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Effectiveness of BFRP confinement on the compressive behaviour of clay brick masonry cylinders

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Abstract

This paper presents the results of an experimental and analytical study on the compressive behaviour of small clay brick masonry cylinders reinforced with a basalt fibre reinforced polymer (BFRP) composite. Fourteen cylinders, manufactured using two assembling schemes and confined using either one or two layers of BFRP grids, were tested under monotonic compression loading. Traditional strain measuring systems were integrated with digital image correlation (DIC) technique. The BFRP confined masonry cylinders showed a ductile behaviour characterised by a softening branch of the stress-strain curve. The experimental strains, strength, and full stress-strain curves were modelled using analytical models available in the literature. A modified version of the CNR model proposed in this study provided the best strength prediction.

Keywords: *masonry, BFRP, confinement, cylinders, digital image correlation*

Introduction

Improving the axial capacity and ductility of masonry columns using passive confinement induced by wraps of fibre reinforced polymers (FRP) has become a common engineering practice. The method is based on the high tensile strength of composites and consequent high confinement pressure achievable. Several experimental and theoretical studies were carried out in the past 20 years to study the confinement effect due to carbon and glass fibre composites on the compressive behaviour of masonry. More recently basalt fibres have gained increasing attention as FRP reinforcement material for strengthening applications, especially as an alternative to glass fibres. Basalt is a natural volcanic rock originating at a depth of hundreds of kilometres beneath the earth's crust and reaching the surface as molten magma [1]. Basalt fibres are produced with a manufacturing process which is similar to that adopted for manufacturing glass fibres. The main difference is that glass is produced from a complex batch of materials, while basalt is a naturally occurring rock which just needs to be molten to produce a filament and then fibres. The simplicity

of this manufacturing process reduces the production cost and the amount of energy compared to glass fibres, with several benefits in terms of environmental impact. Moreover, basalt is a natural occurring rock, which makes it particularly suitable for applications in masonry structures. However, the quality and the chemical composition of the raw material can significantly influence the cost and properties of the fibres and can lead to variability of the mechanical properties of the material [1].

Despite the many studies on columns wrapped with carbon and glass FRPs (CFRP and GFRP respectively), there is very limited experimental data on BFRP-wrapped columns, and most studies investigated concrete members. Campione *et al.* [2] studied the application of a bidirectional basalt fabric with epoxy resin to concrete cylinders by axial compression tests. The specimens confined with BFRP exhibited strain-softening behaviour after the peak load with negligible strength increases but a good enhancement of ultimate strain, up to five times the peak strain of the unconfined specimens. More recently, Ouyang *et al.* [3] presented a comparative study of the seismic behaviour of reinforced concrete square columns retrofitted with CFRP and BFRP sheets. The study demonstrated that the BFRP composites are a promising alternative to conventional FRPs (e.g., CFRPs) for retrofitting square RC columns. Sadeghian and Fillmore [4] studied the distribution of hoop strains along the surface of concrete cylinders confined by two, four or six layers of BFRP. They found that the failure of all specimens wrapped with BFRPs was controlled by the rupture of the composite along the hoop direction in the non-overlap region; in comparison with similar studies on CFRP, a less explosive failure of BFRP-wrapped cylinders was observed; moreover, the number of layers had a negligible effect on the hoop strain distribution.

Huang *et al.* [5] studied the compressive behaviour of concrete columns confined by different basalt fibre-reinforced polymers. The test results showed that the compressive strengths of confined specimens increased by 20%-71% for circular columns, while the ultimate strains improved by 49%-296%. Both the strength and the ultimate strain of confined concrete improved with increasing number of BFRP layers.

Baasankhuu *et al.* [6] investigated the confinement effect of BFRP wrapping applied on concrete cylinders. Different number of FRP layers was investigated. Confinement by BFRP was effective, as underlined by the continuously ascending stress-strain relationship of the confined concrete. The compressive strength of specimens confined by 2-6 layers of BFRP was 1.4-2.5 times that of the unconfined concrete.

Suon *et al.* [7] presented an experimental study on the compressive behaviour of BFRP-confined small-scale concrete specimens. Different parameters were investigated, such as cross-section shape and number of BFRP layers. The

58 results showed the ability of basalt fibre in improving the concrete compressive behaviour. In particular, it was shown
59 that the ultimate condition of confined concrete enhances with the increase of BFRP layers.

60 Regarding masonry members retrofitted with BFRP, Di Ludovico *et al.* [8] presented the results of an experimental
61 investigation on the compressive behaviour of tuff or clay-brick masonry columns confined with carbon, glass and
62 basalt FRP. For clay brick masonry columns, the study found that GFRP and BFRP confining systems led to similar
63 compressive strength gain (about 57%), but BFRP wrapping produced a higher ultimate axial strain gain (413% for
64 BFRP against 259% for GFRP) even if the mechanical external reinforcement ratio was lower than in case of GFRP.
65 Micelli *et al.* [9] investigated the mechanical behaviour of circular masonry columns in compression confined with
66 glass and basalt FRP and FRCM (fibre reinforced cementitious mortar) unidirectional sheets and grids applied in a
67 continuous or discontinuous way along the column. They also studied the effect of active confinement using a GFRP
68 and shape memory alloys (SMA) system. These tests highlighted the effectiveness of the FRP confinement; in
69 particular, the unidirectional basalt and glass sheet wraps produced the highest values of strength and ductility, with
70 failure due to the fibre rupture. Discontinuous wraps produced a significant upgrade of the mechanical properties and
71 discontinuous wrapping with basalt grid produced higher mechanical properties of the confined masonry respect to
72 the other cases with higher FRP amount.

73 Regarding the modeling of FRP confined masonry columns, one of the first studies was carried out by Krevaikas and
74 Triantafillou (2005) [10] who tested 42 clay brick masonry columns confined with glass and Carbon FRP and
75 formulated a simple model for calculating both the strength and ultimate strain gain. Corradi *et al.* 11 (2007) [11]
76 adapted the stress-strain law proposed by Campione and Miraglia (2003) [12] for concrete elements to model the
77 compressive behaviour of Carbon FRP-confined masonry. Di Ludovico *et al.* (2010) [8] , based on their experimental
78 investigation on tuff or clay-brick masonry columns confined by carbon, glass and basalt FRPs, proposed new
79 expressions for evaluating the strength enhancement in masonry columns strengthened by FRP systems. Faella *et al.*
80 (2011) [13] analysed a wide experimental database of published studies to assess how models available for FRP-
81 confined concrete columns perform when adapted to masonry members. They showed that the available models
82 often provide inaccurate estimations, due to the fact that they were calibrated on specific types of masonry. They also
83 calibrated some analytical formulations considering a variable number of parameters.

84 More recently, Lignola *et al.* (2014) [14] summarized previous studies in the literature and proposed a theoretical
85 approach based on the Mohr-Coulomb strength criterion for determining the strength increase due to FRP

confinement. Additionally, the CNR-DT 200/2013 Guidelines [15], the Italian reference standard for upgrading interventions on concrete and masonry structure using FRP, also provides a model for the confined strength of FRP-confined masonry columns.

A comparative analysis of the main theoretical models was carried out by Minafo *et al.* (2017) [16] to estimate increased strength, ultimate strain and full stress-strain curves of FRP confined masonry in compression based on available experimental data. They considered a number of geometrical and mechanical variables, included the influence of the section corner radius. They concluded that the confined strength model proposed by the current Italian CNR DT 200 (2013) guidelines [15] is quite conservative, while the model proposed by Di Ludovico *et al.* (2010) [8] is the most reliable. This summary shows that the experimental studies carried out on columns confined by BFRP wraps are still insufficient to calibrate existing models and design formulations either covering glass, carbon and basalt FRP or specifically formulated for BFRP composites. Moreover, very few experimental studies on FRP-strengthened masonry columns focus circular columns [17-19].

In this study, in order to investigate the effect of pure confinement, masonry specimens with circular cross section were tested. As the absence of corners in the circular section allows avoiding stress concentration in the external wrap and, in these specimens the strengthening system can reach, in principle, its maximum stress in a uniform manner [20, 21]. However, it should be noted that the circumferential rupture strain in the FRP wrap is much smaller than the coupon test failure strain due to various factors including geometrical discontinuities at the ends of the composite. Moreover, the obtained strength increase can be considered as an upper bound of the confinement effect for real case studies. This paper presents the results of an experimental investigation carried out on fourteen small scale brick masonry cylinders confined by BFRP wraps and subjected to uniaxial compression. The test programme included two variables were: the effect of the vertical mortar joints of two different assembly schemes and the number of BFRP layers used for confinement purposes. Strains obtained by traditional measuring instruments were compared with those obtained with the Digital Image Correlation (DIC) technique. The experimental results including confined strength, ultimate strain and full stress-strain curves, were compared to predictions obtained using available models in the literature, and those from a modified versions of the CNR model [15] and Krevaiakas and Triantafillou's model [10].

Experimental program

Fourteen small clay brick cylinders were tested under axial compressive loading in this study. The cylinders, with a diameter of 94 mm and height of 190 mm, were obtained by coring two different assembly schemes (Schemes I and II) prepared using three rows of 50x100x210 mm pressed bricks and 8 mm thick mortar joints, see Fig. 1. The specimen shape and size were selected to assess the effect of uniform confinement on masonry, at material level, under compressive stress. Cylinders cored from Scheme I had only one vertical joint in the middle third while cylinders cored from Scheme II had three staggered vertical joints, one at each level. The cylinders were cored with a laboratory-coring machine after 30 days of curing and then wrapped with one or two layers of basalt FRP composite as listed in Table 1. It should be considered that the same number of specimens was planned to be tested for both schemes, however some cylinders were damaged during the coring or the preparation operations. For this reason, the number of control specimens was different for the two schemes. The cylinders were labelled as Cn_XYL where C represents “cylinder”, n indicates the specimen number, X identifies the assembly scheme (W for Scheme I, C for Scheme II), Y indicates the number of confinement layers (1 and 2 for one or two layers respectively), L means “layer”. In the case of unconfined cylinders, the last two letters were replaced by “Un” (unconfined).

Table 1: Test specimens

Assembly scheme	Specimen	Number of BFRP layers
Scheme I (n.1 vertical joint)	C1_WUn C2_WUn C3_WUn C4_WUn	0
	C1R_W1L C2R_W1L	1
	C1R_W2L C2R_W2L	2
	C1_CUn C2_CUn	0
	C1R_C1L C2R_C1L	1
	C1R_C2L C2R_C2L	2

Fig. 1 Brick assembly schemes: a) Scheme I; b) Scheme II

Materials

The bricks and mortar used for the masonry cylinders were tested according to EN 772-1 [22] and EN 1015-11 [23].

The bricks had a compressive strength equal to 42.53 MPa. The mortar (cement/sand weight ratio of 1/5) had compressive strength equal to 20.93 MPa and tensile strength equal to 5.33 MPa.

A bidirectional primed alkali-resistant basalt fibre grid with cell size of 6x6mm and two-component epoxy resin were used for the BFRP wraps. The grid and epoxy resin geometrical and mechanical characteristics provided by the supplier are reported on Table 2.

139 Table 2: Properties of BFRP components (supplier data)

Material	Unit weight	Mesh size	Density	Tensile strength	Elastic modulus	Equivalent thickness	Elongation at failure
Basalt grid	250 g/m ²	6 x 6 mm	2.75 g/cm ³	60 kN/m	89 GPa	0.039 mm	1.8%
Epoxy resin	-	-	-	40 MPa	2.6 GPa	-	-

140

141 The basalt grid was also tested in tension: twelve specimens in the warp and twelve in the weft direction, from the
 142 same roll used for wrapping the cylinders, were prepared and tested according to ISO 13934-1 [24]. The grid was cut
 143 in strips of 260 x 13.5 mm² and aluminium tabs were glued on the strip edges. Tests were conducted in displacement
 144 control using a Zwick-Roell universal machine, with a loading rate of 1 mm/min. The specimens were lighted up with a
 145 retro-light and displacements were recorded using a video-extensometer to track linear targets over a gauge length of
 146 80 mm. The test setup is shown in Fig. 2 together with a grid sample at failure.

147 The monotonic compressive tests on the cylinders were carried out using a 600 kN electro-hydraulic loading frame.

148 Three loading/unloading cycles were applied under load control up to 40-50 kN on each specimen, followed by

149 monotonic loading up to failure under displacement control at a rate of 0.12 mm/min.

150

151 Fig. 2 Test on basalt grid samples: a) test setup; b) specimen at failure

152 **Test set-up and instrumentation**

153 The cylinder test setup is shown in Fig. 3. A hydraulic jack connected to a manually controlled motor pump was used
154 to apply the axial compression force on the cylinders. The load was measured by a load cell attached to the loading
155 cylinder and recorded by a data acquisition system. A steel spherical head was placed above the upper bearing plate
156 to maintain a uniform distribution of axial stress and avoid load eccentricity.

157 Six linear voltage differential transducers (LVDTs) were installed, four on the upper loading platen and two on the
158 lower platen. Three extensometers connected to two steel rings placed around the specimens were also used to
159 measure the local deformation in the middle half of the specimens, see Fig. 3a and b.

160 Additionally, the strain field on the surface of the specimens was obtained from Digital Image Correlation (DIC)
161 measurements using GOM Correlate [25]. A 22.3 Megapixel camera was used to capture images of the cylinders every
162 four seconds using a remote trigger with a resolution of 16 pixel/mm and an average 4-5 pixel/speckle. The specimens
163 were lighted up using two symmetrical white lights, able to provide a uniform light intensity on the front side of the
164 samples (Fig. 3a). Strains were measured over a rectangular area of about 50x90 mm as shown in Fig. 4, as in [26].
165 Axial strains were computed as the average of 20 virtual strain gauges with a gauge length of 90 mm. In the same way,
166 hoop strains were measured as the average of 45 virtual strain gauges with a gauge length of 50 mm.

167 a) b)
 168
 169 Fig. 3 Cylinder compressive test: a) cylinder before testing; b) setup scheme

170
 171 Fig. 4 Rectangular area used to calculate hoop and axial strains (DIC)

172 Experimental results

173 Basalt grid

174 The experimental stress-strain curves for the basalt grid strip specimens are plotted in Fig. 5. The grid was tested along
 175 both warp direction (the circumferential direction when wrapped on the cylinders), and weft direction (the vertical
 176 direction). As the textile has a discrete distribution of fibres (nominal cell size 6 mm), the stress values in the graph
 177 were obtained considering the effective width corresponding to the number of yarns in the strip (2 cells and 3 yarns,
 178 therefore width=yarn x cell size) and the equivalent grid thickness (0.039 mm).

179 Clearly, the tensile curves exhibited an almost linear elastic brittle behaviour. The average peak stress and strain,
 180 averaged over twelve samples tested along the warp direction, were 2045 MPa and 2.6 % respectively. The
 181 experimental average elastic modulus was 82 GPa (Table 3). The values obtained from the specimens tested along the
 182 weft direction were 1983 MPa, 2.4 % and 82 GPa respectively for the average strength, strain and Young's modulus.

183 Table 3: Results of basalt grid tests

Mechanical property	WARP DIRECTION		WEFT DIRECTION	
	Average	COV	Average	COV
Tensile strength	2045 MPa	10.55%	1983 MPa	7.80%
Young's modulus	81.91 GPa	3.48%	81.88 GPa	4.60%
Ultimate tensile strain	2.55%	8.21%	2.40%	12.05%

184

185

186 Fig. 5 Tensile tests of basalt grid strips: a) warp direction; b) weft direction

187 BFRP confined cylinders

188 The axial stress-strain curves of Schemes I and II specimens obtained using LVDTs and transducers are plotted in Fig.
 189 6a and b. The strain up to the peak was calculated using the displacement recorded over the central half height of the
 190 cylinders, while for the softening branch the LVDT measurements from the top and bottom plate were used as the
 191 ring fixed on the cylinders had to be taken off during the last part of the compression test. For unconfined cylinders
 192 C1_WUn, C2_WUn, and C3_WUn, the strain was calculated using the LVDTs on the top and bottom plates as the
 193 readings in the central area of the cylinders were lost due to technical problems. This explains the apparent lower
 194 stiffness measured for these specimens in Fig. 6. The strains of these cylinders were not used for the calculating the
 195 average strain.

196 The stress-strain curves of the unconfined cylinders showed a brittle behaviour with an almost linear trend up to the
 197 peak followed by a sudden load drop after the peak, see Fig. 6. The confined specimens also have an almost linear
 198 ascending branch up to about 80% of the peak stress, followed by an irregular softening curve with some stress drops.
 199 Scheme II specimens showed a less steep softening branch than Scheme I specimens, indicating the higher influence
 200 of the vertical mortar joints.

201
 202
 203 Fig. 6 Stress-strain curves of cylinders (LVDT readings): a) Scheme I; b) Scheme II.

204
 205 The individual and average experimental results of cylinders are reported on Table 4 and Table 5. The tables contain:
 206 peak axial stress; peak and ultimate axial strains from LVDT/transducer readings; peak axial and hoop strains from DIC.
 207 The ultimate axial strain is calculated as the strain corresponding to a 15% stress reduction from the peak stress. For

208 two of the unconfined cylinders, the ultimate axial strain is the last detected value. Table 5 also provides the ratios
 209 between the confined and unconfined cylinder peak stress (f_{mc}/f_{m0}), the ratios between the confined and unconfined
 210 cylinder peak strain ($\epsilon_{mc}/\epsilon_{m0}$), and the ratios between hoop and axial strains for confined cylinders ($\epsilon_{mch}/\epsilon'_{mc}$).

211 Table 4: Cylinder individual results

	Specimen	BFRP layers	LVDTs/Transducers			DIC	
			Peak axial stress (MPa)	Peak axial strain (mm/mm)	Ultimate axial strain (mm/mm)	Peak axial strain (mm/mm)	Peak hoop strain (mm/mm)
			f_{m0}	ϵ_{m0}	ϵ_{m0u}	ϵ'_{m0}	ϵ_{m0h}
UNCONFINED	C1_WUn	-	25.24	0.0043*	0.0048**	-	-
	C2_WUn	-	24.78	0.0052*	0.0054*	0.0028	0.0030
	C3_WUn	-	19.95	0.0049*	0.0049*	0.0024	0.0029
	C4_WUn	-	30.79	0.0036	0.0038**	-	-
	C1_CUn	-	22.25	0.0036	0.0042	-	-
	C2_CUn	-	17.44	0.0032	0.0035	-	-
			f_{mc}	ϵ_{mc}	ϵ_{mcu}	ϵ'_{mc}	ϵ_{mch}
CONFINED	C1_W1L	1	32.64	0.0044	0.0057	0.0019	0.0020
	C2_W1L	1	32.47	0.0040	0.0056	0.0037	0.0041
	C1_W2L	2	45.08	0.0080	0.0092	0.0069	0.0064
	C2_W2L	2	39.64	0.0051	0.0065	0.0045	0.0034
	C1_C1L	1	26.71	0.0053	0.0075	0.0036	0.0044
	C2_C1L	1	27.95	0.0049	0.0073	0.0053	0.0047
	C1_C2L	2	35.26	0.0051	0.008	0.0031	0.0032
	C2_C2L	2	32.64	0.0065	0.011	0.0052	0.0040

212 *Value not used for calculation of average peak/ultimate strain. **Last detected deformation

213 The average peak stresses for the unconfined specimens were 25.19 MPa and 19.85 MPa for Scheme I and II
 214 specimens respectively, showing a significant detrimental effect of the vertical joints. In comparison with the
 215 unconfined specimens, one layer of BFRP composite enhanced the cylinder average strength by 29% and 38%
 216 respectively for Scheme I and II. For cylinders confined with two BFRP layers the average strength gain was 68% for
 217 Scheme I and 71% for Scheme II, about the double than that with one layer. [The strength increments are](#)
 218 [comparable to those achieved in other studies \[5\]](#). One layer of composite therefore had a larger confinement
 219 effect on the weakest masonry cylinders, while two layers produced similar strength increments.

220 Scheme I cylinders wrapped with one layer exhibited a small peak strain increase (17%) while two layers of BFRP
 221 composite increased the peak strain by 82% compared to control specimens. For Scheme II cylinders confined with
 222 one and with two BFRP layers the average peak strains were 49% and 69% higher than for unconfined specimens.
 223 These increments are about proportional to the corresponding increments of strength.

224 Table 5: Cylinder average results

Assembly	Confinement	LVDTs/Transducers			DIC		
		Peak axial	Peak axial	Ultimate axial	Peak axial	Peak hoop	
		Stress	strain	strain	strain	strain	
		(MPa)	(mm/mm)	(mm/mm)	(mm/mm)	(mm/mm)	
		f_{m0}	ϵ_{m0}	ϵ_{mu}	ϵ'_{m0}	ϵ_{m0h}	$\epsilon_{m0h}/\epsilon'_{m0}$
Scheme I	unconfined	25.19	0.0036	0.0038	0.0026	0.0030	1.15
Scheme II	unconfined	19.85	0.0034	0.0038	/	/	/
		f_{mc}	ϵ_{mc}	ϵ_{mcu}	ϵ'_{mc}	ϵ_{mch}	$\epsilon_{mch}/\epsilon'_{mc}$
Scheme I	1 layer	32.56	0.0042	0.0056	0.0028	0.0030	1.07
	2 layers	42.36	0.0065	0.0078	0.0057	0.0049	0.86
Scheme II	1 layer	27.33	0.0051	0.0074	0.0045	0.0046	1.02
	2 layers	33.95	0.0058	0.0094	0.0042	0.0036	0.86
Confined to unconfined ratios							
		f_{mc}/f_{m0}	$\epsilon_{mc}/\epsilon_{m0}$	$\epsilon_{mcu}/\epsilon_{mc}$	$\epsilon'_{mc}/\epsilon'_{m0}$	$\epsilon_{mch}/\epsilon_{m0h}$	
Scheme I	1 layer	1.29	1.17	1.33	1.06	1.03	
	2 layers	1.68	1.82	1.20	2.18	1.67	
Scheme II	1 layer	1.38	1.49	1.45	/	/	
	2 layers	1.71	1.69	1.62	/	/	

225

226 In terms of ultimate strain, Scheme I cylinders exhibited an average ultimate axial strain gain of 33% and 20% than
 227 peak strain for one and two layers respectively. For cylinders from Scheme II, the ultimate axial strain increased by
 228 45% and 62%.

229 DIC was not used for four unconfined cylinders: C1_WUn, C4_WUn, C1_CUn and C2_CUn. It should be noted that DIC
 230 results are reliable up to the peak load; after that point, local cracks occurred and strains are not anymore
 231 representative of the global behaviour of the cylinders. The average axial strains at peak for confined cylinders
 232 measured with DIC, were lower than those measured with the transducers by a value between 12% and 33%. All the
 233 axial and hoop stress-strain curves from DIC are plotted in Fig. 7 and Fig. 8, for Scheme I and Scheme II cylinders
 234 respectively and together in Fig. 9 for ease of comparison. The plots show a similar initial slope of all confined and
 235 unconfined specimens. This is likely due to strains being measured in a more consistent way in the middle half of
 236 cylinders and averaged over a considerable number of virtual strain gauges.

237 Regarding hoop strains, the ratio between hoop and axial strain at peak was 1.15 for unconfined Scheme I cylinders,
238 reducing to 1.07 for cylinders confined with one layer and further down to 0.86 for cylinders confined with two layers.
239 Similarly, for Scheme II cylinders the ratio was 1.02 for cylinders confined with one layer and 0.86 for cylinders
240 confined by two layers. As for the strength increments these values show that one BFRP layer was more effective on
241 the weakest masonry (Scheme II) while two layers had a similar effect. The hoop strain of Scheme I cylinders with one
242 BFRP wrap also increased slightly compared to unconfined cylinders (3%), while for cylinders confined by two layers
243 the increment at peak was significantly larger (67%).

Fig. 7 Stress-strain curves in the axial and the hoop directions for Scheme I cylinders (DIC and LVDTs measurements).

Fig. 8 Stress-strain curves in the axial and the hoop directions for Scheme II (DIC and LVDTs measurements).

Fig. 9 Stress-strain curves in the axial and hoop direction using DIC: a) Scheme I; b) Scheme II

Failure modes

Fig. 10 shows the failure modes of confined and unconfined cylinders at the end of the compression tests. The unconfined masonry specimens exhibited, as expected, a brittle behaviour and specimens failed due to large and

256 almost vertical cracks along the height of the specimens. There were not evident differences in the failure mode of
 257 Scheme I and II. In general, vertical joints created preferential routes for the development of cracks, which propagated
 258 at the interface between bricks and mortar joints. This was more evident for Scheme II involving three joints than for
 259 Scheme I where cracks developed also in bricks. At failure, due to the cracks, large portion of bricks between mortar
 260 joints were completely detached from the cylinders.

261 The confined cylinders all failed for the tensile rupture of the BFRP jacket. These specimens were characterized by two
 262 or more almost vertical cracks connected horizontally near a horizontal mortar joint. Local bulging was also visible and
 263 crushed masonry could be observed at the end of the test inside the jackets.

264 There were not considerable differences in the failure mode of cylinders wrapped with one or two BFRP layers.

265

266

267 Fig. 10 Cylinder failure modes: a) Scheme I unconfined; b) Scheme I, 1 layer; c) Scheme I, 2 layers;
 268 d) Scheme II unconfined; e) Scheme II-1 layer; f) Scheme II-2 layers

269 Theoretical predictions

270 In this section the experimental data collected has been compared to the prediction given by analytical models in the
271 literature. Different approaches are adopted, evaluating the reliability of currently available formulations to predict
272 the behaviour of BFRP confined masonry.

273 Confined strength

274 Five analytical models are considered: Campione and Miraglia (2003) [12], (C&M), Kreaikas and Triantafillou (2005)
275 [10] (KRE), Corradi *et al.* (2007) [11] (CO), Di Ludovico *et al.* (2010) [8] (DIL) and the Italian CNR-DT 200/2013
276 Guidelines [15] (CNR). The effective confinement pressure was calculated by the well known rigid body equilibrium of
277 the section:

$$278 \quad f_l = \frac{2t_f f_r}{D} \quad (1)$$

279 where t_f is the grid equivalent thickness and D is the cylinder diameter. In all the above models, except the CNR, the
280 stress in the fabric f_r is calculated based on the maximum strain at failure:

$$281 \quad f_r = \varepsilon_{fu} E_f \quad (2)$$

282 being ε_{fu} its ultimate tensile strain and E_f the elastic modulus.

283 In the CNR model a reduced maximum strain, $\varepsilon_{fd,rid}$ in the composite is used con calculating f_r :

$$284 \quad f_r = \varepsilon_{fd,rid} E_f \quad (3)$$

285 $\varepsilon_{fd,rid}$ being a function of the environmental conversion factor η_a , the characteristic value of the ultimate tensile strain
286 of the FRP ε_{fk} and the partial safety factor γ_f .

$$287 \quad \varepsilon_{fd,rid} = \min \left\{ \eta_a \cdot \varepsilon_{fk} / \gamma_f ; 0.004 \right\} \quad (4)$$

288 The CNR model has also been evaluated using the same confinement pressure equation used for the other models
289 (see Eq. 2) and is indicated by CNR_{mod} in the following.

290 The expressions for calculating the compressive strength of FRP-confined masonry f_{mc} as a function of the effective
291 confinement pressure f_l' and unconfined masonry strength f_{m0} are reported on Table 6.

Confined strain and stress-strain curves

The strain at peak stress of BFRP-reinforced specimens was evaluated taken into account three models proposed by Campione and Miraglia (2003) [12] (C&M), Krevaikas and Triantafillou (2005) [10] (KRE), Cascardi *et al.* (2017) [27] (CAS). Table 7 presents the used formulations. Moreover, a modification of the equation provided by Krevaikas and Triantafillou (2005) is here proposed, in which the coefficient k_2 is modified adopting the value 0.015 instead of the value 0.034 proposed by the authors (indicated by KRE_{mod} in the following).

The full stress/strain curves for BFRP-confined cylinders is obtained by adopting the constitutive law proposed by La Mendola and Papia (2002) [28] for calcarenite masonry members:

$$\frac{\sigma}{f_{mc}} = \frac{A \cdot \bar{\varepsilon} + (U+1) \cdot \bar{\varepsilon}^{-2}}{1 + (A-2) \cdot \bar{\varepsilon} + U \cdot \bar{\varepsilon}^{-2}} \quad (5)$$

$$\bar{\varepsilon} = \frac{\varepsilon}{\varepsilon_{mc}} ; \quad A = \frac{E_{m0}}{E_{sec}^*} ; \quad E_{sec}^* = \frac{f_{mc}}{\varepsilon_{mc}} \quad (6)$$

where f_{mc} and ε_{mc} are respectively the strength and the corresponding strain of FRP-confined masonry, E_{m0} is the Young's modulus of unconfined masonry and U is a parameter which rules the slope of the softening branch. Here two values of U are proposed, equal to 0.75 and 1 for Scheme I and Scheme II respectively, in order to fit the post-peak behaviour of cylinders from the two schemes.

For these curves the strain at peak stress ε_{mc} is evaluated using the modified model of Krevaikas and Triantafillou (2005) ($k_2 = 0.015$) while for the strength the modified CNR_{mod} value was used.

308 Table 6: Analytical models for compressive strength of FRP-confined masonry

Model	Compressive strength of FRP-confined masonry
Campione and Miraglia, 2003 (C&M)	$f_{mc} = f_{m0} + k_1 \cdot f_l'$ $k_1 = 2$
Krevaikas and Triantafillou, 2005 (KRE)	$\begin{cases} f_{mc} = f_{m0} & \text{if } \frac{f_l'}{f_{m0}} \leq 0.24 \\ f_{mc} = f_{m0} \cdot \left(0.6 + 1.65 \cdot \frac{f_l'}{f_{m0}} \right) & \text{if } \frac{f_l'}{f_{m0}} \geq 0.24 \end{cases}$
Corradi <i>et al.</i>, 2007 (CO)	$f_{mc} = f_{m0} + k_1 \cdot f_l'$ $k_1 = 2.4 \cdot \left(\frac{f_l'}{f_{m0}} \right)^{-0.17}$
Di Ludovico <i>et al.</i>, 2010 (DIL)	$f_{mc} = f_{m0} + k_1 \cdot f_l'$ $k_1 = 1.53 \cdot \left(\frac{f_l'}{f_{m0}} \right)^{-0.10}$
CNR-DT 200/2013, (CNR)	$f_{mc} = f_{m0} + k_1 \cdot \left(\frac{f_l'}{f_{m0}} \right)^{\alpha_1} \text{ where } \alpha_1 = 0.5$ $k_1 = \alpha_2 \cdot \left(\frac{g_m}{1000} \right)^{\alpha_3} \text{ where}$ <p>g_m : mass density of masonry</p> $\alpha_2 = \alpha_3 = 1$

309

310 Table 7: Analytical models for strain at peak stress of FRP-confined masonry

Model	Strain at peak stress of FRP-confined masonry
Campione and Miraglia, 2003 (C&M)	$\frac{\varepsilon_{mc}}{\varepsilon_{m0}} = 1 + \rho_f \cdot \frac{1}{\varepsilon_{m0}} \cdot \frac{f_r^2}{E_f} \cdot \frac{1}{f_{m0} + k_e \cdot f_l'}$ <p>where $\rho_f = \frac{2 \cdot [2 \cdot (b - 2r_c) + \pi r_c] \cdot t_f}{b^2 - 4 \cdot [r_c^2 - (\pi r_c^2 / 4)]}$</p>
Krevaikas and Triantafillou, 2005 (KRE)	$\frac{\varepsilon_{mc}}{\varepsilon_{m0}} = 1 + \frac{k_2}{\varepsilon_{m0}} \cdot \frac{f_l'}{f_{m0}} \text{ where } k_2 = 0.034$
Cascardi <i>et al.</i>, 2017 (CAS)	$\frac{\varepsilon_{mc}}{\varepsilon_{m0}} = 1 + \left(\frac{f_l'}{f_{m0}} \right)^{0.5}$

311

312 The experimental/analytical comparisons of strength and peak strain for the BFRP confined cylinders values are

313 reported on Table 8 and Table 9. On Table 8 is reported the effective confinement pressure normalized by the

unconfined masonry strength f'_1/f_{m0} . For each model the relative error (RE) is also reported. The best performing models are printed in bold.

Among the models available in the literature Corradi *et al.* (2007) (CO) provides the lowest relative error. The model slightly underestimates the confined strength by -5% at most for cylinders confined by one layers and by -14% for cylinders confined with two layers. The modified CNR model (CNR_{mod}) provides the best estimates for cylinders confined by two layers (maximum relative error -3%). The other models all underestimate the confined strength by values up to -42% with the maximum errors occurring for cylinders confined by two BFRP layers. A graphical representation of the strength model prediction is given in Fig. 11.

Table 8: Confined strength increment: experimental values vs model predictions

	Specimen	Exp	C&M	KRE	CO	DIL	CNR _{mod}	CNR		
		(f_{mc}/f_{m0})	(f_{mc}/f_{m0})					(f'_1/f_{m0})	(f_{mc}/f_{m0})	(f'_1/f_{m0})
			(RE=relative error %)						(RE)	
Scheme I	C1R_W1L	1.29	1.13	1	1.26	1.13	1.44	0.070	1.18	0.011
	C2R_W1L		-(12%)	-(23%)	-(3%)	-(12%)	(12%)		(-9%)	
	C1R_W2L	1.68	1.27	1	1.45	1.25	1.63	0.130	1.25	0.022
	C2R_W2L		-(25%)	-(41%)	-(13%)	-(26%)	-(3%)		(-26%)	
Scheme II	C1R_C1L	1.38	1.17	1	1.31	1.17	1.50	0.090	1.20	0.014
	C2R_C1L		-(15%)	-(27%)	-(5%)	-(15%)	(9%)		(-13%)	
	C1R_C2L	1.71	1.34	1	1.55	1.31	1.71	0.170	1.28	0.027
	C2R_C2L		-(22%)	-(42%)	-(9%)	-(23%)	(0%)		(-25%)

Fig. 11 Compressive strength increase as a function of normalized effective confinement pressure for BFRP-confined cylinders: a) C&M, KRE, CO, DIL; b) CNR; and c) CNR_{mod}

A comparison between theoretical and experimental strain at peak values of confined cylinder is reported in Table 9. Among the models already available in the literature Cascardi *et al.* (2017) provides the best estimates of the strain (maximum error equal to -14% for one BFRP layers and -17% for two layers). The modified Krevaiakas and Triantafillou (2005) model (KRE_{mod}) also gives very good estimates with maximum relative error for cylinders with two layers equal to -8%.

Table 9: Strain at peak stress of confined cylinders: experimental values vs model predictions

		Exp	C&M	KRE	CAS	KRE _{mod}
Specimen		ϵ_{mc}	ϵ_{mc}			
(RE=relative error)						
Scheme I	C1R_W1L	0.0042	0.0072	0.0063	0.0050	0.0050
	C2R_W1L		(71%)	(50%)	(19%)	(19%)
	C1R_W2L	0.0065	0.0099	0.0086	0.0055	0.0060
	C2R_W2L		(52%)	(32%)	-(15%)	-(7%)
Scheme II	C1R_C1L	0.0051	0.0073	0.0063	0.0044	0.0047
	C2R_C1L		(43%)	(24%)	-(14%)	-(8%)
	C1R_C2L	0.0058	0.0107	0.0092	0.0048	0.0060
	C2R_C2L		(84%)	(59%)	-(17%)	(3%)

The stress-strain results obtained from the analytical model are plotted in Fig. 12. The adopted model is able to predict the average compressive response in terms of peak stress, corresponding strain and slope of ascending and softening branches. The compressive strength of BFRP confined masonry is predicted with enough accuracy, although predictions slightly overestimate the average values of experimental data in the case of one-layer reinforced specimens. In particular, percentage differences between the average experimental values of compressive strength

339 and predicted quantities are equal to 11.5% and 8.7% for one-layer reinforced specimens from Scheme I and Scheme
 340 II respectively. In the case of specimens confined with two BFRP layers, there is almost no scatter between predicted
 341 and experimental average strength values.

342 a) b)

343 c) d)

344 Fig. 12 Comparison between experimental and analytical compressive response of BFRP-confined cylinders:
 345 a) Scheme I and one layer; b) Scheme I and two layers; c) Scheme II and one layer; d) Scheme II and two layers

346 Conclusions

347 Based on the experimental and analytical analyses in the previous sections the following conclusions can be drawn:

- 348 - Unconfined cylinders with three vertical joints (Scheme II) showed an average strength about 20% lower
 349 compared to cylinders with one vertical joint only (Scheme I);
- 350 - BFRP wrapped cylinders failed by tensile rupture of the BFRP jacket. No debonding at the overlapping zone
 351 was observed. The inner masonry core of wrapped cylinders was crushed at failure;

- The BFRP composite significantly increased the strength of the confined cylinders: Increaments of 29% and 38% were observed for one-layer confined cylinders and 68% and 71% for two-layer confined cylinders (Scheme I and II respectively).
- The strain at peak stress increased by 17% and 49% for one-layer confined cylinders (Scheme I and II respectively) and by 82% and 71% for two-layer confined cylinders (Scheme I and II respectively).
- BFRP confined brick masonry cylinders showed a ductile behaviour characterised by a softening branch of the stress-strain curve.
- Among the models available in the literature Corradi *et al.* provides the best strength estimates and a modified version of the CNR model proposed by the authors reduces the relative error further down. Regarding the strain at peak Cascardi *et al.* provides the best estimates and a modified version of Krevaiakas and Triantafillou, 2005 proposed by the authors further improves the predictions.
- The axial stress-strain curves are well predicted by the La Mendola and Papia (2002) model.
- BFRP wraps proved to be an effective method for confining brick masonry cylinders, in addition to other advantages in terms of environmental impact and cost reduction in comparison with carbon or glass fibres production.

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