Influence of bond conditions on the confinement effectiveness of FRCM composites

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Abstract. The behavior of Fabric Reinforced Cementitious Composites (FRCM) have shown to be highly dependent on the bonding conditions of both fabric-matrix and matrix-substrate interfaces. One of the main applications involving FRCM composites concerns the confinement of axially loaded concrete elements. The present paper presents the results of an extensive experimental campaign carried out with the aim of evaluating the confinement effectiveness of FRCM composites when applied with different bond conditions. Cylindrical specimens were confined with two layers of carbon FRCM and tested under cyclic axial loading. The following bond aspects were analyzed: overlapping length, fabric weight, discontinuous and continuous FRCM layer application and fabric impregnation (no impregnation (dry), epoxy resin and fluid cementitious matrix impregnation). Experimental results are discussed in terms of failure modes, axial stress-strain curves, plastic strains, strength and stiffness deterioration due to cyclic loading. The results highlight that bond conditions can influence the confinement effectiveness of FRCM jackets. Among the investigated bond variables fiber impregnation proved to have the highest affect both in terms of axial strength enhancement and axial strain capacity. Lastly, the main parameters that define unloading and reloading paths during axial cyclic loading were analyzed and new formulations were proposed for their prediction in FRCM-confined concrete.

Keywords: confined concrete, FRCM, bond, carbon fabric, cyclic load.

1 Introduction

Confinement is the main technique to enhance strength and ductility of under designed axially loaded elements. Initially the confinement on existing elements was obtained by welded or bolted steel plates while FRP (Fiber Reinforced Polymer) composites have been widely used since the 1990s. Recently FRCM composites have gained popularity among new retrofitting materials due to some advantages as easy application in wet and dry environments, high compatibility with existing masonry and concrete substrates and better performance at high temperatures compared to FRPs [1]. FRCM composites have been proven efficient in confinement techniques both for masonry [2] and concrete elements [3], even though a lower effectiveness with respect to FRPs was observed [2,4]. Compressive axial cyclic loading of FRCM confined concrete has been also investigated [5-7]. Main results indicate that the envelope of the cyclic stress-strain curve matches the monotonic one. Recently, FRCMs has been proven effective also for retrofitting of reinforced concrete (RC) structures affected by corrosion [8,9] or as a repair technique for seismically damaged RC columns [10].

However, when dealing with FRCM composites bond is particularly important as failure generally occurs in the matrix-concrete or fiber-matrix interfaces before reaching the fibers ultimate tensile stress. Different bond conditions can lead to different fiber exploitation in the confining jacket and therefore different confinement effectiveness. In this context, in the present experimental campaign, some main aspects affecting bond in FRCM composites are investigated. Cylindrical plain concrete specimens are confined with FRCM jacketing differing in: 1) overlapping length, 2) fabric nominal thickness, 3) fabric continuity through the layers, 4) fiber coating (dry fabric vs epoxy resin and fluid cementitious matrix coating).

2 Materials and specimens

2.1 Materials characterization

Cylindrical concrete specimens (*b x h* = 150 x 300 mm) were casted using a low class mix design. They were left curing for 28 days in water before FRCM confinement application and, after that, before testing, the FRCM jacket was left curing for other 28 days in plastic bags, in order to maintain the moisture content.

Mechanical characteristics of concrete were determined through compressive tests on three 150 x 300 cylindrical specimens and through indirect tensile test and elastic modulus test that were carried out on three 100 x 200 mm cylindrical samples for each case following the respective test methods standards [11-13]. The results of the tests are summarized in Table 1.

The confining FRCM jacket is realized as a combination of a premixed fiber reinforced thixotropic mortar and a carbon bidirectional fabric. The composites matrix flexural strength ($f_{f,m}$) was characterized by three point bending tests on standard 40 x 40 x 160 mm prismatic specimens while the compressive strength ($f_{c,m}$) was evaluated on the two remaining half's after the bending test following the EN1015-11 recommendations [14]. The mean and standard deviation values, based on at least three tested specimens, are: $f_{c,m}$ = 23.1 ± 2.7 MPa and $f_{f,m}$ = 5.1 ± 0.7 MPa.

The properties of the carbon fabric were provided by the manufacturer in terms of tensile strength (4900 MPa), ultimate elongation (1.8%) and elastic modulus (240 GPa). Two types of carbon fabrics, with the same mechanical properties, that differ only on their nominal thickness (0.047 and 0.061 mm) were used in the experimental campaign.

Table 1. Mechanical characteristics of unconfined concrete.

	f_{c0} [MPa]	f_{ct} [MPa]	E_c [GPa]
Mean	22.4	2.9	23.4
Standard dev.	0.5	0.5	1.4

2.2 Confinement jacket application

The experimental campaign investigates the influence of different bonding conditions on the effectiveness of FRCM confining systems. The bonding parameters considered are: overlapping length (200 and 300 mm), fabric nominal thickness (0.047 and 0.061 mm), fabric layer configuration (continuous and discontinuous layer application) and fiber coating (dry (uncoated); epoxy resin and fluid cementitious matrix coated). The reference confined specimen (Ref), based on previous works by some of the authors [5-6], is considered the ones confined using dry carbon fabric with nominal thickness being 0.047 mm, applied continuously with a final overlapping length of 200 mm. Other specimens nomenclature is obtained by a first letter C (confined) and a second part that highlights the investigating bonding condition and are: *C_061, C_300, C_ disc, C_epoxy* and *C_cement* respectively for fabric with 0.061 nominal thickness, 300 mm overlapping length, discontinuous layer application, epoxy and fluid cement matrix fabric coating.

The confining jacket was applied after 28 days of curing of the initial concrete cylinders. The FRCM application steps were: 1) saturation of the concrete surface with water; 2) application of a first layer of mortar of about 3-4 mm; 3) application of the first carbon fabric layer; 4) application of a second layer of mortar that cover and imbeds the fabric; 5) step 3 is repeated for the second carbon fabric layer application and 6) the last covering mortar layer is applied. To avoid load application on the confining jacket 10 mm space at the top and bottom of the specimens were left uncovered by the jacket.

Fig. 1. Steps of the FRCM confinement jacket application on the cylindrical concrete specimens.

3 Test setup

Specimens were tested under compressive cyclic loading using a universal loading machine. Single loading-unloading cycles were applied using a displacement control mode with a displacement rate of 0.6 mm/min. To ensure a uniform stress distribution in the specimens during testing, both faces (top and bottom) of the cylinder were capped using high strength mortar. Unloading paths are not complete since reloading started when the descending axial load reached about 0.5-0.6 MPa. The test was considered terminated when axial load was lower than 50% of the maximum one.

Test setup is shown in Fig. 1. The axial load was recorded using the load cell (600 kN capacity) of the testing machine. On the other hand, axial strains were recorded using three mechanical strain gages (mSGs) which were installed directly at the surface of the specimens and three linear voltage displacement transducers (LVDTs) that recorded the displacements of the top and bottom steel plates. Strain measuring instrumentation was positioned equally spaced (120^o) with respect to the cylindrical specimens tested.

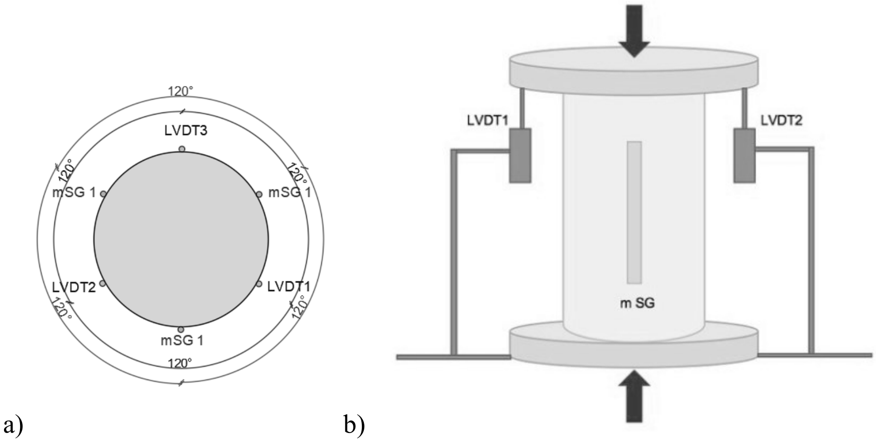

Fig. 2. a) in plane axial strain measurement instrumentation disposition and b) test setup.

4 Results

In this section the test results will be discussed in terms of unconfined concrete peak stress and strain (f_{c0}, ε_{c0}), unconfined ultimate stress and strain (f_{cu}, ε_{cu}), confined concrete first peak stress and corresponding axial strain (f_{cc}, ε_{cc}) and confined concrete ultimate stress and relative axial strain (f_{ccu}, ε_{ccu}). For unconfined concrete ultimate stress is taken at 0.8Pmax while, for confined specimens, peak and ultimate axial stress-strain points are considered as shown in [5], also shown in a simplified way in Fig. 2.

4.1 Failure modes

Crack pattern of some of the tested specimens are shown in Fig. 3. Visible cracks on the FRCM surface were observed only when the axial load equaled approximately the unconfined peak strength. Numerous vertical crack appear during the loading history, however, when the load is close to the ultimate point, one main crack propagates more than the others until failure is reached. Generally, the main crack is located close to the overlapping end of the applied composite. Failure of the confined specimens is mainly due to the reach of the fiber-matrix bond limit with the consequent slippage of the fiber inside the matrix. Failure due to the reach of the fibers tensile strength was observed only for specimens confined with coated carbon fibers.

Fig. 3. Crack pattern observed after testing.

4.2 Influence of bond conditions

Figure 4 compares the mean stress – strain curve of the reference confined specimens (black solid line) with that of specimens that consider different bonding conditions. Later, testing results are discussed for each bonding parameter considered.

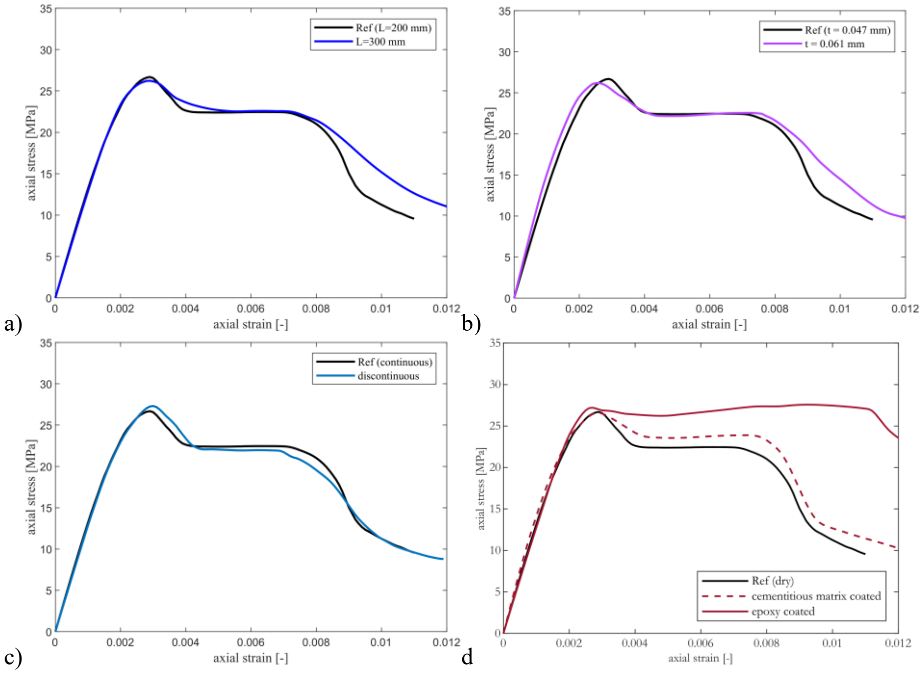

Fig. 4. Mean axial stress-strain curves of the tested specimens. a) 200 vs 300 mm overlapping length, b) 0.047 vs 0.061 mm fabric thickness, c) continuous vs discontinuous layer application and d) dry vs coated fabric.

Overlapping length. Two overlapping lengths were considered on the presented experimental campaign, 200 and 300 mm. [15] suggests for FRCM composites employed in confinement techniques a minimum overlapping length calculated as the maximum between 25% of the specimens perimeter and 300 mm. However, previous research [5, 16] has shown that 200 mm overlapping length can be enough to adequately exploit the confinement jacket. The same is also proven by the present study as can be graphically observed in Fig. 4a where the mean stress-strain curves for specimens with 200 and 300 mm overlapping lengths are compared. Axial stress-strain curves are almost identical with the only difference that curves with higher overlapping length show a slower strength loss after the ultimate point. In both cases, after the first peak (between 1.17 and 1.19 xf_{c0}) the confined strength decreases until reaching f_{c0} and that strength is maintained until axial strains reach nearly 0.8%.

Fabric thickness. The nominal thickness represents the amount of fibers present in the fabric hence, the amount of reinforcement embedded in the composite. However, the limit of the composite system is often determined by the bond capacity between the fiber and the matrix and therefore, a greater quantity of reinforcement may not be fully exploited by the system. Comparing the confinement with two different carbon fabrics, respectively with a nominal thickness of 0.047 mm for the reference and 0.061 mm for the counterpart (Fig. 4b), no clear difference can be observed in the mean stress-strain curves. A similar strength enhancement is obtained in the first peak (slightly lower than 20%) and, after that, axial stress is maintained almost constant close to the f_{c0} value.

Table 2. Summary of test results for confined specimens.

Specimen ID	N. specimens	f_{cc} (MPa)	ε_{cc} (%)	f_{ccu} (MPa)	f_{cc}/f_{c0}	f_{ccu}/f_{c0}	ε_{ccu} (%)	$\varepsilon_{ccu}/\varepsilon_{cc}$
Ref ave.	3	26.7	0.29	22.5	1.19	1.00	0.76	2.62
dev. st.		*0.46*	*0.01*	*0.99*	*0.02*	*0.04*	*0.02*	*0.02*
C_061 ave.	3	26.5	0.27	22.6	1.18	1.01	0.80	3.01
st. dev.		*1.24*	*0.02*	*1.35*	*0.06*	*0.06*	*0.05*	*0.20*
C_disc ave.	3	27.5	0.31	21.9	1.22	0.98	0.72	2.30
st. dev.		*1.05*	*0.03*	*2.85*	*0.05*	*0.13*	*0.03*	*0.25*
C_300 ave.	3	26.3	0.30	22.6	1.17	1.01	0.77	2.61
st. dev.		*0.41*	*0.02*	*1.83*	*0.02*	*0.08*	*0.03*	*0.13*
C_epoxy ave.	3	27.5	0.30	27.7	1.23	1.23	1.10	3.77
st. dev.		*0.08*	*0.06*	*1.88*	*0.00*	*0.08*	*0.05*	*0.69*
C_cement ave.	2	26.6	0.29	24.0	1.19	1.07	0.79	2.77
st.dev.		*0.21*	*0.01*	*0.43*	*0.01*	*0.02*	*0.03*	*0.03*

Layers application. FRCM application for concrete confinement can be carried out in different ways. The two main methods regard the fabric layer application that can be continuous or discontinuous. In the former a single fabric sheet is wrapped around the element and the overlapping zone is one, at the end of the fabric. In the later, one fabric sheet is used for each applied layer and each layer has its own overlapping zone. Discontinuous application is easier as the length of the fabric to be managed is lower but the amount of material (both reinforcement and matrix) is higher due to repeated overlaps and higher jacket thicknesses.

The overall performance of the two methods results quite similar and as can be observed in Fig. 4c no significant differences were recorded. Specimens confined with discontinuous layers showed slightly higher gains in the first peak (22% vs 19%) which is believed to be due to the slightly thicker jacket applied in this case. However, after the first peak, load for discontinuous layers settles to a slightly lower value and ultimate axial strain (ε_{ccu}) is about 0.7%.

Fiber coating. The presence of coating in the fabric effects directly the interface bond between the fabric and the matrix and allows to better exploit even the innermost fibers in the yarns. Generally fabrics can be epoxy resin or SBR coated. However, polymeric coating can also have some drawbacks as poor performance high temperatures. For this, herein two fiber coatings are considered: epoxy-resin and fluid cementitious matrix coated. Their mean axial stress-strain curves are compared to the one for dry carbon fabric in Fig- 4d.

In the first peak no significative differences are observed within the considered parameters with the epoxy-coated fabric showing a slightly higher gain (23%) with respect to the other two (19%). A clear improvement is observed after this point with the epoxy coated specimens performing significantly better than the other two and showing almost a hardening behavior. Specimens with fibers impregnated in the fluid cementitious paste showed also a slight improvement recording a mean ultimate stress 7% higher with respect to the ones confined with dry fibers. Specimens confined with epoxy coated fibers showed also the best axial ductility with a mean ultimate axial strain of 1.1%.

5 Conclusions

The presented research work investigated the influence of bond aspects on the effectiveness of FRCM confinement jackets. The considered parameters are: overlapping length, fabric nominal thickness, fabric layer continuity and fiber coating. The experimental results showed that overlapping length and nominal thickness had no significant influence on the overall confined-concrete behavior. FRCM jackets applied with continuous and discontinuous layers showed only slight differences in the first peak and in the post peak with discontinuous layers performing better in the former and worse in the later. Fiber coating was the parameter that most influenced the behavior of FRCM-confined concrete. Fluid cementitious coating improved the ultimate strength in the post-peak branch by 7% while the best results were observed for epoxy coating both in terms of strength and strain capacity and showing also a clear hardening behavior in the stress-strain curves.

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