Effect of Confinement with FRCM Composites on Damaged Concrete Cylinders

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ABSTRACT

Confinement of axially loaded concrete members in existing structures is required when a change in use is expected or when there is a need to upgrade the structure to meet current design standards. In addition, after unusual overloading events (e.g., earthquakes), axially loaded members can suffer damage that increases the need of their retrofitting by means of confinement. The study of fiber reinforced cementitious matrix (FRCM) composites for confinement of compression members has gained attention in recent years due to the capability to overcome some of the disadvantages associated with more traditional strengthening techniques. However, the available experimental evidence is still scarce, and research on the topic is necessary. In this paper, the results of an experimental campaign performed on concrete cylinders confined with FRCM jackets are presented. Before strengthening, some specimens were preloaded in order to achieve specified damage levels. The specimens were then subjected to uniaxial concentric compressive loading. The axial load and axial strain response was recorded for each specimen. In addition, the elastic modulus of confined and unconfined specimens was determined. Results show that confinement with FRCM composites is able to provide an increase in the axial capacity of undamaged and damaged concrete cylinders.

Keywords: FRCM composites, strengthening, confinement, concrete, damage.

INTRODUCTION

When uniaxially loaded concrete is restrained from dilating laterally, it exhibits increased strength and axial deformation (De Lorenzis & Tepfers 2003). This behavior becomes useful for the strengthening of existing concrete structures in which higher axial load capacities are required, or for improving the seismic performance of deficient concrete structures.

Traditional techniques for constraining the lateral dilatation of concrete, i.e., confinement, include concrete and steel jacketing. These techniques have been used to increase the confinement action in either the potential plastic hinge regions or along the entire member (Triantafillou et al. 2006). However, drawbacks associated with these techniques have been pointed out, such as undesirable changes in weight and handling of heavy steel parts. The use of Fiber Reinforced Polymer (FRP) composites has become a viable alternative to these techniques and has become increasingly popular worldwide. FRP composites are well known by their high strength-to-weight ratio and ease of installation, which allows them to overcome the shortcomings of more traditional methods. Nevertheless, the use of organic resins to impregnate the fibers has been linked to some disadvantages of this system, such as the susceptibility to UV radiation and poor behavior for high temperatures, among others (Al-Salloum et al. 2012).

For this reason, in recent years there has been a growing interest in the development of strengthening techniques that combine the positive characteristics of FRP composites but address their limitations. Among these techniques, the use of Fiber Reinforced Cementitious Matrix (FRCM) composites has shown promising results, as proven by their capability to increase the axial, flexural, shear, and torsional capacity of strengthened elements (Triantafillou et al. 2006; Ombres 2011; Tetta et al. 2015; Alabdulhady et al. 2017). FRCM composites are comprised of high strength fibers embedded in an inorganic matrix, usually cementitious, which replaces the organic resins present in FRP composites. Regarding the use of FRCM composites as means of providing confinement for concrete members, the limited available experimental evidence has shown that the increase in axial capacity and deformability provided by the system, although generally lower than their FRP counterparts, presents a less abrupt failure mode (Colajanni et al. 2014; Triantafillou et al. 2006).

Currently there is only one available design guideline (ACI Committee 549 2013) that deals with the use of FRCM composites for strengthening of concrete structures. However, the equations proposed in that guideline were calibrated using a limited database of experimental data, and therefore, there is a need to carry out research on the topic to obtain more accurate and reliable design formulations. In addition, aspects such as the effect of FRCM confinement on damaged members has not been well established as research on this topic is extremely limited.

In this paper, the results of an ongoing experimental campaign aimed to increase the limited experimental database of tests carried out on concrete members confined with FRCM composites are presented. Furthermore, the effectiveness of the strengthening technique in restoring the axial capacity of pre-damaged concrete cylinders is studied.

EXPERIMENTAL PROGRAM

In order to study the effect of FRCM confinement on damaged and undamaged concrete members, compressive strength tests were performed on concrete cylinders of 150 mm diameter and 300 mm height. Three different experimental series, named according to the convention CC*a*L*b*D*c*-#, where *a* corresponds to the type of surface preparation (N for specimens without surface preparation, and M for mechanical grinding), *b* refers to the number of FRCM layers, *c* is the level of damage (0 for undamaged specimens, and 100 for damaged specimens), and # is the specimen number, were tested. Each series is comprised of three identical specimens.

The planarity and parallelism of the top and bottom surfaces of the specimens was achieved by mechanical grinding. In order to inflict damage in specimens of series CCL1D100, specimens were tested in compression past the peak load until the load dropped below 95% of the peak load and then unloaded. This procedure took place after 28 days of casting of the cylinders.

Materials. The concrete cylinders were cast in three batches with an average compressive strength f'_c at 28 days of 35.1 MPa (COV= 0.055). Normal weight portland cement concrete with a maximum aggregate size of 12.5 mm was employed.

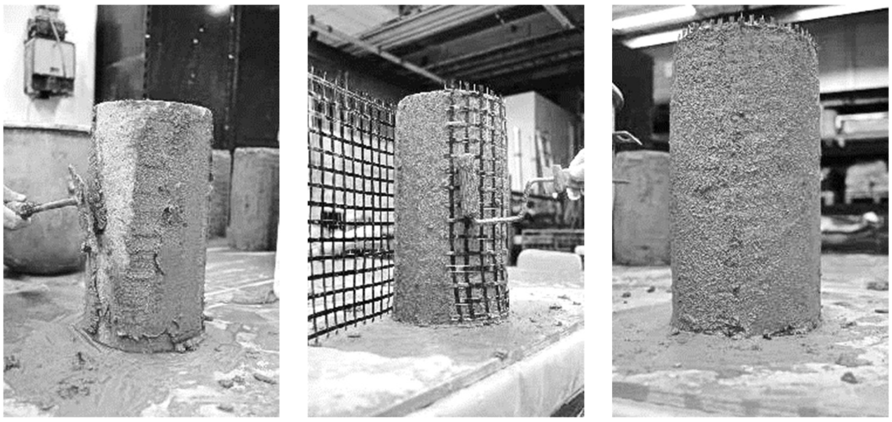
The FRCM system employed in this study was commercially available from a single manufacturer. A fiber-reinforced mono-component cementitious matrix, with an average compressive strength f_{cm} is 25.0 MPa, as reported by the manufacturer (G&PIntech 2016), was employed. Carbon fibers consisted of a bidirectional, balanced, dry, open mesh textile. The overall area weight W, elastic modulus E_f, tensile strength f_u, ultimate strain ε_{fu}, and equivalent nominal thickness in each direction t_f of the fibers, as reported by the manufacturer (G&PIntech 2016), are summarized in Table 1.

Table 1. Fiber properties reported by the manufacturer (G&PIntech 2016)

Fiber Type		W	E_f	f_u	ε_{fu}	t_f
		g/m^2	GPa	MPa	%	mm
Carbon	Bidirectional (balanced)	170	240	4700	1.8	0.047

Strengthening procedure. Before installing the FRCM system, the concrete surface of the cylinders was subjected to mechanical grinding, and any loose sand grains were removed. The concrete surface was then wetted, and the first layer of cementitious matrix, of approximately 2-4 mm thickness, was applied as shown in Figure 1a.

Immediately after, the fibers were placed on top of the matrix, applying a slight pressure with a plastic roll (see Figure 1b). The overlapping length of the fibers was approximately 200 mm. While the first layer of matrix was still fresh, the second layer was applied on top of the fibers (see Figure 1c). The second layer surface was then superficially wetted, and the specimens were covered with a plastic sheet. After three days, the specimens were uncovered, superficially wetted and covered again and remained in the laboratory until the day of testing.

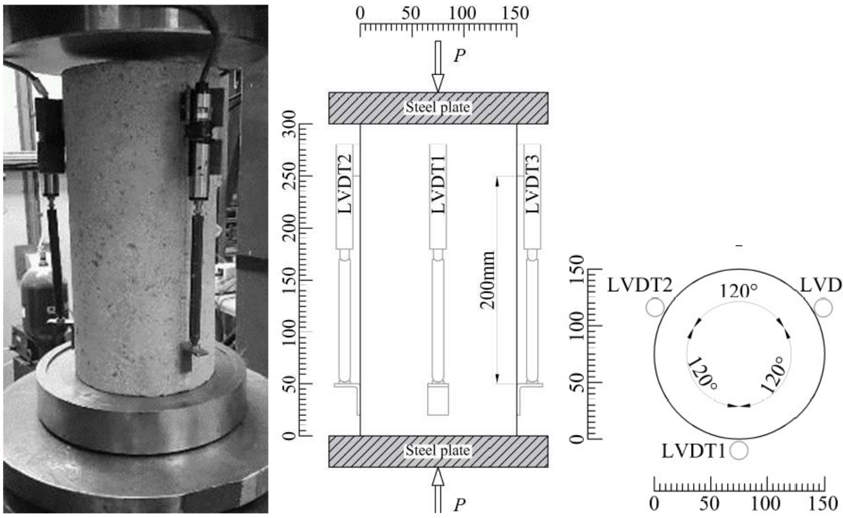


a) **b)** **c)**

Figure 1. Strengthening procedure: a) application of first layer of matrix, b) placement of carbon fiber mesh, c) strengthened specimen.

Test Set-up.

The test set-up used to measure axial load and strains is presented in Figure 2.



a) **b)** **c)**

Figure 2. Test setup: a) overview, b) schematic

Tests were carried out in a 6 MN uniaxial compressive testing machine (see Figure 2a) equipped with load cell (certified for class 1 accuracy). The load P was applied in load control at a rate of 11 kN/s up to 2/3 of the expected maximum load following the sequence described in (EN-12390-13 2016). The expected maximum load was the average load measured during the damage infliction phase. Subsequently the load was applied in stroke control at a rate of 0.005 mm/s. The loading sequence was stopped when the load dropped below 200 kN. Three linear variable displacement transducers (LVDTs) with a measurement range of 5 mm were used to measure the concrete strain in axial direction. The LVDTs were attached directly to the concrete for the unstrengthened specimens as shown in Figure 2b,c and to the mortar jacket for the strengthened specimens. Readings obtained from the three LVDTs and load cells were recorded using a data acquisition system at a frequency of 10 Hz.

RESULTS AND DISCUSSION

Table 2 summarizes the values of compressive strength and elastic modulus for unconfined (f_{co}, E_{co}) and confined (f_{cc}, E_{cc}) cylinders, as well as the respective coefficient of variation (COV).

Table 2. Compressive strength and elastic modulus of tested specimens.

	Compressive strength			**Elastic modulus**		
SPECIMEN	**f_{co} or f_{cc} (MPa)**	**f_{co} or f_{cc} Mean [COV]**	**f_{cc}/f_{co}***	**E_{co} or E_{cc} (MPa)**	**E_{co} or E_{cc} Mean [COV]**	**E_{cc}/E_{co}***
CCNL0D0-1	34.5	36.8 [0.054]	-	22.5	22.8 [0.011]	-
CCNL0D0-2	38.3			23.0		
CCNL0D0-3	37.6			22.9		
CCML1D0-1	38.8	40.1 [0.031]	1.09	25.3	26.9 [0.055]	1.18
CCML1D0-2	40.2			28.0		
CCML1D0-3	41.3			27.5		
CCNL0D100-1	32.0	33.5 [0.040]	(0.91)	18.9	19.7 [0.036]	(0.86)
CCNL0D100-2	34.1			20.1		
CCNL0D100-3	34.5			20.2		
CCML1D100-1	35.3	36.5 [0.055]	1.09 (0.99)	23.7	25.5 [0.074]	1.29 (1.12)
CCML1D100-2	35.4			27.6		
CCML1D100-3	38.8			25.3		

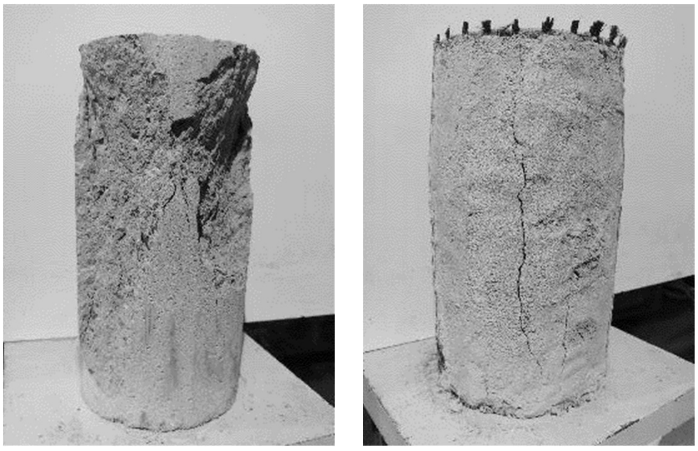
*Value in parenthesis is with respect to the CCNL0D0 series.

Values of f_{cc} and f_{co} are computed as the ratio between the peak axial load P_{peak} and the cross-section area of the cylinders, without including the jacket, A (f_{cc}, $f_{co} = P_{peak}/A$). Values of E_{co} and E_{cc} were computed according to (EN-12390-13 2016). Table 2 also includes the variation in compressive strength and elastic modulus with respect to the corresponding unconfined specimens, i.e., damaged or undamaged, provided by the confinement system, computed as f_{cc}/f_{co} and E_{cc}/E_{co}, respectively. For damaged specimens, Table 2 also includes values of f_{cc}/f_{co} and E_{cc}/E_{co} (shown in parenthesis) with respect to the CCNL0D0 series.

Comparing the results of Series CCNL0D0 and CCML1D0, results in Table 2 show that the confinement was able to increase the axial capacity by 9% for undamaged specimens. An increase in the elastic modulus was also observed (18%), but it is worth noting that such increase is not proportional to the increase in the axial capacity.

Comparing the results of Series CCNL0D0 and CCML1D100, it is observed that the confinement allowed the damaged specimens to reach the original compressive strength of the undamaged cylinders. Regarding the elastic modulus, E_{cc}/E_{co} of the series CCML1D100 specimens is equal to 1.12 when compared to CCNL0D0 specimens and 1.29 when compared to CCML100DO series. This means that the confinement is not only able to restore the original stiffness of the specimen, but it actually enhances it. This increase in stiffness is explained by the fact that in damaged specimens the concrete dilates quickly when loaded because of the disintegration of material caused by predamage (Wu et al. 2014).

For specimens of series CCL0D0, i.e. unconfined cylinders, a typical compression failure was observed (see Figure 3a). For confined specimens (CCML1D0 and CCML1D100 series), longitudinal cracks distributed around the cylinders on the surface of the composite started to develop before the peak load was attained.



a) **b)**

Figure 3. Failure mode: a) specimen CCL0D0-1, b) specimen CCML1D0-1

As the load P increased, the cracks continued to grow in length and width (see Figure 3b), which indicates slippage of the fibers, and the concrete started to crush inside the FRCM jacket. Full detachment of the FRCM jackets was not observed, but for some specimens, small sections of the external matrix layer were easily removed after the specimens were unloaded. The failure mode of confined specimens was less brittle than that observed for unconfined cylinders.

CONCLUSIONS

The effectiveness of FRCM composites to increase the axial capacity and elastic modulus of concrete cylinders was evaluated in this paper by means of uniaxial concentric compressive tests performed on damaged and undamaged concrete cylinders. The main conclusions that can be drawn from the experimental results of the FRCM strengthened cylinders are summarized as follows:

- Confinement of concrete cylinders with FRCM jackets was able to increase the axial strength of the undamaged, strengthened members by approximately 9%. For the case of damaged cylinders, the confinement system restored the original axial capacity of the members.
- Confinement of concrete cylinders with FRCM jackets resulted in an increase in the elastic modulus relative to the unconfined control specimens of 18% for undamaged cylinders. For damaged specimens, the increase in stiffness was equal to 12% and 29% when compared to unconfined undamaged and damaged specimens, respectively.
- The failure mode of the concrete cylinders with FRCM jackets can be described as crushing of the confined concrete. Before failure, longitudinal cracks in the cementitious matrix, which indicate the occurrence of fiber slippage, were observed. The failure mode of FRCM confined cylinders was less abrupt than unconfined specimens.

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