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Behavior of masonry columns repaired using small diameter cords

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Abstract. The innovative technique here illustrated is the result of historical evolution of ancient systems of hooping and is conditioned by design criteria that take into account the structural life in the respect of existing elements. It consists in the application of small diameter cords able to provide overlapping hoops at every course over the entire height of the column. Three series of uniaxial compression tests, with a total of 22 specimens, were conducted on model brick masonry columns with these variables: cross-section geometry, amount and scheme of confining reinforcement. Laboratory outcomes have shown how the investigated confining systems are able to provide significant gains in terms of compressive strength. Test results have been finally used to assess the reliability of the existing design equations suggested by Italian National Research Council for design of FRP strengthening of masonry columns.

Introduction

Structural enhancement of masonry elements, built with natural stones or clay bricks, is frequently needed; in particular, compressed members, as columns, are prone to brittle failure under seismic forces or static overloads. Recent earthquakes in Molise (2002), Umbria (2009), Abruzzo (2009) and Emilia-Romagna (2012) have demonstrated that masonry structures are extremely susceptible to the forces imposed during such events [1], [2]. Thus, there is an urgent need to upgrade these deficient masonry elements to meet the current design standards in seismic regions.

Steel jacketing and reinforced concrete have been extensively used in Europe, particularly Italy, to retrofit the masonry columns and have proved to be effective, but have some drawbacks [3], [4]. Such techniques are in fact often time consuming to apply, not cost-effective and add mass to the structure. Such problems have led researchers to investigate new retrofit solutions using innovative materials such as Fiber Reinforced Polymers (FRP) or Steel fiber-Reinforced Polymer (SRP) composites in the form of bonded surface reinforcements [5], [6], [7], [8], [9], [10], [11], [12]. Wrapping with FRP or SRP reinforcement offers the designer an outstanding combination of properties, including ease of handling, speed of installation, durability and high strength-to-weight ratio. On the other hand, some considerations advise against the use of such techniques. More specifically, since it usually violates the aesthetic and conservation requirements, FRP/SRP jacketing appears to be inappropriate for structures belonging to the architectural heritage. Without considering that frequent natural masonry blocks are subjected to moisture entrapment from the ground, released through the external surface during their service life; for that reason it is not always recommendable to apply continuous epoxy-bonded jacketing, inhibiting the material transpiration. In addition, it is worth noting that the high strength of composites is often not mobilized unless the lateral strain in the confined column is very high. This means that, even if the premature local failure of fibers, due to stress concentration, can be prevented, the masonry crushing occurs before the FRP or SRP sheets are fully utilized.

As a result of such considerations, beside the "traditional" FRP/SRP wrapping this paper presents the results of a second experimental investigation in a series dealing with the possibility of application of an innovative confining technique based on the application of pre-tensioned cords so to provide overlapping hoops at every course over the entire height of the column.

This gives a promising technique that may represent a new opportunity to restoring ambit, since it is reversible, aimed at integrating the masonry rather than transforming it and compatible with the preservation of the building materials. This application could combine in fact, to the traditional advantages proper of composite jacketing, the performances of such a strengthening system, able to reduce the invasiveness of jacketed masonry columns while maintaining a high degree of effectiveness.

As in a previous experimental campaign [13], different cross-section geometry (octagonal, square and rectangular) as well as different amounts and different schemes of confining reinforcement were here investigated, the difference being the type of mortar used to build the specimens: weak lime-based instead of cement-based mortar.

Details of the strengthening technique

The idea illustrated in this paper represents the result of the evolution of an innovative confining technique recently proposed by Jurina [14] and then developed by the authors for reinforcing facing stone or brick columns of buildings restricted by building protection laws and for buildings of historical and/or architectural interest in general.

The technique is as follows (Borri et al. 2013): before wrapping the cords, mortar joints were first carefully raked out to a depth of 15 mm (being careful to remove only the damaged mortar) and then their corners were rounded up to 20 mm to avoid stress concentration (Fig. 1a). After rounding, steel angles were located around each corner and the joint surface was well prepared by grinding and fiber reinforced mortar (or epoxy resin) to provide smooth surface to facilitate pre-tensioning of the cords (Fig. 1b).

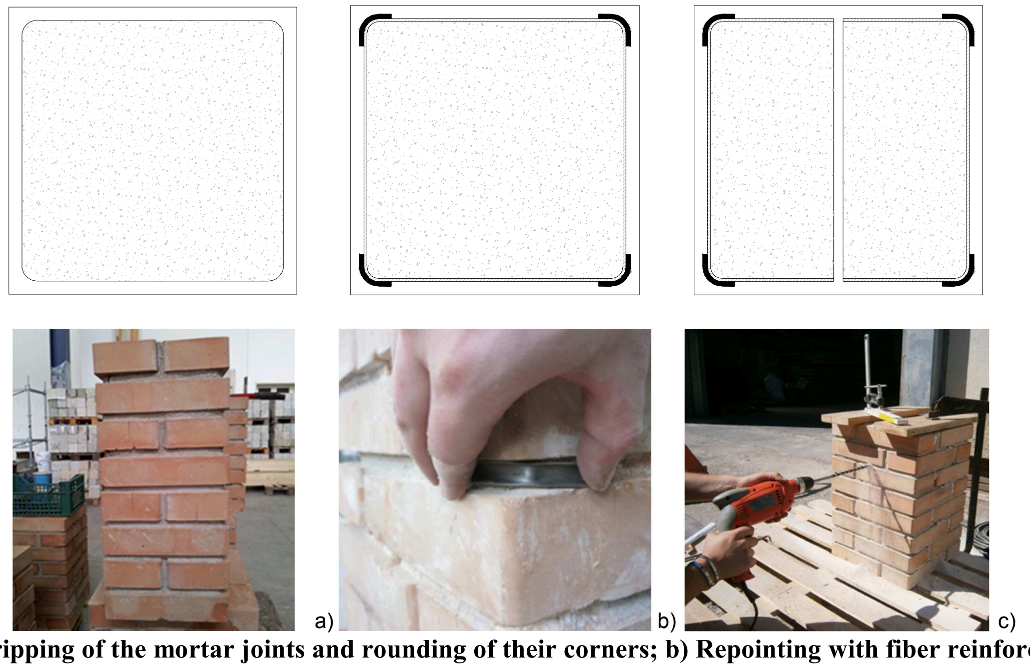
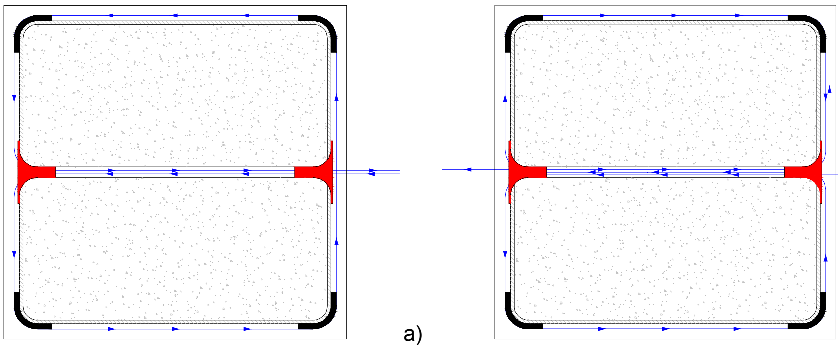


Fig. 1 a) Stripping of the mortar joints and rounding of their corners; b) Repointing with fiber reinforced mortar and application of steel angles; c) Hole drilled through the member cross section.

Then a Φ3 mm cord was cut in a desirable length needed for being inserted in a hole drilled through each joint of the member cross section (Fig. 1c) and wrapping around the column (once or twice) according two different strengthening schemes (referred to as Type HA and HB, Fig. 2).

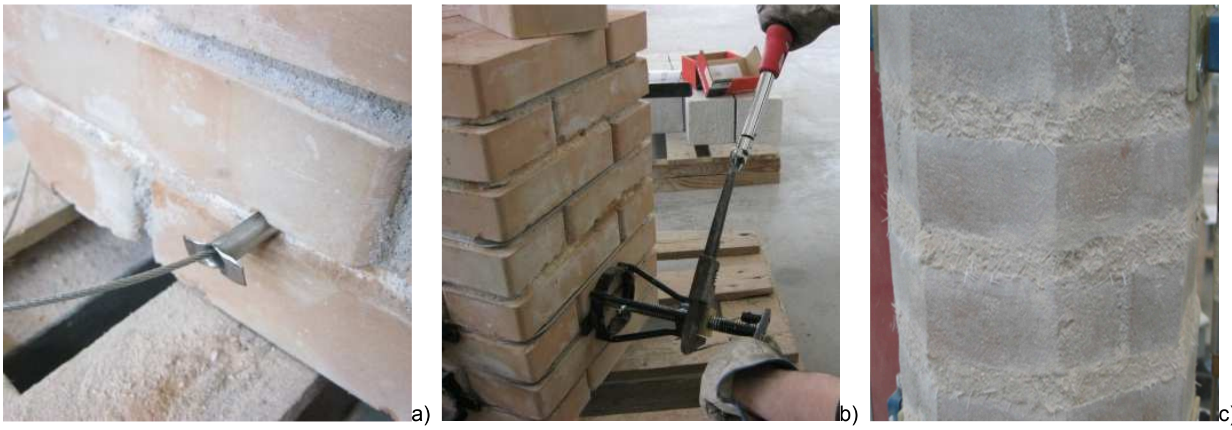


a) b)

Fig. 2 Reinforcement layout: a) Type HA; b) Type HB.

In order to increase the area effectively confined, the continuity between external wrapping and cords inserted into pre-drilled holes can be ensured by putting a couple of steel devices, look like funnels, at both ends of each hole and then, passing the cords through such devices (Fig. 3a). Then both ends of each cord were anchored to a pre-stressing device and a pre-stressing force was given by using an hand-held device (Fig. 3b).

Due to the low mechanical properties of the mortar used in this study, the pre-stressing level of about a tenth of the ultimate strength seemed to be a maximum value, which could be achieved practically on site, since an higher value might cause some local damage to the masonry joints during the pre-stressing procedure. The cords were then anchored to the column by injecting the pre-drilled holes and after about 24 h of curing time the pre-stressing devices were removed and the mortar joints were filled with fiber reinforced mortar (or epoxy resin), which completely covers the reinforcement (Fig. 3c).



a) b) c)

Fig. 3 a) Increasing the area effectively confined by putting a couple of steel devices; b) Pre-stressing of the cord by using an hand-held device; c) Filling the mortar joints with fiber reinforced mortar (or epoxy resin).

Experimental program

Characterization of the materials. In order to represent field applications, standard solid clay bricks (nominal dimensions 250x120x55 mm) were used. The main mechanical properties of the bricks were determined by unidirectional compressive (ASTM C1314) and flexural tests (ASTM C349). The mean compressive strength of thirty bricks was found to be equal to 20.99 MPa. Flexural tests on ten specimens provided an average value equal to 6.75 MPa.

The mortar mix has been chosen with the aim of reproducing the quality and the mechanical behavior of rather weak mortars usually connecting the bricks in existing masonry historical structures; consequently, a lime-based mortar manufactured by Colacem S.p.a. was used. The mix proportions of the mortar (lime:sand:cement) are 1:2:0.15 (by volume). The water-lime ratio is in the range of 30 to 60%, depending on the required workability. Three 40x40x160 mm prisms were cast along with the specimens in order to monitor the evolution of mortar strength during the various stages of the experimental program. Note that the 60-day mean compressive strength was

5.60 MPa, whereas a value of 0.22 MPa was measured for the flexural strength according to ASTM C348.

Ultra High Tensile Strength Steel (UHTSS) cords were used as reinforcing phase for this strengthening system. Furthermore, since in many cases it is essential to guarantee absolute protection against corrosion, Ultra High Molecular Weight Polyethylene (UHMWPE) cords, which allow greater resistance to attack by aggressive agents at the expense of less tensile strength (Table 1), were used as an alternative to the steel cords.

Table 1. Mechanical properties of the cords.

Property	UHTSS cords	UHMWPE cords
Diameter (mm)	3.00	3.00
Tensile strength (N/mm^2)	1211	637
Elastic modulus (N/mm^2)	117000	116000
Ultimate strain (%)	1.03	3 - 4

Tests on masonry columns. To study the behavior of the strengthened columns, 22 specimens (4 unstrengthened and 18 strengthened) were casted horizontally using wooden formworks and were cured in air for at least for 28 days before test. Each specimen was 530 mm high; bricks were placed in 8 rows, with 7 bed joints in between (Fig. 4).

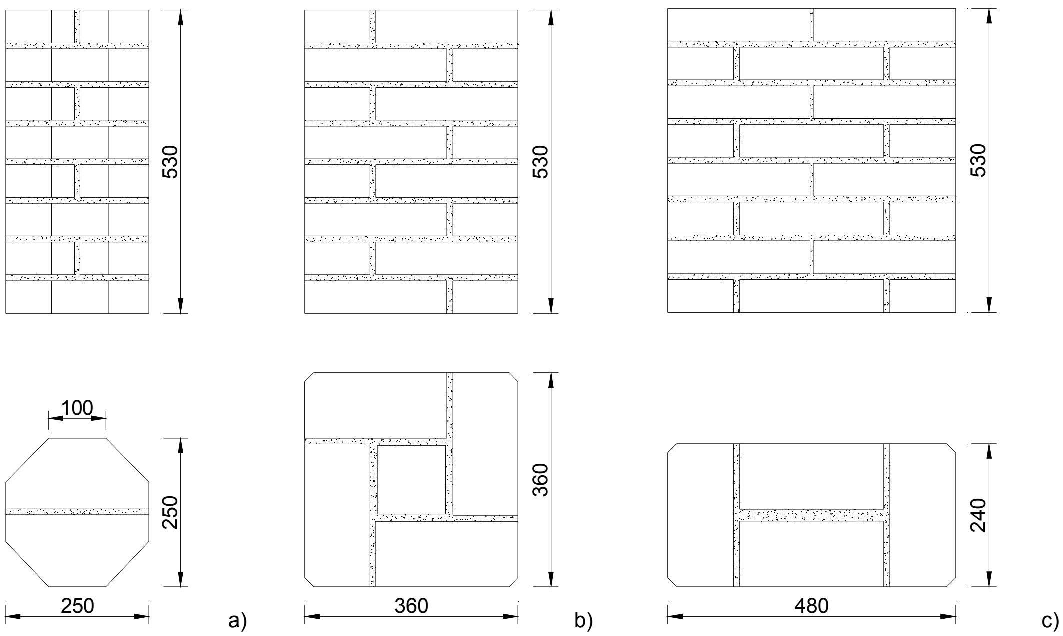


Fig. 4 Specimens details (dimensions in mm).

All specimens were tested through monotonically applied axial compressive loading under displacement control mode with a rate of 0.005 mm/s. On each specimen, four stringer-type LVDTs, placed one on each side of the column, were vertically mounted in order to record axial displacements. Two LVDTs were also placed to monitor possible displacement of the lower steel beam of the frame, in order to take into account only the displacement of the specimen. Finally, two spherical hinges were placed at both ends of the specimens in order to avoid load eccentricity during the test.

As already noted, the columns were all tested by varying the cross-section geometry (octagonal, square and rectangular), scheme of confining reinforcement (type HA or HB, Fig. 2), number of hoops (one or two) and boundary conditions (mortar or resin as protection of reinforced mortar joints, UHMWPE cords rather than UHTSS cords as reinforcement). All the specimens, except for the control ones, were strengthened using a different combination of the above test variables (Table 2).

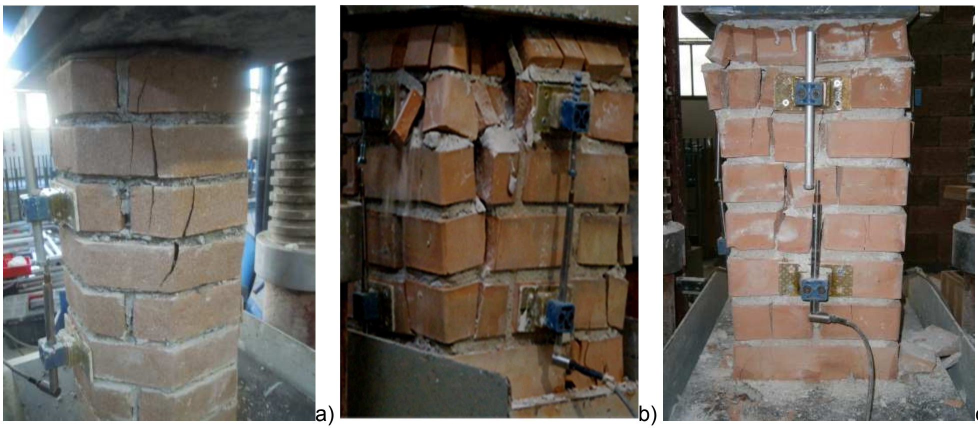
Table 2. Test matrix.

Specimens	Cross-section geometry	Strengthening scheme	Number of hoops	Boundary conditions
OC.UN.01		-	-	-
OC.UN.02		-	-	-
OC.HA.01		HA	1	-
OC.HA.02		HA	1	Resin rather than mortar as protection
OC.HA.03	Octagonal (side average dimension 100 mm)	HA	2	
OC.HA.04				UHMWPE cords rather than UHTSS cords as reinforcement
OC.HA.05				
OC.HA.06				
OC.HB.01		HB	1	-
OC.HB.02		HB	2	-
SQ.UN.01		-	-	-
SQ.HA.01		HA	1	-
SQ.HA.02	Square (360×360 mm)	HA	1	Resin rather than mortar as protection
SQ.HA.03		HA	2	
SQ.HB.01		HB	1	-
SQ.HB.02		HB	2	-
RL.UN.01		-	-	-
RL.HA.01		HA	1	-
RL.HA.02	Rectangular (480×240 mm)	HA	1	Resin rather than mortar as protection
RL.HA.03		HA	2	
RL.HB.01		HB	1	-
RL.HB.02		HB	2	-

Experimental results

The present section summarizes the experimental results obtained in the compression tests on both confined and unconfined specimens. In particular, the latter ones have been considered as "control tests" with the aim of determining the contribution of hooping in terms of stiffness, strength and failure mode.

Unconfined columns. Fig. 5 shows three pictures representing the failure mode observed in tests on the control specimens. The weakness of the mortar joints with respect the higher quality of the clay bricks led to a failure mode characterized by a principal vertical crack running throughout all the bricks and resulting in the final failure of the column segment.



a) b) c)

Fig. 5 Failure modes of unconfined specimens: a) Octagonal column; b) Square column; c) Rectangular column

Considering the notable variations in results typical of tests on masonry, the scattering of the compressive strength results obtained with this experimental work is quite low (Table 3).

Table 3 Experimental results: unconfined columns

Specimens	Reinforcement ratio (%)	Maximum stress (MPa)	Ultimate axial strain (-)	Normalized strength	Normalized axial strain
OC.UN.01	-	3.92	0.0243	-	-
OC.UN.02	-	3.97	0.0183*	-	-
SQ.UN.01	-	4.81	0.0197	-	-
RL.UN.01	-	4.62	0.0104	-	-

* LVDTs produced unreliable data from this point

Although the presence of undesirable variables (such as handwork) that may have arisen from the construction of the masonry columns, values of compressive strength range in fact between 3.92 and 4.81 MPa, with a mean value of 4.34 MPa and a coefficient of variation of 0.10. Conversely, as to the axial strain, a greater scattering was observed. High values were measured in the case of octagonal cross-section (2.43%), while smaller values were obtained for square (1.97%) and rectangular (1.04%) cross-section.

Confined columns. The brittle mode of the unconfined columns (i.e. concentrated cracking and failure of the column segment) are somehow restrained by the presence of the external cords which results in a radical change in the observed failure mode and the mechanical behavior as a whole. As far as phenomenological aspects are of interest, it is worth noticing that failure generally occurred before cords tearing. It was dictated, in fact, by the difference in terms of deformability between masonry bricks and mortar joints. Due to its higher deformation capacity, the mortar tends, in fact, to expand radially through the joint, but the steel hoops and adhesion forces of the masonry bricks restrain this tendency, so producing tensile stresses in the bricks. When the tensile strength limit of the bricks was reached, vertical cracks formed within the specimens, they increased in number and propagated with the applied load, until failure. Consequently, a more widespread and diffused crack pattern was found, with thinner cracks distributed along the entire column (Fig. 6).

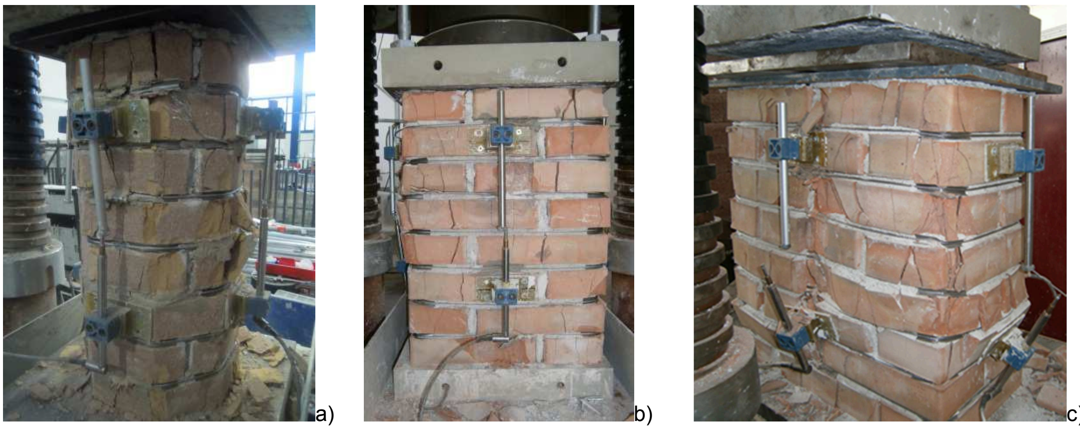

a) b) c)

Fig. 6 Failure modes of confined specimens: a) Octagonal column; b) Square column; c) Rectangular column

The different behavior observed for unconfined and confined specimens can be also regarded by considering the ultimate load capacity. As concerns octagonal columns, regardless the scheme of confining reinforcement (type HA or HB), the use of a single steel hoop permitted the attainment of strength increases ranging between 123% and 143%, whereas the use of overlapping hoops evidenced an average increase in strength equal to 196%. Conversely, as to the use of polyethylene cords, it is observed that an almost equal axial strength increase (approximately 40%) was recorded in all specimens.

The effect of confinement seemed to be less effective in the case of square columns confined by the same strengthening schemes utilized above, because of the higher cross-section dimensions that, consequently, led to a lower confining pressure. Table 4 shows that the average gains in terms of strength provided by steel hooping were equivalent for the columns reinforced with overlapping hoops (approximately 70%), whereas they were considerably higher (97% and 93% for columns SQ.HA.02 and SQ.HB.01, respectively) when the amount of reinforcement was halved (single hoop). A single exception was in the case of column SQ.HA.01, reinforced with mortar rather than resin as protection, where the increase in strength was equal to 45%.

Table 4 Experimental results: confined columns

Specimens	Reinforcement ratio (%)	Maximum stress (MPa)	Normalized strength
OC-HA-01	0.113	8.83	2.23
OC-HA-02	0.113	9.64	2.43
OC.HA.04	0.113	5.53	1.39
OC.HA.05	0.113	5.61	1.42
OC.HA.06	0.113	5.05	1.27
OC-HB-01	0.114	9.06	2.28
OC-HA-03	0.225	11.60	2.93
OC-HB-02	0.223	11.89	3.00
SQ-HA-01	0.075	6.97	1.45
SQ-HA-02	0.075	9.46	1.97
SQ-HB-01	0.076	9.30	1.93
SQ-HA-03	0.151	8.11	1.69
SQ-HB-02	0.151	8.25	1.72
RL-HA-01	0.086	8.69	1.88
RL-HA-02	0.088	9.02	1.95
RL-HB-01	0.084	7.80	1.69
RL-HA-03	0.171	7.60	1.65
RL-HB-02	0.169	7.29	1.58

A similar increase in terms of axial strength can be observed (84% and 61% for specimens reinforced by using single and overlapping hoops, respectively) in specimens with rectangular cross-section, even if the displacement capacity is significantly different.

Design and modeling

In the present section, the available experimental data related to a previous experimental campaign [12] have been collected and joined to the results provided by the presented experimental tests. The main objective of this experimental data collection was the assessment of the reliability of existing design equations suggested by Italian CNR [15] to predict strength gains of masonry columns confined by steel hooping.

Even though, in fact, the proposed formulations are not specifically introduced for steel cords, at present no more appropriate approaches are available. In such a context, the proposed comparison could represent a first step toward the development of code recommendations for the design of steel hooping.

Design recommendations available in CNR bulletin suggest expressing the strength of confined masonry (f_{mcd}) as:

$$f_{mcd} = f_{md} + k' \cdot f_{1,eff} \quad (1)$$

where f_{md} = strength of plain masonry; k' = hardening factor for compressive strength; and $f_{1,eff}$ = effective lateral confining pressure.

The value of k' is indicated as $\gamma_m/1000$, where γ_m = masonry mass density expressed as kg/m^3, whereas the effective lateral confining pressure ($f_{1,eff}$) can be expressed as:

$$f_{1,eff} = k_h \cdot k_v \cdot f_1 \tag{2}$$

where the horizontal efficiency factor (k_h) represents the confined-to-gross area within the cross sections represented in Fig. 7:

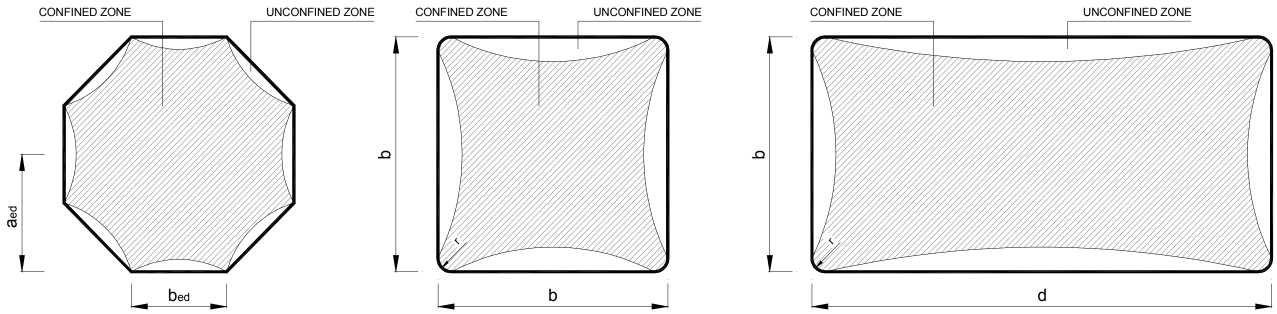


Fig. 7 Effective areas of confinement for different cross sections

$$k_h = \begin{cases} 1 - \dfrac{\pi \cdot b_{ed}}{12 \cdot a_{ed}} & \text{(Polygonal cross-section)} \\ 1 - \dfrac{2}{3}\dfrac{(b-2\cdot r)^2}{A_m} & \text{(Square cross-section)} \\ 1 - \dfrac{(b-2\cdot r)^2 + (d-2\cdot r)^2}{3 \cdot A_m} & \text{(Rectangular cross-section)} \end{cases} \tag{3}$$

in which A_m is the gross section of the confined member.

Conversely, the vertical efficiency factor (k_v) generally indicates the effect of wrapping throughout the column axis; hence, it can be assumed k_v = 1.0 in the case of continuous jacketing, whereas for discontinuous wrapping it is given by:

$$k_v = \left\{ \left(1 - \frac{p_f - b_f}{2 \cdot \min\{b; d; 2 \cdot a_{ed}\}} \right)^2 \right. \tag{4}$$

where p_f = distance between two successive reinforcement strips measured by two axes; and b_f = width of reinforcement along the vertical direction.

Finally, the nominal lateral pressure (f_1) can be evaluated as a function of the Young modulus of reinforcement (E_f) and the axial strain ($\varepsilon_{fd,rid}$) developed inside the wrapping layer:

$$f_1 = \frac{1}{2} \rho_f \cdot E_f \cdot \varepsilon_{fd,rid} \tag{5}$$

with the following definition of the wrapping ratio (ρ_f) depending on the area (A_{reinf}) of the reinforcement:

$$\rho_f = \begin{cases} \dfrac{4 \cdot A_{\text{reinf}}}{b \cdot p_f} & \text{(Square cross-section)} \\ \dfrac{4 \cdot A_{\text{reinf}}}{b \cdot p_f} & \text{(Rectangular cross-section)} \\ \dfrac{2 \cdot A_{\text{reinf}}}{a_{ed} \cdot p_f} & \text{(Polygonal cross-section)} \end{cases} \tag{6}$$

Fig. 8 briefly represents all the results obtained in the present experimental campaign reporting the observed strength ratio f_{mcd}/f_{md} on the y-axis and the corresponding lateral pressure-to-unconfined strength ratio $f_{l,eff}/f_{md}$ on the x-axis. The points are represented by different symbols depending on the nature of the mortar and the cross-section geometry of the columns. A significant scatter can be observed among those points, as a huge variation in terms of the f_{mcd}/f_{md} can be observed even for similar values of the $f_{l,eff}/f_{md}$ ratio. The formula provided by the CNR Italian Guidelines (1), and represented by the two segments whose different slope basically depends on the density of masonry, generally leads to conservative predictions, particularly in the case of columns built with lime-based mortar which are probably the most common ones in existing masonry historical structures (note that the mentioned formula is applied in Fig. 8 without partial safety factors for both the masonry and external reinforcement).

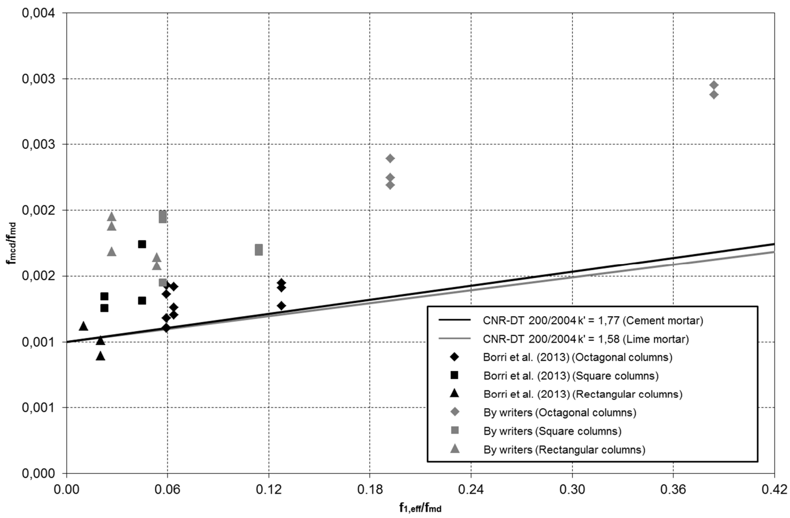


Fig. 8 Experimental versus theoretical values of f_{mcd}/f_{md} as a function of $f_{1,eff}/f_{md}$

A similar trend is substantially confirmed when referring to Fig. 9, that reports the comparison between the experimental results ($f_{mcd,exp}$) and the corresponding theoretical predictions obtained ($f_{mcd,th}$) through (1). The bunch of points corresponding to the couples formed by the experimental and theoretical values pointed out the clear asymmetry of that distribution resulting by a general underestimation of the experimental results.

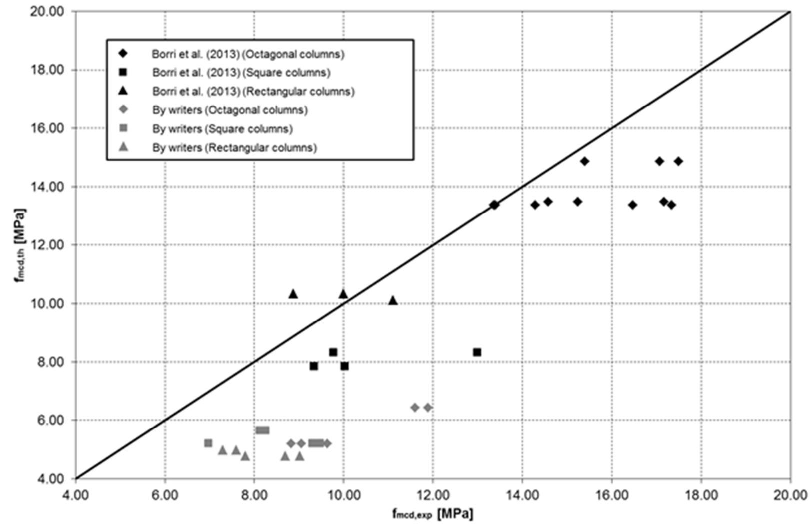


Fig. 9 The model proposed by the Italian Guidelines: distribution of the experimental and theoretical values.

More specifically, it is possible to observe that the mean values differ by less than 20% and 45% for columns built with cement-based and lime-based mortar, respectively; moreover, it can also be seen how just in two cases the proposed approach leads to un-conservative values when comparing with the experimental results. Therefore, until new approaches to predict the strength of confined masonry are available, the formula proposed by CNR Italian Guidelines appears to be adequate for design purposes, showing how the same approach used for masonry reinforced with FRP can be satisfactory used for steel hooping.

Conclusions

Three series of uniaxial compression tests, with a total of 22 specimens, were conducted on model masonry columns with these variables: cross-section geometry, amount and scheme of confining reinforcement. The retrofit scheme consisted in the application of small diameter cords at every horizontal course over the entire height of the column. In such a context, the effectiveness of the method was improved further by pre-tensioning the cords.

The pre-stressing procedure was simple (since it can be implemented manually using a wrench), but efficient in arriving at a desirable level for pre-stressing.

The same failure modes have been observed in the various tests on confined columns and values of the confined-to-unconfined strength ratio ranging between 1.45 and 3.00 have been obtained for specimens confined with UHTSS cords. As a rule, they are generally higher in the case of octagonal masonry columns and for overlapping hoops, confirming the influence of the basic parameters on the behavior of confined members.

More specifically, it has been observed that different results were obtained by varying the amount of reinforcement (single or overlapping hoops). While octagonal columns showed a nontrivial increase of the ultimate capacity with the reinforcement ratio, since doubling the amount of reinforcement the strength increase resulted in almost 30%, a higher amount of reinforcement in square and rectangular specimens produced lower confinement effect. Far from being exhaustive, this can be explained considering that the presence of sharp corners combined with a stiffer reinforcement could cause high local stress concentration in the case of square and rectangular cross-section, thus making the steel cords confinement less effective.

Furthermore, as for the different schemes of confining reinforcement, the use of epoxy resin rather than mortar in the application of steel hoops seems to have a nontrivial influence in column behavior. A comparison between columns with equivalent cross-section geometry highlights, in fact, that columns with epoxy resin as protection (columns OC.HA.02, SQ.HA.02 and RL.HA.02) permitted the attainment of strength increases ranging between 1.05 and 1.30 times the maximum increase obtained with reinforced mortar (columns OC.HA.01, SQ.HA.01 and RL.HA.01).

Conversely, the effect of confinement seemed to be less effective in the case of columns confined by UHMWPE cords, the columns strengthened with such cords permitted in fact the attainment of strength increases ranging between 27 and 42%.
Finally, since technical recommendations are non-existent, a comparison between experimental results and the predictions obtained by existing design equations suggested by Italian National Research Council were made to evaluate the possibility of the use of such formulations in predicting the behavior of confined columns. Even though, in fact, the proposed formulations are not specifically introduced for steel hooping, they may represent a useful instrument to calculate the reinforcement and can be considered as a point of departure for eventual more in-depth analyses. In such a context, the formula proposed by Italian CNR has led to an acceptable difference between analytical and experimental results. The obtained values differ by less than 20 and 45% for columns built with cement-based and lime-based mortar, respectively, and, in almost all cases, the proposed approach leads to conservative values when compared with the experimental results. Therefore, until new approaches to predict the confinement capacity are available, the abovementioned formula appears to be adequate for design purposes, showing how the same approach used for masonry reinforced with FRP can be satisfactorily employed for masonry reinforced with steel hooping.

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