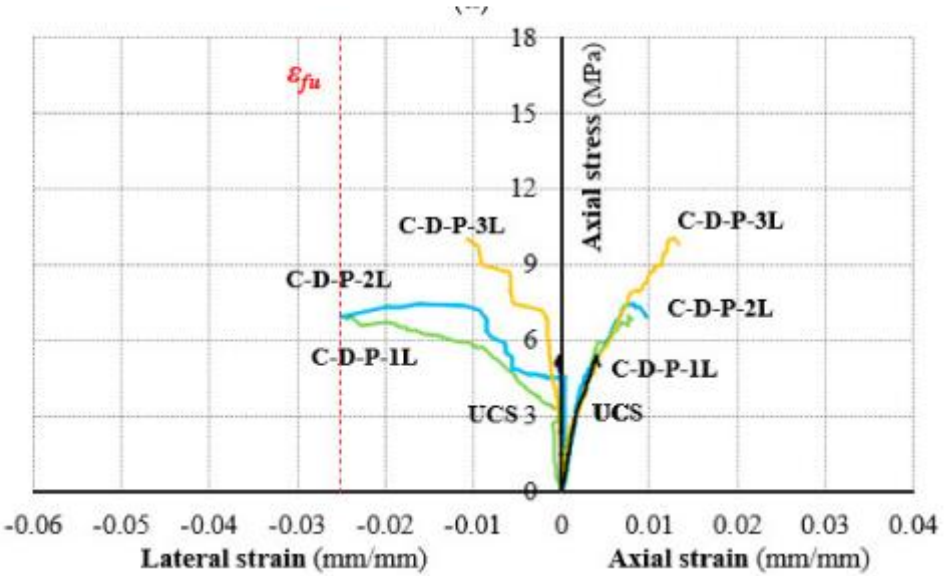
SERIES I

TEST RESULTS

Fully confined columns



Partially confined columns



In both cases the curves axial stress-strain can be approximated with a bi-linear trend. The first linear part has a slope similar to that of the un-confined masonry while the second linear part is of the hardening type with a slope affected by the number of FRCM-ply

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Failure modes

Unconfined columns: crushing of the masonry

Fully wrapped columns: the failure occurred with the formation of a wide vertical crack, mainly in correspondence with two corners, causing the rupture of the PBO textile while the masonry resulted in being extensively damaged

Partially confined columns: a vertical crack formed in the middle of the columns; then, other cracks appeared on the FRCM jackets at the overlapping zone. The unconfined part of the columns was clearly damaged. Immediately before the collapse the FRCM jacket at the mid-height of the columns opened completely at the overlapperd zone.

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MAIN RESULTS

- **the gain of the axial strength increases with the number of textile's plies**. In particular, passing from one to three layers of textile, the gain was about 50% for fully confined columns and 43% for partially confined columns.

-. **partial confinement resulted in being less effective with respect to full-confinement even if the load bearing capacity of the masonry was improved**

In particular the following considerations can be made:

Amount of textile ratio partially/fully confinement: 0,5844

Confinement ratio partially/fully wrapped columns:

1 layer	0,658
2-layers	0,545
3-layers	0,658

- the ductility index computed as the ratio (ε_{ul}-ε_{el})/ε_{el} being ε_{ul} and ε_{el} the ultimate strain and the elastic strain values, respectively, ***for fully confined columns was not influential by the number of textile's pli***es while it increases with the number of textile's plies for partially-confined columns

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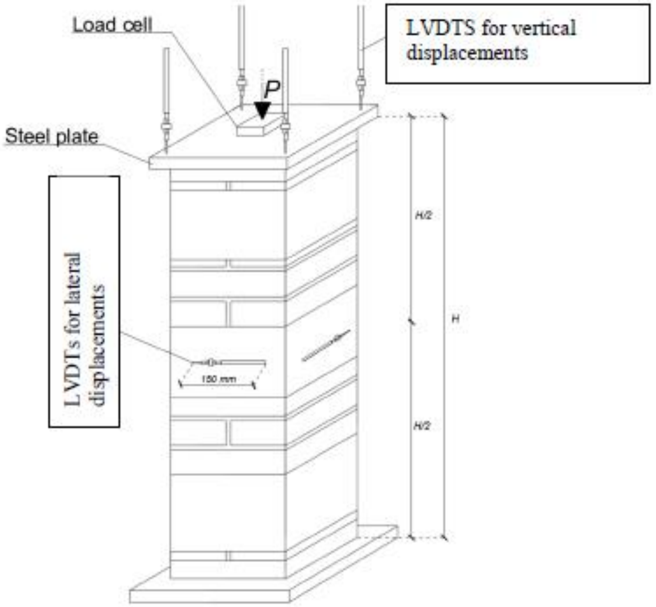
Series II*

The series refers to clay brick masonry columns with square cross section, 250 x 250 mm, and overall height 770 mm. Columns had rounded edges (radius of curvature r_c=20 mm)

Two confining system, basalt-FRCM and steel-FRCM (SRG, steel reinforced grout) were adopted; the variable parameter was the confining layers (1,2 and 3 textile layers).

For each configuration the width of the FRCM strip was set to b_f= 150 mm and the **vertical spacing ratio** was set to 0,50 (s'_f=b_f= 150 mm; s_f= 300 mm).

Tests were performed on 7 columns; one un-confined (reference column), three partially confined with basalt-FRCM and three partially confined with SRG strips.



* L. Ombres, M. Guglielmi and S. Verre (2022) «*Structural performances of clay brick masonry columns partially confined with FRCM/SRG composites*», Key Engineering Materials, Trans Tech Publication Ltd, Switzerland, Vol. 916, 297-304

DISCONTINUOUS FRCM-CONFINEMENT OF MASONRY COLUMNS

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Materials

Commercial clay brick units with dimensions 250x120x55 mm were used to built columns. The compression strength of clay brick, determined by tests on 5 units, was 56,80 MPa (C.o.V.=0,02); compression and flexural strength of the mortar used to bind the clay units, determined by standard tests were 12,85 MPa (C.o.V.=0,15) and 2,65 MPa (C.o.V.=0,05), respectively.

Both FRCM systems were commercially available. SRG consists of open meshes of twisted high-strength galavnized steel cords: the fiber density was 1200 g/m^2, the equivalent thickness 0,169 mm.
The density of the basalt textile was 400 g/m^2, the equivalent thicknees 0,064 mm.
In both system a mineral –NHL mortar containing kaolin, bauxite and hydraulic lime binder was used.

The mechanical properties of the textiles and the FRCM systems, reported in the Table , were determined by tensile tests carried out on 5 specimens according to the Italian guidelines.

Textile	Elastic modulus (GPa) (C.o.V.)	Tensile strength (MPa)(C.o.V.)	Ultimate strain (mm) (C.o.V.)
Basalt	60,70 (0,018)	0,98 (0,022)	0,018 (0,039)
Steel	200 (0,081)	3,00 (0,010)	0,019 (0,072)
FRCM	**Elastic cracked modulus** (GPa) (C.o.V.)	**Tensile strength** (MPa)(C.o.V.)	**Ultimate strain** (mm) (C.o.V.)
Basalt FRCM	37,0 (0,091)	434 (0,12)	0,018 (0,035)
SRG	141,0 (0,110)	1203 (0,29)	0,019 (0,015)

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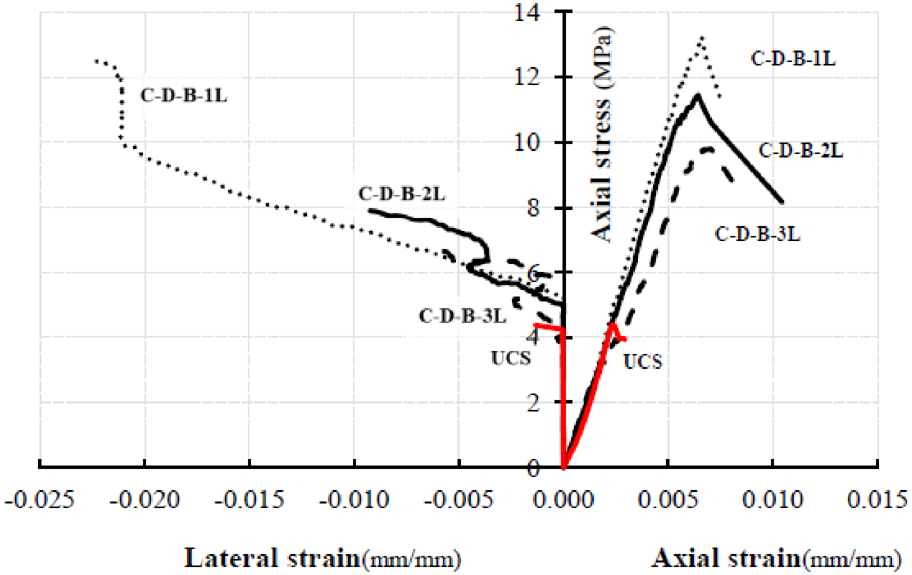
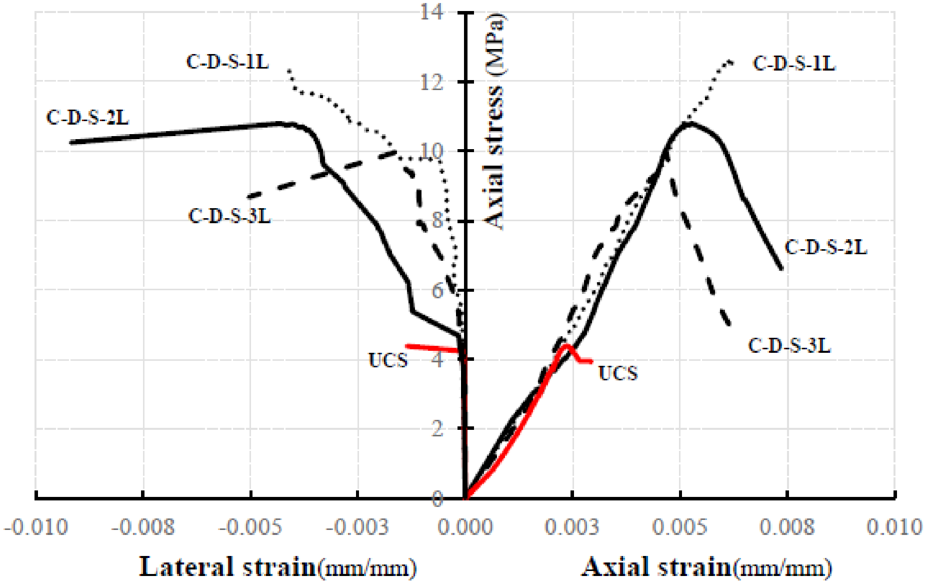
Series II*

Axial stress-axial strain and axial stress-lateral strain

Test results



Basalt FRCM-confined columns



SRG-confined columns

Series II*

Test results

The results in terms of cracking load P_{cr}, peak load, P_p, **confinement ratio $\xi = P_{pconf}/P_{punc}$**, ultimate strain, elastic modulus, E, the «*ductility index*» (energy index) $\gamma = E_{tot}/E_{peak}$ being E_{tot} the area under the stress-strain curve up to the ultimate stress and E_{tot} the one up to the peak stress.

Specimen designation	Type of fibers	P_{cr} (kN)	P_p (kN)	ξ	ε_{hmax} (mm/mm)	E (MPa)	E_{tot} (MPa mm/mm)	E_{peak} (MPa mm/mm)	γ
UCS	-	*52.78*	*273.94*	*1.00*		*1857.26*	*0.00699*	*0.00699*	*1.00*
C-D-B-1L	*Basalt*	*239.05*	*827.12*	*3.02*	*0.0223*	*2038.72*	*0.04891*	*0.04506*	*1.08*
C-D-B-2L	*Basalt*	*204.45*	*715.33*	*2.61*	*0.0092*	*2132.08*	*0.04454*	*0.03915*	*1.14*
C-D-B-3L	*Basalt*	*171.15*	*607.72*	*2.22*	*0.0062*	*1586.02*	*0.04332*	*0.03826*	*1.13*
C-D-S-1L	*Steel*	*233.17*	*789.05*	*2.88*	*0.00414*	*2196.06*	*0.04056*	*0.03867*	*1.05*
C-D-S-2L	*Steel*	*196.98*	*674.20*	*2.46*	*0.00433*	*1898.44*	*0.03007*	*0.02764*	*1.09*
C-D-S-3L	*Steel*	*157.85*	*598.60*	*2.19*	*0.00167*	*2022.83*	*0.02469*	*0.02333*	*1.06*

The confinement ratio is always higher than 1, evidencing the effectiveness of the partial confinement

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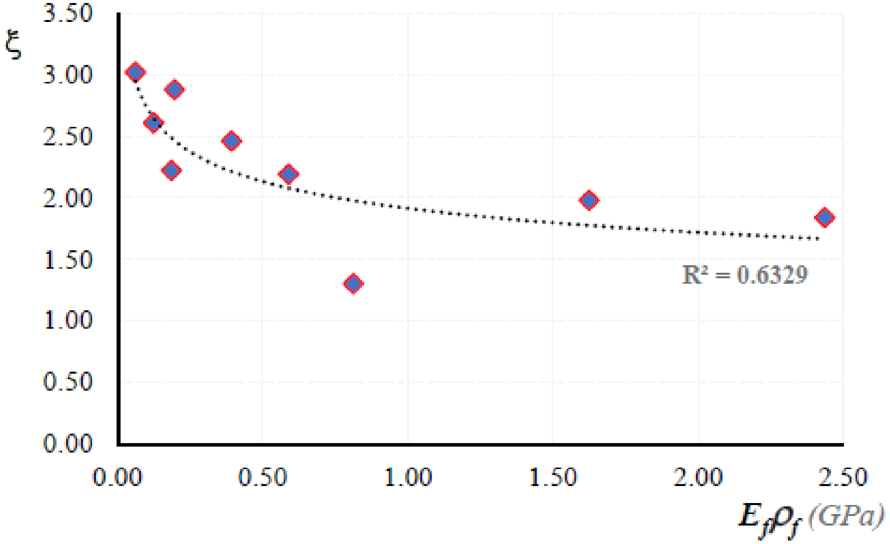
Influence of the reinforcement (number of confining layer)

Test results

Axial rigidity $E_f\rho_f$

$\rho_f = 2\,t_f b_f (b+d)/(s'_f b\,d)$ volumetric ratio of the textile

b,*d* width and height of the column's cross-section; t_f total thickness of the textile; b_f width of the confining strip; s'_f the width of the unconfined region between two consecutive strips



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Series II*

Failure modes

Test results

Basalt FRCM confined columns

1-layer confined column

2-layers confined column

<u>1-layer confined column</u>: the failure was due to the detachment of the textile in the overlap regions. A sudden detachment of the textile in the strip at the mid-height of the column occurred, followed by the crushing of the masonry.

<u>2-layers confined column</u>: the failure occurred by the detachment of the external textile layer in the strip at the mid-height of the column after the formation of vertical cracks in the un-confined regions;

<u>3-layers confined columns</u>: the failure was due to the crushing of the masonry in the un-confined region after the formation of many vertical cracks; no detachment took place in the confining strips.

DISCONTINUOUS FRCM-CONFINEMENT OF MASONRY COLUMNS

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Series II*

Failure modes

Steel FRCM confined columns

Test results

1-layer confined column

2-layers confined column

3-layers confined column

<u>1-layer confined column</u>: the failure was due to the detachment of the textile in the overlap regions. A sudden detachment of the textile in the strip at the mid-height of the column occurred, followed by the crushing of the masonry.

<u>2-layers confined column</u>: the failure occurred by the detachment of the strip at the mid-height of the column after the formation of many vertical cracks in the un-confined regions. In this region the masonry resulted excessively damaged and locally crushed; the geometric configuration of the column varied, and the load resulted eccentrically applied

<u>3-layers confined columns</u>: the un-confined region near the top of the column was strongly damaged until the crushing of the masonry. Even if damaged, all strips remained active until collapse.

Series II*

Test results

Main results

- the partial confinement is effective both in terms of strength and ductility;
- the stress-strain behavior of the confined columns is influenced from the rigidity of the confining FRCM strips. The 1-layer confined columns exhibited good performances and a stress-strain curve with ascending branches; increasing the number of confining layers, earlier failures manifested and the stress-strain curves shown a strain softening branch;
- the **vertical spacing ratio** strongly influences the structural behavior of partially FRCM confined masonry columns;
- **increasing the rigidity of the FRCM system (i.e. incresing the number of confining layers) the strength of confined masonry decreases while the ultimate strain increases**. This unexpected result depends on the high vertical spacing ratio ζ which reduces the effectiveness of the unconfined region due to arch-like shape cracks.

DISCONTINUOUS FRCM-CONFINEMENT OF MASONRY COLUMNS

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Series III*

Tests were carried out on small-size clay brick masonry columns confined with PBO FRCM composites.

Parameter variable was the vertical spacing ratio $\xi = s'_f/s_f$ and the confinement configuration (full and partial confinement).

A single-layer of PBO textile was used for all tested columns. Each PBO-FRCM strips has the width set to 55 mm.

The volumetric ratio V_f/V_{f0} is the ratio between the volume of fibers used in partially confined columns and V_{f0} the volume of fibers in fully confined columns

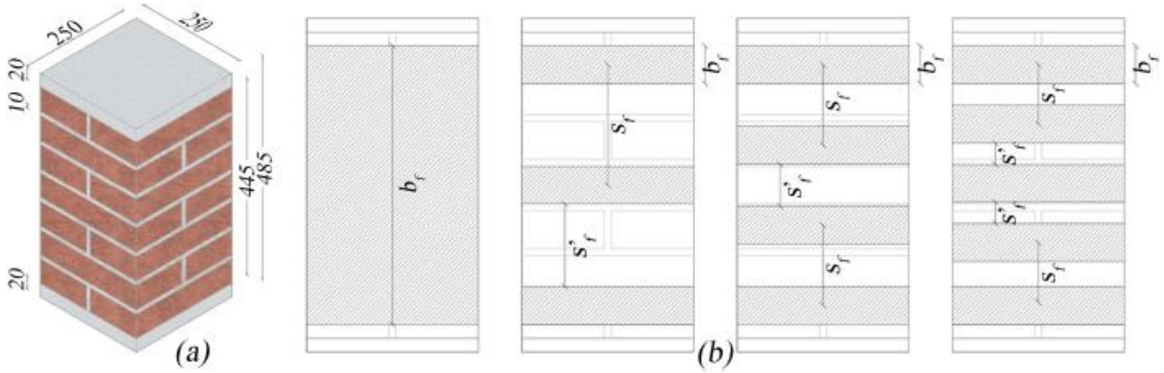

Figure 1. (**a**) Geometry of the specimens (dimensions are in mm) and (**b**) configuration of the confinement: from left to right $\zeta = 0$ (fully wrapped), $\zeta = 0.68$, $\zeta = 0.52$, $\zeta = 0.36$, respectively.

Table 1. Geometrical details of tested columns.

Specimen Designation	Type of Confinement	b_f (mm)	s'_f (mm)	s_f (mm)	$\zeta = s_f'/s_f$ (-)	s'_f/b_f (-)	V_f/V_{f0}
UCS (I)	–	–	–	–	–	–	-
UCS (II)	–	–	–	–	–	–	-
CC1L-PBO (I)	Continuous	445	0.0	–	0	0	1.0
CC1L-PBO (II)	Continuous	445	0.0	–	0	0	1.0
CD1L-PBO3 (I)	Discontinuous	55	120.0	135.0	0.89	2.18	0.32
CD1L-PBO3 (II)	Discontinuous	55	120.0	135.0	0.89	2.18	0.32
CD1L-PBO4 (I)	Discontinuous	55	61.7	116.7	0.53	1.12	0.48
CD1L-PBO4 (II)	Discontinuous	55	61.7	116.7	0.53	1.12	0.48
CD1L-PBO5 (I)	Discontinuous	55	32.5	87.5	0.37	0.59	0.60
CD1L-PBO5 (II)	Discontinuous	55	32.5	87.5	0.37	0.59	0.60

* L. Ombres, F. Campolongo, M. Guglielmi, S. Verre (2023). Experimental analysis of the mechanical response of masonry columns partially confined with PBO FRCM (Fabric Reinforced Cementititous Mortar). *Materials*, 16,4812

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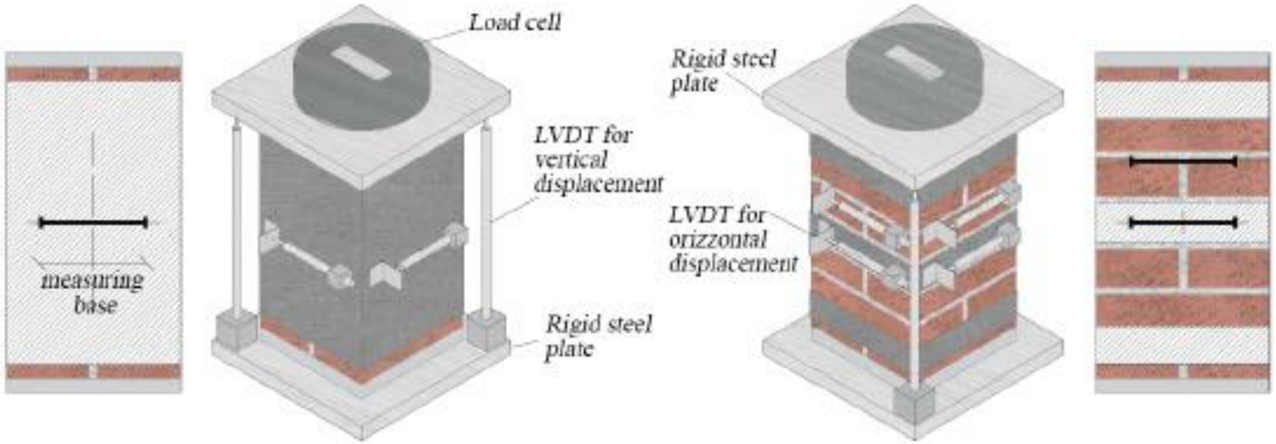
Test set-up



Tests were conducted in displacement control at a rate of 0,2 mm/min

LVDTs with a gauge length of 150 mm were used to measure the lateral displacements in correspondence of the FRCM jacket at the mid-height of the column and in the adiacent un-confined zone

PBO textile: bidirectional unbalanced mesh equivalent thickness: 0,046 mm (longitudinal direction); 00012 mm(transversal direction)

Mechanical properties

Textile	Elastic modulus (GPa) (C.o.V.)	Tensile strength (MPa)(C.o.V.)	Ultimate strain (mm) (C.o.V.)
PBO	218,00(0,055)	3409(0,13)	0,0156 (0,13)
FRCM	Elastic cracked modulus (GPa) (C.o.V.)	Tensile strength (MPa)(C.o.V.)	Ultimate strain (mm) (C.o.V.)
PBO FRCM	115,00 (0,07)	1434 (0,18)	0,0125 (0,28)

Mortar: compression strength f_{cm}= 24,8 Mpa

Commercial clay brick units with dimensions 250x120x55 mm were used to built columns. The compression strength of clay brick, determined by tests on 6 units, was 28,30 MPa (C.o.V.=0,02); compression and flexural strength of the mortar used to bind the clay units, determined by standard tests were 5,20 MPa (C.o.V.=0,04) and 1,90 MPa (C.o.V.=0,04), respectively.

Series III*

Failure modes

Test results

Unconfined columns

Crushing of the masonry in one of the upper corners of the columns. A sub-vertical crack formed along the height of the columns and numerous wide cracks developed near the zone where the crushing occurred

Fully confined columns

The failure was due to the masonry crushing after the FRCM jacket detachment that occurred at the corner of the columns in correspondence with the overlap of the jackets.

DISCONTINUOUS FRCM-CONFINEMENT OF MASONRY COLUMNS

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Series III*

Failure modes

Test results

Partially confined columns

At failure the FRCM-free regions (un-confined) were crushed (arching effect) while the confined ones induced the corner failure.
Vertical cracks formed initially at the mid- height of the columns; then the crack pattern of the masonry extended to the entire un-confined zone and a series of vertical cracks began to appear on the composite jackets, particularly in the overlap zone.

The higher the number of FRCM jackets (i.e. the lower vertical spacing ratio) the more the failure was dominated by the corner effect .

For high value of the vertical spacing ratio the arching effect takes place and the failure occurred in the un-confined zone by crushing of the masonry ; the FRCM jackets resulted damaged but no detachment was observed.

For low values of the vertical spacing ratio, the failure occurred by the detachment of the FRCM jackets at the corners; the un-confined masonry suffered limited damages

Series III*

Test results

Peak loads, strain and ductility

Specimen Designation	Axial Peak Load (kN)	Average Axial Peak Load (%Scatter) (kN)	Confinement Ratio ξ (-)	Axial Peak Strain ε_{peak} (-)	Ultimate Axial Strain ε_u (-)	Ductility Index μ (-)	Elastic Modulus E_{mas} (MPa)
UCS (I)	737.16	765.45 (7.1)	-	0.01134	0.01368	1.206	1110.70
UCS (II)	793.75		-	0.01488	0.01780	1.196	1441.10
CC1L-PBO (I)	1463.76	1453.76 (1.4)	1.910	0.01853	0.0237	1.279	1749.50
CC1L-PBO (II)	1443.75		1.886	0.02299	0.02768	1.314	2122.70
CD1L-PBO3 (I)	1137.48	1137.52 (0.0)	1.486	0.01532	0.01892	1.235	1457.50
CD1L-PBO3 (II)	1137.56		1.486	0.01426	0.01530	1.073	1581.10
CD1L-PBO4 (I)	1203.76	1223.71 (3.2)	1.572	0.01353	0.01566	1.157	1570.40
CD1L-PBO4 (II)	1243.67		1.625	0.01494	0.01718	1.150	1816.20
CD1L-PBO5 (I)	1290.36	1263.94 (4.1)	1.686	0.01355	0.01702	1.256	1616.70
CD1L-PBO5 (II)	1237.52		1.617	0.01317	0.01676	1.272	2093.30

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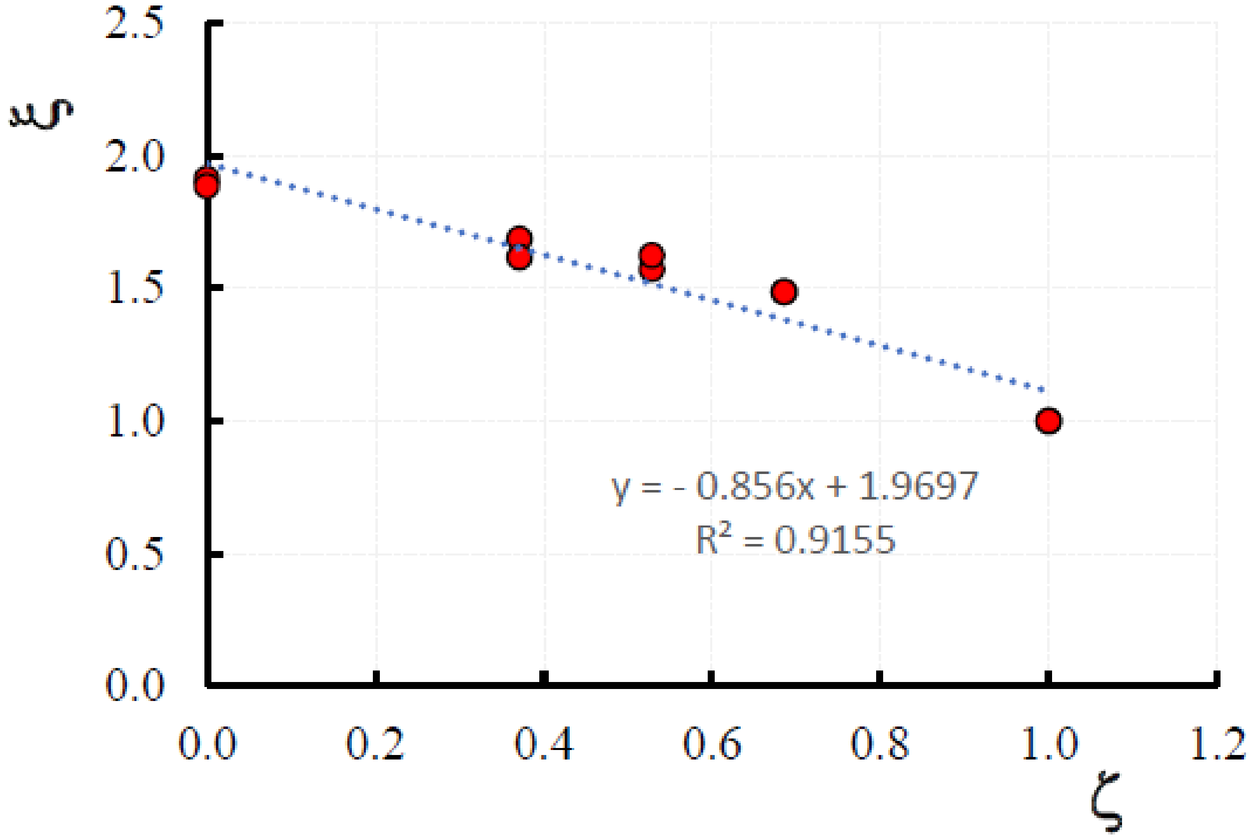
Series III*

Test results

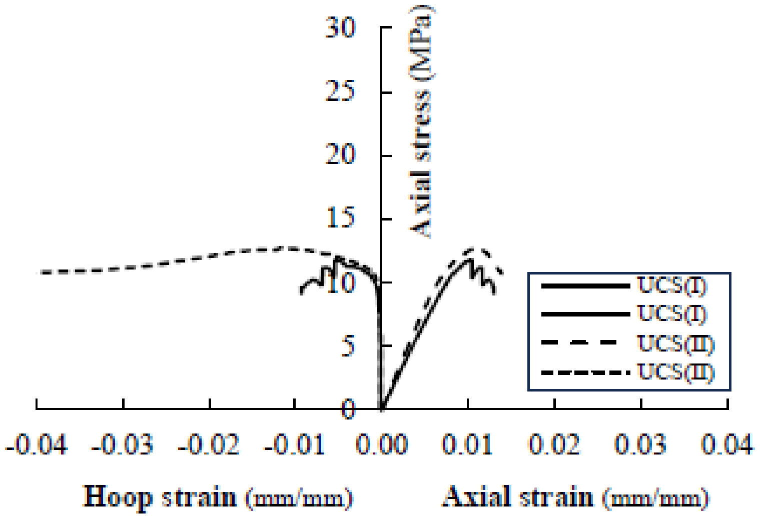
Peak loads, strain and ductility



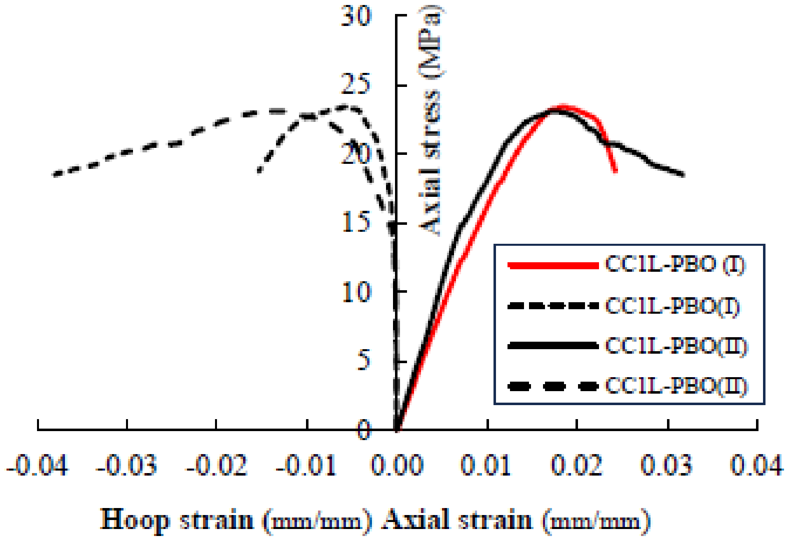
Series III*

Test results

Axial stress-strain curves



Un-confined columns



Fully confined columns

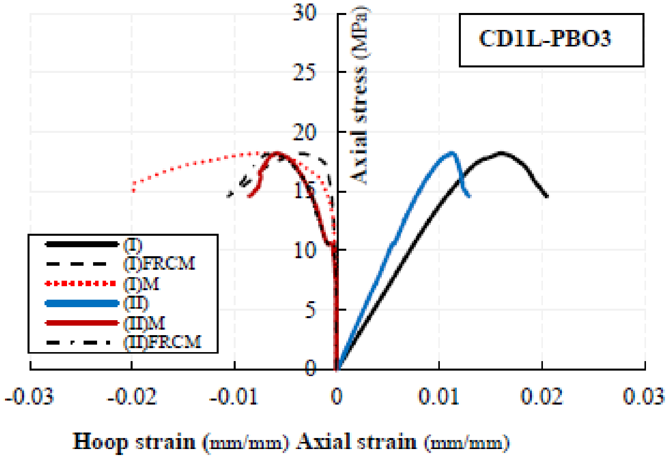
DISCONTINUOUS FRCM-CONFINEMENT OF MASONRY COLUMNS

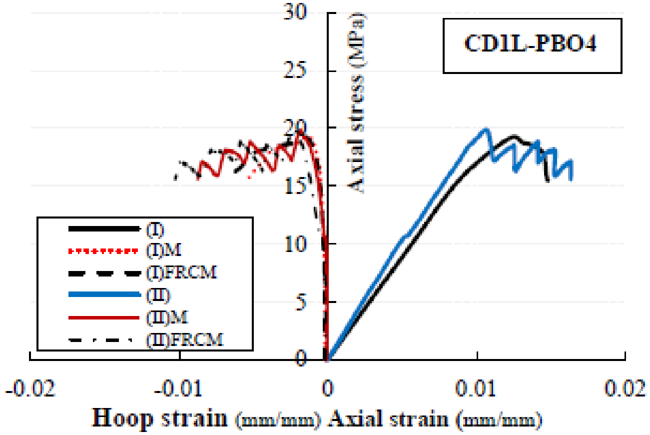
L. Ombres

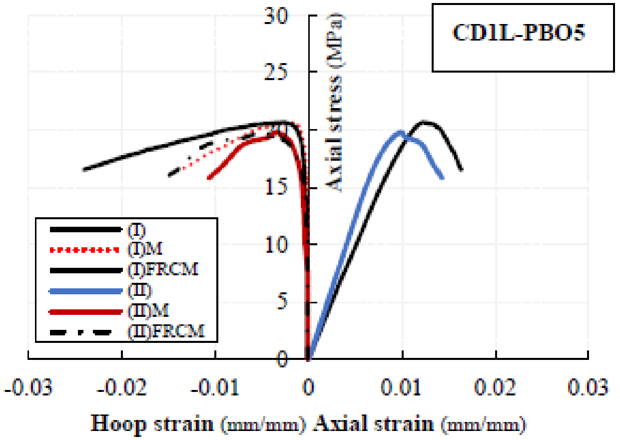
Series III*

Test results

Axial stress-strain curves





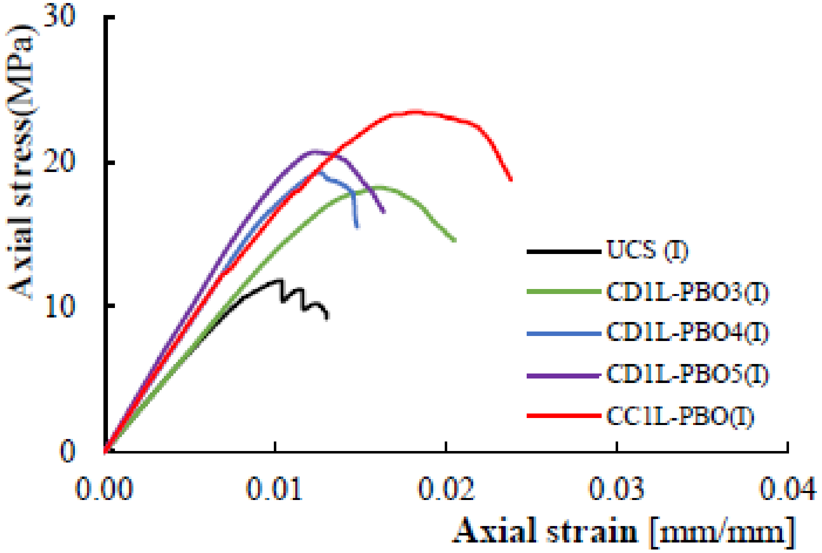


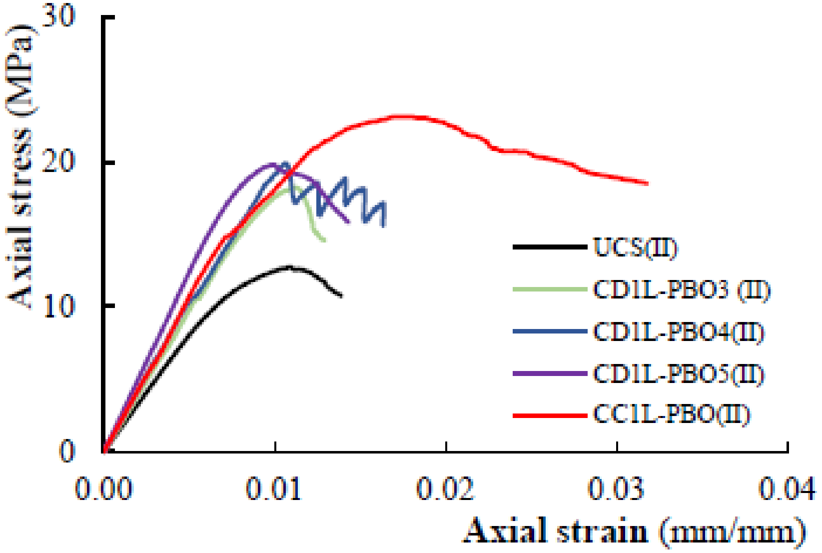
Partially confined columns

Series III*

Test results

Axial stress- axial strain curves





The comparison between curves varying the vertical spacing ratio, evidences that: the initial linear behavior of the confined columns (both fully and partially confined) follows that of the unconfined columnsas the axial stress reaches the masonry strength the behavior of the confined columns becomes non-linear until the peak stress.

After the peak stress

- un-confined columns evidence a strong reduction of the stiffness and a fragile rupture (no softening);
- the behavior of the fully confined columns is described by a plateau followed by a softening branch;
- a typical softening branch has been observed for partially confined columns

DISCONTINUOUS FRCM-CONFINEMENT OF MASONRY COLUMNS

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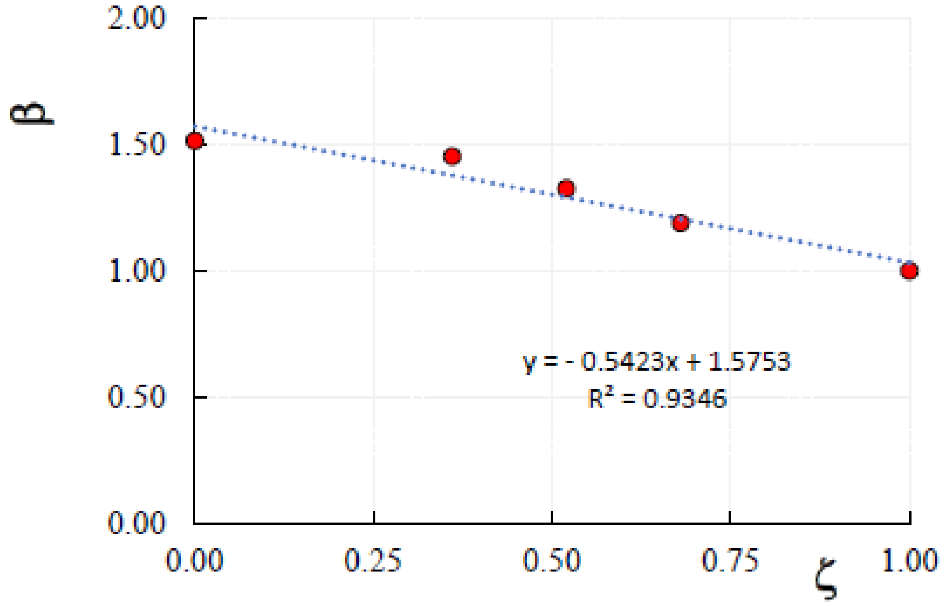
Test results

$$\beta = E_{confmas} / E_{uncma}$$



The elastic modulus was calculated by the slope of the axial stress-axial strain curves from 5 to 40% of the maximum axial stress.

The variation of the elastic modulus corresponds to that of the stiffness of the confined columns.
The elastic modulus in partially confined columns reduced from 4.1% to 21.5% .
These reductions are related to the cracking patterns that occurred in the un-confined area of the columns.

The reduction of the stiffness with the volume ratio, evidences that even with large reductions in the amount of the textile, it was small (for ζ=0,59, V_f/V_{f0}=0,60 the reduction was 21,5%)

DISCONTINUOUS FRCM-CONFINEMENT OF MASONRY COLUMNS

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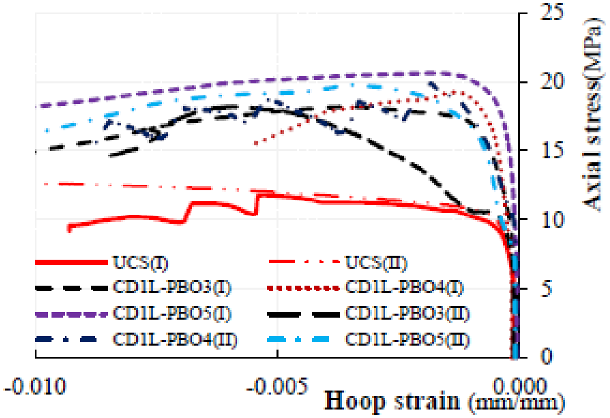
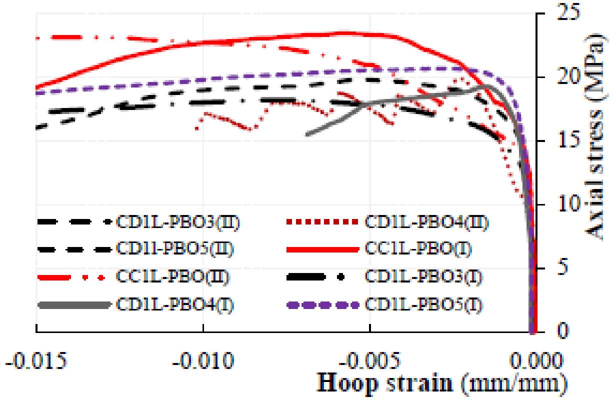
Test results

Axial stress-Hoop strain (Partially confined columns)



Confined zone



Un-confined zone

The hoop strains were recorded during tests by horizontal LVDTs; these measurement, however, are reliable in the un-cracked stage of the masonry. After cracking they are strongly influenced from the cracks; it means that in the post-peak stage they are not reliable. Consequently the maximum value of the hoop strain has to be considered in correspondence of the maximum stress.

For low load values the stress-strain curves are characterized by an almost linear trend; in this stage the columns are un-cracked and the confinement is not activated. After the crack formation the dilation of the masonry activates the confinement of the FRCM jackets and a progressive increase of both tensile stress in the composites and confining stress in the masonry occur. When the FRCM is fully activated (i.e. after the peak strength is reached), the confinement stress varies with the stiffness of the FRCM jacket. However due to the damage in the un-confined zones, the strength decreases as the strain increases (softening phase).

DISCONTINUOUS FRCM-CONFINEMENT OF MASONRY COLUMNS

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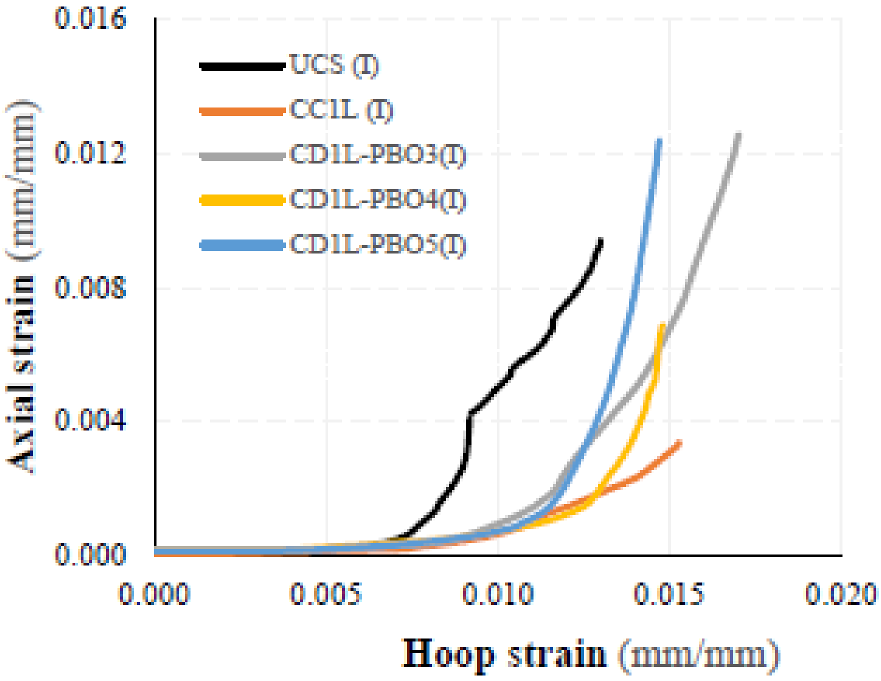
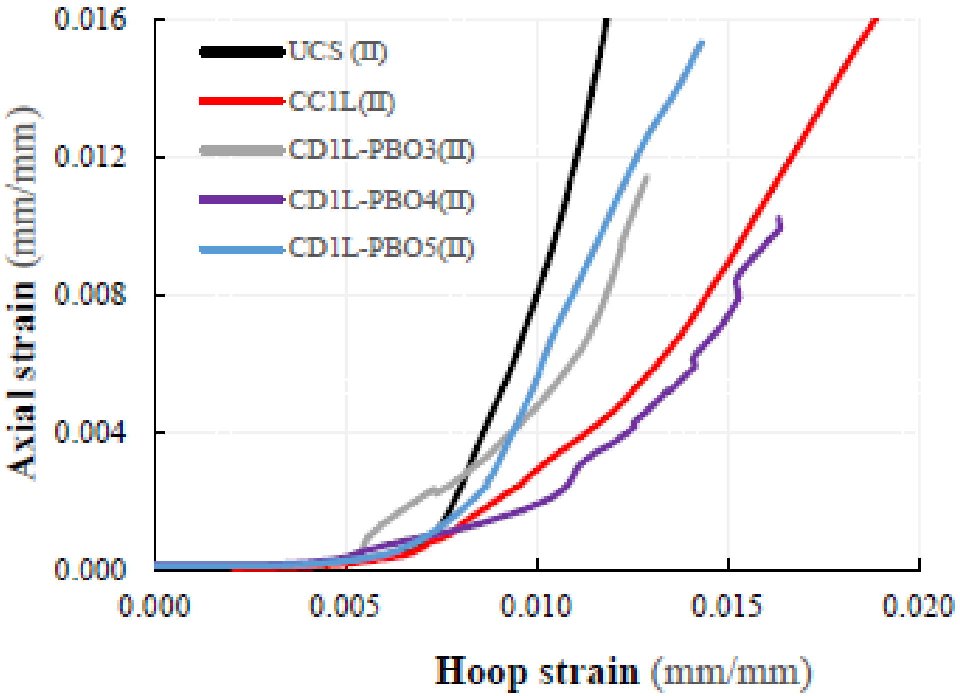
Series III*

Test results





DISCONTINUOUS FRCM-CONFINEMENT OF MASONRY COLUMNS

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Series III*

Test results

Specimen Designation	Hoop Strain in Confined Zone ε_{hFRCM} (mm/mm)	Hoop Strain in Unconfined Zone ε_{hmas} (mm/mm)	Exploitation Ratio $\varepsilon_{hFRCM}/\varepsilon_{fu}$ (-)
UCS (I)	-	0.05584	-
UCS (II)	-	0.01135	-
CC1L-PBO (I)	0.00567	-	0.363
CC1L-PBO (II)	0.01347	-	0.863
CD1L-PBO3 (I)	0.00700	0.00400	0.449
CD1L-PBO3 (II)	0.00642	0.00588	0.411
CD1L-PBO4 (I)	0.00149	0.00130	0.096
CD1L-PBO4 (II)	0.00230	0.00184	0.147
CD1L-PBO5 (I)	0.00115	0.00185	0.074
CD1L-PBO5 (II)	0.00500	0.00300	0.321

The exploitation ratio allows for the evaluation of the potential confining action of the FRCM jackets.
The obtained values (lesser than 0,5) evidence that the confining effectiveness did not seems to be used at all, especisally for low values of the vertical spacing ratio

DISCONTINUOUS FRCM-CONFINEMENT OF MASONRY COLUMNS

L. Ombres

Series IV*

In this experimental series small-size masonry column partially confined with PBO-FRCM were tested under axial compression load.
The parameter varied was the confinement configuration (i.e. the vertical spacing ratio); differently to the previous investigations in this series of tests the amount of textile was keep constant.

Twelve specimens were manufactures, two un-confined and ten partially confined with different configurations as illustrated in the Table

Column	No of FRCM jackets	s'_f	s_f	b_f	ζ
URM 01	0	-	-	-	-
URM 02	0	-	-	-	-
2 strips 01	2	145,00	295,00	150	0,492
2 strips 02	2	145,00	295,00	150	0,492
3 strips 01	3	72,50	172,50	100	0,421
3 strips 02	3	72,50	172,50	100	0,421
4 strips 01	4	48,33	123,3	75	0,392
4 strips 02	4	48,33	123,33	75	0,392
5 strips 01	5	36,25	96,25	60	0,376
5 strips 02	5	36,25	96,25	60	0,376
6 strips 01	6	29,00	79,00	50	0,367
6 strips 02	6	29,00	79,00	50	0,367

Test set up

DISCONTINUOUS FRCM-CONFINEMENT OF MASONRY COLUMNS

L. Ombres

Series IV*

Test results

Failure mode

Un-confined columns maifested the crushing failure of the masonry. Vertical cracks formed in all four lateral faces of the columns

Confined columns: masonry crush was visible especially in case of higher values of the vertical spacing ratio. The FRCM jackets exhibited multiple transversal cracks being the corner-cracks the most evident. Sliding and detachment were also observed in the post-peak behavior of the columns.

All columns reached a strength increment. It should be remarked that the 2,3 and 4 configuration produced a comparable averaged strength gain . The increase of strength in columns confined with 5 and 6 jackets was significant (35-38%).
Consequently, the typical correspondence between the effective confined volume and the strength gain was not met. It means that the strength gain is not proportional to the amount of textile used in the confinement (in this case it was the same for all tested columns).

The peak strain was almost comparable for each specimen.

Label	Peak stress [MPa]		Δ Strength [%]	Peak strain [%]		Maximum strain [%]	
URM 01	11.79	12.26	0	1.04	1.06	1.31	1.35
URM 02	12.73			1.07		1.39	
2 strips 01	14.15	14.58	19	1.13	1.11	1.35	1.32
2 strips 02	15.01			1.09		1.28	
3 strips 01	15.03	14.71	20	1.38	1.19	1.88	1.79
3 strips 02	14.39			0.99		1.69	
4 strips 01	13.06	13.02	6	0.86	0.98	1.11	1.29
4 strips 02	12.98			1.10		1.46	
5 strips 01	16.52	16.90	38	1.10	1.12	1.42	1.40
5 strips 02	17.28			1.13		1.37	
6 strips 01	17.38	16.59	35	1.15	1.16	1.61	1.57
6 strips 02	15.80			1.17		1.53	

DISCONTINUOUS FRCM-CONFINEMENT OF MASONRY COLUMNS

L. Ombres

Series IV*

Test results

UCS (I)

CD1L-PBO3 (I)

CD1L-PBO4(I)

CD1L-PBO5 (I)

CC1L-PBO(I)

UCS (II)

CD1L-PBO3(II)

CD1L-PBO4(II)

CD1L-PBO5(II)

CC1L-PBO(II)

DISCONTINUOUS FRCM-CONFINEMENT OF MASONRY COLUMNS

L. Ombres

Series IV*

Test results

Damage patters for the confined cross-section of the columns

2 strips | 3 strips | 4 strips | 5 strips | 6 strips

The observation of the arching effect in the cross-section of the confined columns evidences a manifest trend in the horizontal efficiency of the confinement. The damage plan, in fact, describes four parabolas just in case of 5 and 6 strips (i.e. lower vertical spacing ratio) while partial or null arching failure was noticeable for columns confined with 4,3 and 2 FRCM strips (i.e. higher vertical spacing ratio).

A plausible explanation of this result is related to the vertical spacing ratio values; for higher values of the vertical spacing ratio, the unconfined masonry zone deforms more than the confined ones and then the plan corresponding to the confined zones has a greater possibility of hunching over and therefore not remaining flat. Consequently the lateral confinement pressure is no longer uniform and the arching effect does not manifest or manifest partially.

DISCONTINUOUS FRCM-CONFINEMENT OF MASONRY COLUMNS
L. Ombres

Series IV*

Test results

In addition the FRCM strips were damaged differently due to the non-uniformity of the confining pressure which it is able to exert because the tensions concentrated in the corners of the cross-section are not equal to each other. These inhomogeneities affect negatively the effectiveness of the confinement. On the other hand, when the vertical spacing ratio is low (the strips are closer together›), the unconfined protion of the masonry deforms moderately and continues to support the confined portion which therefore mantains the cross-section flat. Whereby, hunching does not occur and the confinement pressure is more uniform that means more effective.

Larger space between the FRCM strips compromised the confining pressure's work in counteracting the lateral expansion of the column subject to axial load.

In agreement to this, the failure mode evidenced that the confining pressure was uniform in four corners just in the case of low-spacing since the arching effect clearly exhibited in the cross-section.

ANALYTICAL INVESTIGATION

Currently the analytical models proposed to predict the axial strength of FRCM confined masonry columns refer to fully confined configurations. Even if derived from different approaches, prediction models present a non-linear form and differences between them in evaluating the effective confining pressure.

Two main design codes were considered in this analysis: the Italian CNR DT-215/2018 and the American Concrete Institute –ACI 549,4R-20 guidelines.

The models are founded on the following equations

DISCONTINUOUS FRCM-CONFINEMENT OF MASONRY COLUMNS

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CNR-DT 215/18

$$\frac{f_{mc}}{f_{m0}} = 1 + k\left(\frac{f_{l,eff}}{f_{m0}}\right)^{0.5}$$

$$k = \alpha_2\,(g_m/1000)^{\alpha 3}$$

$$f_{l,eff} = k_H f_l$$

$$\text{being } f_l = \frac{2n_f t_f E_f \varepsilon_{fred}}{max(h,b)}\,\frac{b_f}{s'_f}$$

$$\text{and } k_H = 1 - \frac{(b-2r)^2 + (h-2r)^2}{3bh}$$

$$\varepsilon_{fred} = \min\left[k_{mat}\eta_a\frac{\varepsilon_{fu}}{\gamma_m};0.004\right]$$

$$k_{mat} = 1.81(\rho_{mat} f_{cmat}/f_{m0})^2$$

$$\rho_{mat} = 4t_{mat}/D$$

ACI 549R-20

$$\frac{f_{mc}}{f_{m0}} = 1 + 3.1k_a\left(\frac{f_l}{f_{m0}}\right)$$

$$k_a = \frac{A_e}{A_c}\left(\frac{b}{h}\right)^2$$

$$f_l = \frac{2n_f t_f E_f \varepsilon_{fe}}{D}$$

$$\frac{A_e}{A_c} = 1 - \frac{\left(\frac{b}{h}\right)(b-2r)^2 + \left(\frac{h}{b}\right)(h-2r)^2}{3bh}$$

$$\varepsilon_{fe} = \varepsilon_{fd} < 0.012$$

f_{mc}=compression strength of the confined masonry;
f_{m0}=compression strength of the un-confined masonry;
f_{m0}=compression strength of the mortar (FRCM);
g_m=mass density of the masonry;
n_f= number of textile's plies;
t_f= thickness of the textile (mm);
b,h= length and width of the cross-section of the column(mm);
r=radius of the rounding corner of the column (mm);
α_2, α_3 coefficients set equal to 1,0 if experimental results are not available to justify different assumptions ;
t_{mat}= thickness of the mortar (FRCM);
η_a= environmental factor (tahken as 1 in this study);
η_m= partial safety factor (taken as 1 in this study)

Two models refer to fully confined masonry columns; no provisions are given for partially confined masonry columns.
In order to take partial confinement into account in this analysis the «**vertial coefficient of efficiency**» provided by the CNR DT200 guideline for evaluating the strength of concrete columns confined with FRP jackets is used:

$$k_v = \left(1 - \frac{s'_f}{2\mathrm{d}_{min}}\right)^2$$

being d_{min}= min (b,h).

Consequently the equations of the considered models become

$$\frac{f_{mc}}{f_{m0}} = 1 + k\left(\frac{k_v f_{l,eff}}{f_{m0}}\right)^{0.5}$$ CNR DT 215/18 model

$$\frac{f_{mc}}{f_{m0}} = 1 + 3.1 k_a k_v \left(\frac{f_l}{f_{m0}}\right)$$ ACI -459-R20 model

Specimen	CNR-DT215	ACI 549-R20	Pred/Exp CNR-DT215	Pred/Exp ACI549-R20	Experimental
CC1L-PBO (I)	1.0575	1.0093	0.5537	0.5282	1.910
CC1L-PBO (II)	1.0575	1.0093	0.5607	0.5350	1.886
CD1L-PBO3 (I)	1.0352	1.0052	0.6966	0.6764	1.486
CD1L-PBO3 (II)	1.0352	1.0052	0.6966	0.6764	1.486
CD1L-PBO4 (I)	1.0566	1.0069	0.6721	0.6405	1.572
CD1L-PBO4 (II)	1.0566	1.0069	0.6502	0.6196	1.625
CD1L-PBO5 (I)	1.0832	1.0078	0.6425	0.5978	1.686
CD1L-PBO5 (II)	1.0832	1.0078	0.6425	0.6233	1.617

Codes predictions are conservative

Improvement of the CNR DT-215 model

An estimation of the coefficients α_2 and α_3 founded on available experimental results, for clay brick masonry with g_m=1600 kg/m^3 as those used in the present experimentations, furnishes the following values α_2 = 3,5 and α_3 = 4,6

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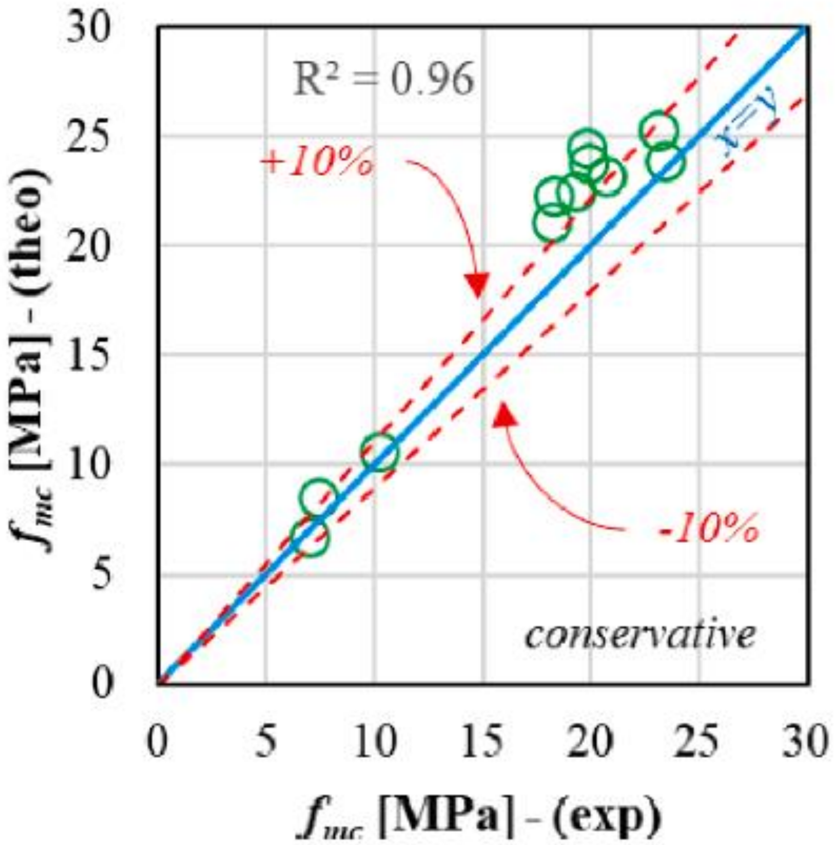
Specimen	CNR DT 215 prediction, $f_{mc\ pred}$ (MPa)	Experimental results, $f_{mc\ exp}$ (MPa)	$f_{mc\ pred}/f_{mc\ exp}$
CC1L-PBO(I)	24,64	23,41	1,052
CC1L-PBO(II)	24,64	23,10	1,067
CD1L-PBO5(I)	23,87	20,64	1,156
CD1L-PBO5(II)	23,87	19,77	1,207
CD1L-PBO4(I)	23,13	19,26	1,200
CD1L-PBO4(II)	23,13	19,88	1,163
CD1L-PBO3(I)	21,73	18,19	1,195
CD1L-PBO3(II)	21,73	18,22	1,193
CDP-1L	6,75	6,97	0,968
CDP-2L	8,51	7,41	1,148
CDP-3L	10,61	10,20	1,040



PROPOSED DESIGN-ORIENTED MODEL

The analysis of experimental results evidences that the stiffness of the confined columns varies as the geometric configuraions of the partial confinement changes.

Accordingly a new parameter, $\mathbf{k_E}$, is introduced in the relationship used to calculate the effective lateral pressure of the confined columns.

$$f_{l,eff} = k_{eff} \bullet f_l = k_H \bullet k_v \bullet k_E \bullet f_l$$

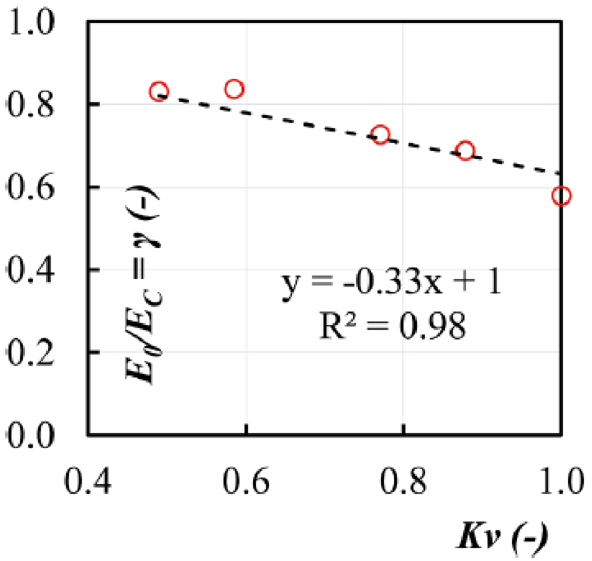
Being the stiffness is represented by the value of the elastic modulus E, the coefficient $\mathbf{k_E}$ is expressed as

$$k_E = (1-\gamma)^{\beta}$$

$$\gamma = \frac{E_0}{E_c}$$

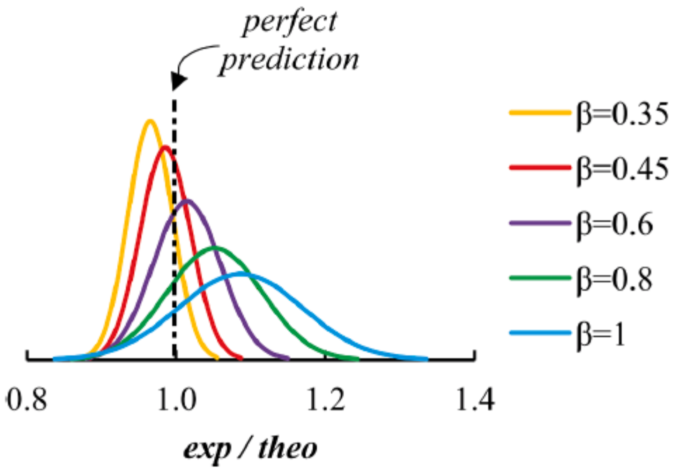
where E_0 and E_c are the elastic moduli of the un-confined and confined columns.

In Figure is reported the variation of E_0/E_c versus k_v for the tested PBO FRCM partially confined columns



$$\gamma = -0.33K_V + 1$$

The calibration of the β-coefficient was made by a best fitting of the experimental results in terms of probability density function of the experimental/theoretical ratio.



The best performances is obtained for **β=0,45**

DISCONTINUOUS FRCM-CONFINEMENT OF MASONRY COLUMNS

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Therefore $k_E = (0{,}33\, k_v)^{0{,}45}$

$$f_{l,eff} = k_{eff} \bullet f_l = k_H \bullet k_v \bullet k_E \bullet f_l$$

$$\frac{f_{mc}}{f_{m0}} = 1 + k\left(\frac{f_{l,eff}}{f_{m0}}\right)^{0.5}$$

$$f_l = \frac{2 \bullet n_f \bullet t_f \bullet E_f \bullet \varepsilon_{fd,rid}}{D}$$

$$\varepsilon_{fd,rid} = \min\left(k_{mat} \bullet \eta_a \bullet \frac{\varepsilon_{fu}}{\gamma_m}; 0,004\right)$$

$$k_{mat} = \alpha_1\left(\rho_{mat} \bullet \frac{f_{c,mat}}{f_{md}}\right)^2 \le 1$$

$$\rho_{mat} = \frac{4 \bullet t_{mat}}{D}$$

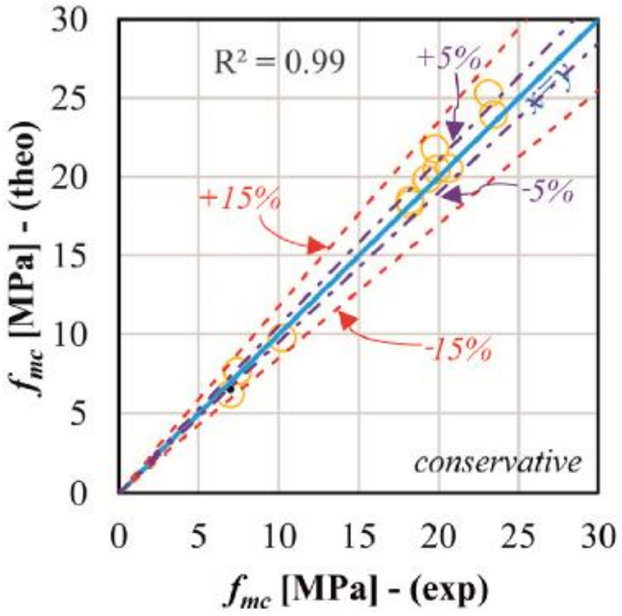
$$f_{l,eff} = k_{eff} \bullet f_l = k_H \bullet k_v \bullet f_l$$

$$k_H = 1 - \frac{b'^2 + h'^2}{3 \bullet A_m}$$

$$A_m = b \bullet h$$

$$k_v = \left(1 - \frac{p_f'}{2 \bullet D}\right)^2$$

Specimen	Proposed model prediction, $f_{mc\,pred}$ (MPa)	Experimental results, $f_{mc\,exp}$ (MPa)	$f_{mc\,pred}/f_{mc\,exp}$
CC1L-PBO(I)	24,64	23,41	1,052
CC1L-PBO(II)	24,64	23,10	1,067
CD1L-PBO5(I)	20,25	20,64	0,981
CD1L-PBO5(II)	20,25	19,77	1,204
CD1L-PBO4(I)	19,23	19,26	0,998
CD1L-PBO4(II)	19,23	19,88	0,967
CD1L-PBO3(I)	17,50	18,19	0,962
CD1L-PBO3(II)	17,50	18,22	0,960
CDP-1L	6,24	6,97	0,895
CDP-2L	7,69	7,41	1,038
CDP-3L	9,77	10,20	0,958



The proposed model is able to improve the predictions of the axial strength of the partially PBO FRCM confined masonry columns. Further investigations is needed to confirm the proposed design-oriented model by varying the number of textile layers, the types of fibers and type of masonry.