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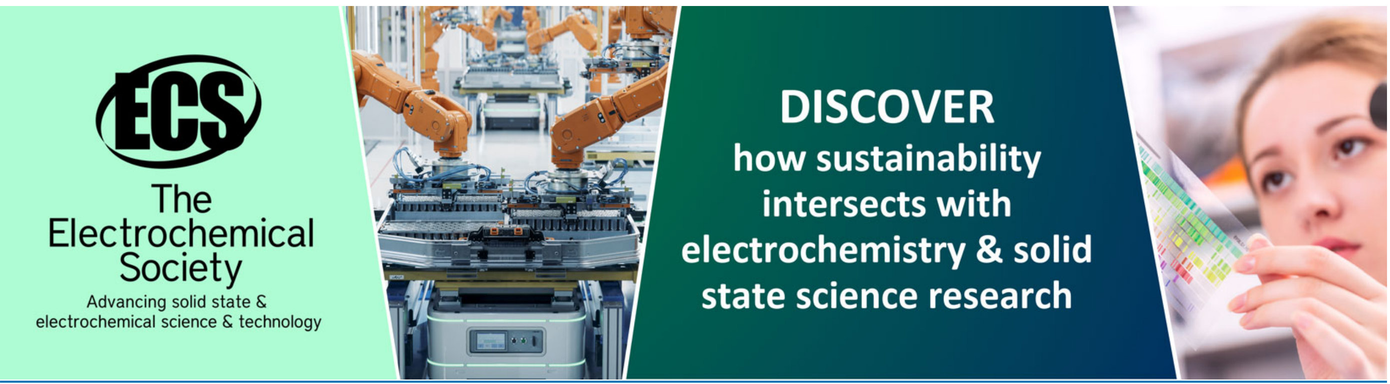

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# Experimental and numerical investigation of plain concrete columns strengthening by FRCM composite material

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**Abstract**. The Fibre Reinforced Cementitious Matrix (FRCM) composite material is a relatively new retrofitting system which overcomes the limitations related with the use of organic adhesives. FRCM system is used to increase the strength and overall ductility of masonry and concrete structures. This paper presents the results of an experimental program on plain concrete columns strengthened by FRCM under uniaxial compression loading. Six columns of square 30x30 cm cross-section and 100 cm height made of low-strength concrete were cast in place. Two columns without confinement are used as reference, while two columns with one layer of FRCM and two columns with two layers of FRCM are used to investigate the influence of FRCM confinement level. The FRCM system consists of high-strength carbon fibre mesh and cementitious mortar. The performance of FRCM strengthened columns is evaluated in terms of ultimate axial load carrying capacity, ultimate axial deformation, ultimate stress and ultimate strain. The experimental results are also compared with the numerical results obtained according to ACI 549.4R-13 code.

## 1. Introduction

Throughout the last decades, researchers have proposed different retrofitting techniques to increase the load carrying capacity and ductility of concrete structures. Some of them use traditional materials, like reinforced-concrete jacketing and steel jacketing, while more recent techniques use fiber reinforced polymer (FRP) jacketing [1]. FRP jacketing were developed to overcome the problems of using the traditional materials: increased dimensions and weight (concrete jacketing), steel corrosion (steel jacketing). FRP jacketing has several advantages: high strength-to-weight ratio, resistance to corrosion and fast and easy application [2]. However, FRP jacketing has disadvantages related to the organic matrices, which are combustible and requires special treatment of the surface of the retrofit element prior its application. Therefore, Fibre Reinforced Cementitious Matrix (FRCM) material was proposed as a retrofitting system to overcome the limitations related with the use of organic adhesives.

The FRCM system consists of high strength fibre mesh and cementitious mortar. FRCM has several advantages over the traditional FRP jacketing: it is less affected by temperature fluctuations, it is inherently incombustible, possesses porous properties, can be applied to concrete elements in low temperature conditions and also on wet surfaces, is an effective retrofit system for concrete elements loaded in bending [3-5], in torsion [6], but also in compression [7-12].

There are many types of FRCM currently available on the market based on the type of fibres used, which can include glass, carbon and polyparaphenylene benzobisoxazole (PBO). With each type of fibre, certain polymer-modified and or fibre-reinforced cement mortars should be used [13]. In this experimental study, the carbon fibre was adopted in combination with fibre mortar.

The FRCM composite material is applied on the external surfaces of compression members to enhance the axial load capacity; the stress-strain for FRCM-confined concrete is illustrated in figure 1 [14]. It was shown by [15] that the effective confined area depends on the shape of the column's cross-section (see figure 2). The entire cross-sectional area is confined for the case of circular columns, and only partial confinement for the cases of square and rectangular cross-sections. In practical engineering square columns are more commonly used due to technological and architectural reasons. Thus, in this study the square cross-section was used with corner radius to improve the effectiveness of confinement.

Since the FRCM is a relatively recent strengthening system, the number of experimental research on short plain concrete columns is limited [7-9]. Different parameters were investigated (cross-section shape, eccentricity, ratio and orientations of fibers) and the outcome of the studies was that the FRCM increased the strength and the ductility of the specimens. The aim of this experimental study is to investigate the influence of the number of layers of the fiber mesh, as part of the FRCM system, on the axial load carrying capacity and axial deformation of the short plain concrete columns made of low strength concrete. Also, the stress-strain curves of the confined and unconfined specimens and their corresponding failure modes are investigated.

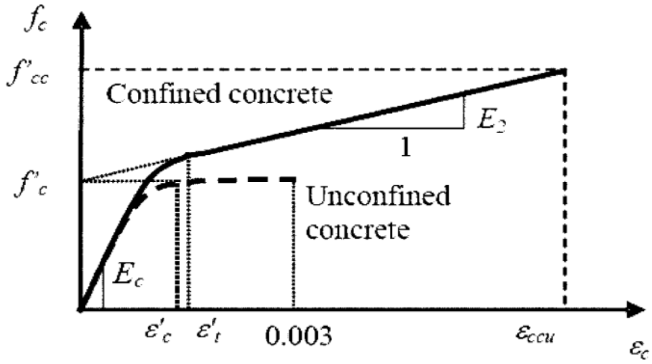


**Figure 1.** Idealized stress-strain diagram for FRCM-confined concrete [14].

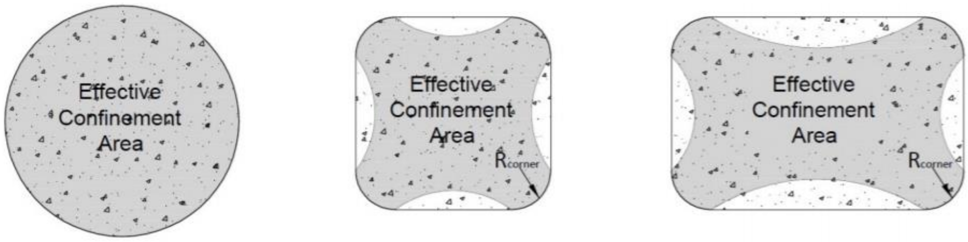


**Figure 2.** Effective confinement areas in circular, square and rectangular columns [15].

## 2. Experimental program

### *2.1. Column typologies*

Six plain concrete columns of 100 cm height were cast-in-place from a low-strength concrete. A squared cross-section 30x30 cm with fillet rounds of radius 3 cm was adopted. The columns are grouped in three typologies, as follows. Two specimens (CP-1, CP-2) were considered reference specimens and therefore were tested without being strengthened with FRCM composite material (see figure 3 a)). The remaining four columns were confined with FRCM: two specimens (CP-3, CP-5) were confined with one layer of FRCM (see figure 3 b)), while two specimens (CP-4, CP-6) with two layers of FRCM (see figure 3 c)).

The FRCM system consists of a fiber mesh and a mortar. The thickness of the FRCM jacket depends on the number of layers of fiber mesh, because a 0.5 cm layer of mortar is required before and after application of a layer of mesh. Therefore, two layers of mortar were applied for columns with one layer of mesh, and three layers (one additional intermediate layer) of mortar were applied for columns with two layers of mesh. After FRCM jacketing, the cross-section of the specimens CP-3 and CP-5 resulted 32x32 cm, while for specimens CP-4 and CP-6 resulted 33x33 cm.

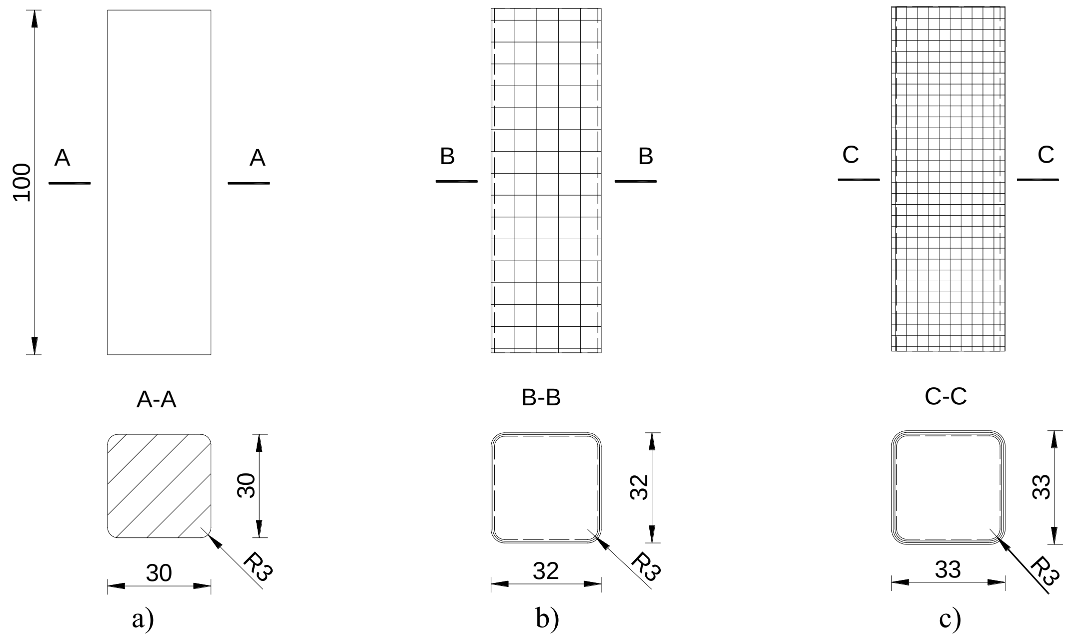


**Figure 3.** Geometry of specimens: a) CP-1, CP-2, b) CP-3, CP-5, c) CP-4,CP-6 (dimensions in cm).

### *2.2. Materials*

A low-strength concrete material was used for the columns. The mixture was designed to provide class C20/25 concrete. For that, a water/cement ratio equal to 0.67 was used, resulting a cement dosage of 280 kg/m$^3$, and river sand as the fine aggregate and gravel with maximum size 16 mm as a coarse aggregate. Prior mixture, the aggregates were thoroughly washed and dried. Cube samples (15x15x15 cm) were taken from each cast and tested under uniaxial compression at 7 and 28 days after curing. The average strengths are summarized in table 1.

A high-strength carbon fibre with 1x1 cm mesh, Mapegrid C170, was used to confine the columns. For a density of fibers of 1.83 g/cm$^3$ it has a tensile strength of 5000 N/mm$^2$. The modulus of elasticity is 252000 N/mm$^2$, while the elongation at failure is 2%. The equivalent thickness of the dry fabric is 0.048 mm.

Planitop HDM mortar was used as matrix for FRCM system. It is a two-component (component A powder and component B liquid), high-strength, cement-based, fibre-reinforced mortar with fine-grained selected aggregates, special admixtures, and synthetic polymers in water dispersion. According to data sheet, the compressive strength after 28 days reaches at least 28 N/mm$^2$, while the compressive modulus of elasticity is 11000 N/mm$^2$.

### *2.3. Experimental program*

The experimental program included two sets of tests: on concrete columns and on concrete base material. While the tests on base concrete material were discussed at section 2.2, the tests on columns are summarized in table 2. It consists of six short concrete column specimens monotonically loaded under uniaxial compression up to failure. Two specimens CP-1 and CP-2 were not confined with FRCM as to be considered as reference. While for the other specimens, the number of layers of FRCM varied, cross-sectional area and compressive strength of concrete material.

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**Table 1.** Compression strength of concrete samples.

| Specimen | Average compressive strength of concrete at 7 days (N/mm$^2$) | Average compressive strength of concrete at 28 days, $f_{c,cube}$ (N/mm$^2$) | Equivalent cylinder compressive strength, $f_{c,cyl} = 0.8 f_{c,cube}$ (N/mm$^2$) |
|---|---|---|---|
| CP-1 | 14.63 | 22.50 | 18.00 |
| CP-2 | 14.72 | 24.54 | 19.60 |
| CP-3 | 17.52 | 21.00 | 16.80 |
| CP-4 | 17.52 | 21.00 | 16.80 |
| CP-5 | 16.39 | 20.00 | 16.00 |
| CP-6 | 16.39 | 20.00 | 16.00 |

**Table 2.** The experimental program.

| Specimen | Cross-section area (cm) | Compressive strength of concrete, $f_{c,cube}$ (N/mm$^2$) | No. of FRCM layers |
|---|---|---|---|
| CP-1 | 30x30 | 22.50 | - |
| CP-2 | 30x30 | 24.54 | - |
| CP-3 | 32x32 | 21.00 | 1 |
| CP-4 | 33x33 | 21.00 | 2 |
| CP-5 | 32x32 | 20.00 | 1 |
| CP-6 | 33x33 | 20.00 | 2 |

### *2.4. Experimental setup*

The experimental setup is presented in figure 4. It consists of a short column under uniaxial centric compression. The column was placed vertically and centered to the two steel plates. An electro-hydraulic universal testing machine with a vertical load capacity of 3000 KN was used to monotonically apply the load. The tests were performed at the Laboratory of Technical University of Civil Engineering of Bucharest.

The reaction force recorded by the press and the axial deformation measured using mechanical dial gauge were monitored. The axial stress was obtained by dividing the reaction force to the initial cross-sectional area of the column. The axial strain was obtained by dividing the monitored deformation to the initial gauge length of 50 cm. Axial strains were noted for every 200 KN increment of load in the first 1000KN and every 100KN from 1000KN up to the failure load. The centering of the specimen was necessary to avoid eccentric loading before the test, which was achieved by comparing the axial strain readings of the front side and back side, respectively.

## 3. Experimental results

The column performance is evaluated through the parameters axial load carrying capacity $N_{max}$, maximum axial deformation $D$, maximum axial strain $\varepsilon_{max}$. The results are summarized in table 3.

### *3.1. Axial load carrying capacity and axial compressive strength*

The axial load carrying capacity $N_{max}$ and the axial compressive strength of confined specimens $f_{c,exp}$ is increased compared to the reference (unconfined) specimens (see table 3). The axial load carrying capacity and axial compressive strength increases with the number of FRCM layers. The increase in axial load carrying capacity for confined specimens is expressed in table 3 relative to the average load capacity of CP-1 and CP-2. The results are grouped according to the number of FRCM layers provided (reference, 1 layer, 2 layers). Thus, adding one layer of FRCM provided the specimens CP-3 and CP-5 with an additional 13.17% capacity, relative to average capacity of reference specimens CP-1 and CP- 2. A 14.53% capacity increase was obtained for two-layer specimens CP-4 and CP-6, relative to the reference average capacity. Similar results were obtained for the axial compressive strength.

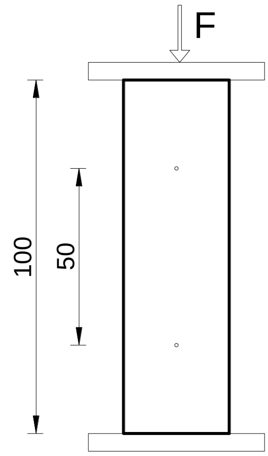



**Figure 4.** Experimental test setup and instrumentation (dimensions in cm).

**Table 3.** Experimental results on concrete columns.

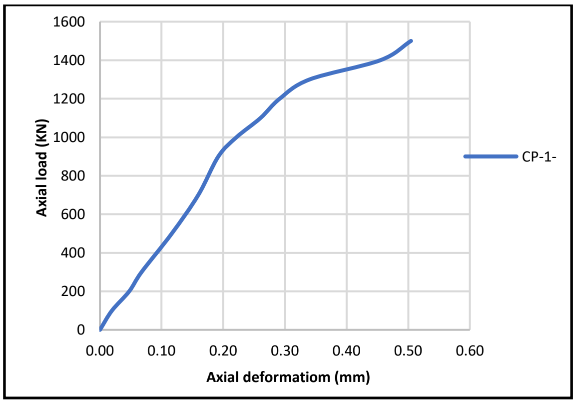
| Speci-men | FRCM layers | $N_{max}$ (kN) | $N_{max,ave}$ (kN) | $N_{max}$ increase (%) | $f_{c,exp}= N_{max}/A_c$ (N/mm$^2$) | $f_{c,ave}$ (N/mm$^2$) | $f_c$ increase (%) | $D$ (mm) | $\varepsilon_{max}$ (mm/mm) |
|---|---|---|---|---|---|---|---|---|---|
| CP-1 | - | 1830 | 1875 | - | 20.33 | 20.83 | - | 0.505$^*$ | 0.001009$^*$ |
| CP-2 | - | 1920 | | | 21.33 | | | 0.445$^*$ | 0.000889$^*$ |
| CP-3 | 1 | 2130 | 2122 | 13.17 | 23.67 | 23.58 | 13.20 | 0.424$^*$; 0.615$^{**}$ | 0.000848$^*$; 0.001230$^{**}$ |
| CP-5 | 1 | 2114 | | | 23.49 | | | 0.472$^*$; 0.645$^{**}$ | 0.000944$^*$; 0.001289$^{**}$ |
| CP-4 | 2 | 2160 | 2147.5 | 14.53 | 24.00 | 23.86 | 14.54 | 0.416$^*$; 0.567$^{**}$ | 0.000831$^*$; 0.001133$^{**}$ |
| CP-6 | 2 | 2135 | | | 23.72 | | | 0.431$^*$; 0.533$^{**}$ | 0.000862$^*$; 0.001066$^{**}$ |

$^*$ measured at 1500 kN. $^{**}$ measured at 1700 kN. $A_c$ cross-sectional area of concrete only.

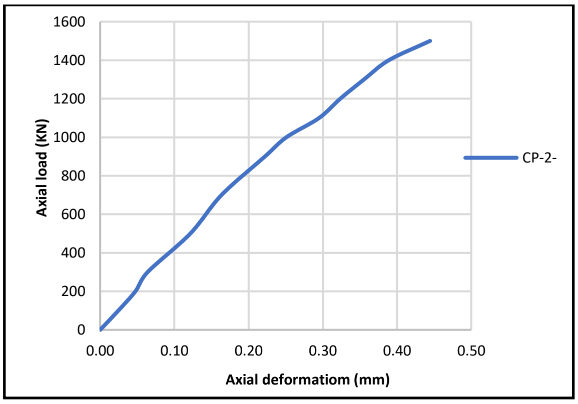
### *3.2. Axial deformation and axial strain*

Due to the damage of the exterior surface of columns caused by cracking during testing, the measurements of the axial deformation $D$ were possible up to 1500 kN for CP-1 and CP-2 and up to 1700 kN for the other specimens. Table 3 presents the values at both force level, where available, in view of comparison. It can be observed that the use of FRCM system reduced the maximum deformation for the same level of axial force; for example, in case of unconfined specimen CP-1 the deformation at 1500kN is 0.505 mm, while for one layer FRCM specimen CP-3 the corresponding deformation is 0.424 mm. Also, using two layers of FRCM (CP-4, CP-6) slightly reduces the deformation with respect to one-layer specimens (CP-3, CP-5); for example, in case of one layer specimen CP-3 the deformation at 1500kN is 0.424 mm, while for tow-layer FRCM specimen CP-4 the corresponding deformation is 0.416 mm. In figure 5 are presented the axial load -deformation curves for all specimens.

The maximum strains are summarized in table 3 and follow the same trend as the deformation.




a)

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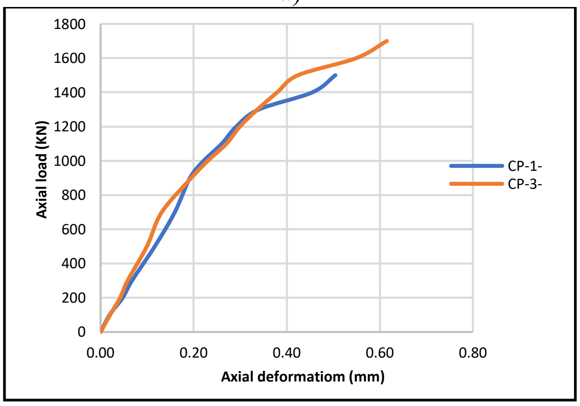
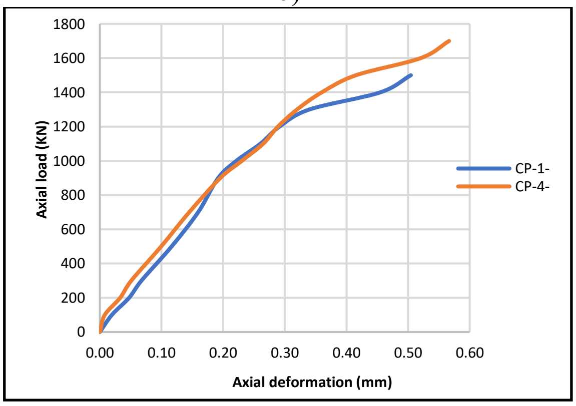
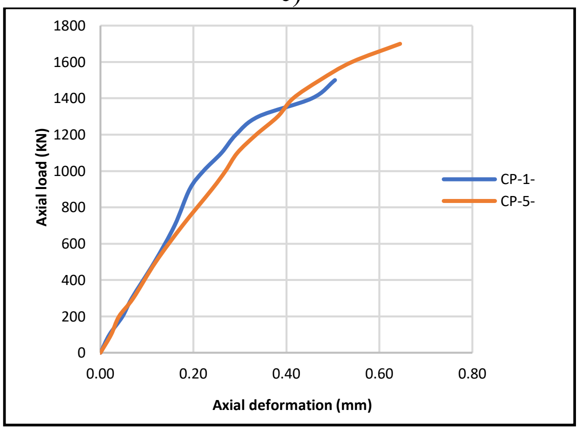


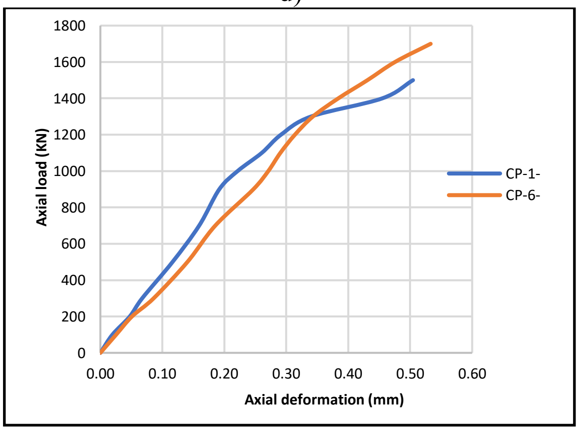

c)




d)




e)




f)

**Figure 5.** Axial load–deformation curves: a) CP-1, b) CP-2, c) CP-3, d) CP-4, e) CP-5 f) CP-6.

### *3.3. Failure mode*

The failure of the specimens confined by carbon FRCM jackets was observed at/near mid-height of the specimens. The failure starts as a crack at mid-height of specimen and starts to vertically grow to extremities of the specimen until the failure occurs (figure 6). As the axial load increased, the cracks continued to grow in length and width, which indicated slippage of the fibers, and the concrete started to crush inside the carbon FRCM jacket. While increasing the axial load, the cracks initiate at about 95 % of the maximum axial load applied, then the failure occurred suddenly. Full detachment of the carbon FRCM jackets was not observed, but for some specimens, small parts of the mortar layer were easily removed after the specimens were unloaded. The failure mode of confined specimens was less brittle than that observed for unconfined specimens.

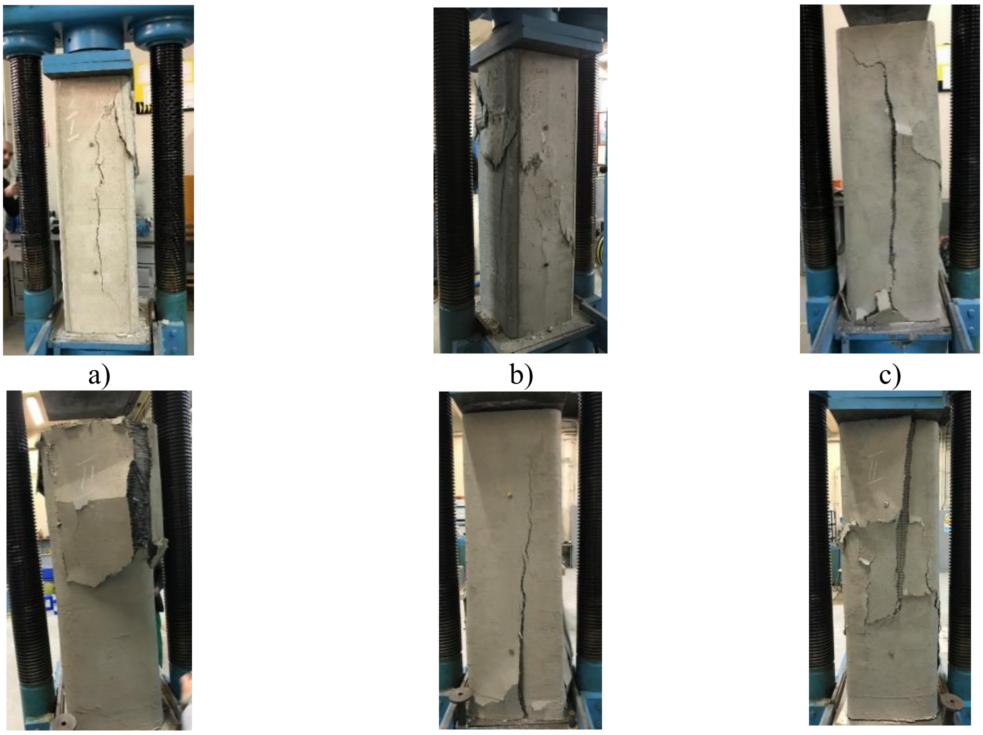



**Figure 6.** Failure modes: a) CP-1, b) CP-2, c) CP-3, d) CP-4, e) CP-5 f) CP-6.

**Table 4.** Numerical results on confined concrete columns [14] [16].

| Specimen | $P_n$ (kN) | $P_{nNew}$ (kN) | Capacity increase (%) | $P_{nNew}/N_{max}$ |
|---|---|---|---|---|
| CP-3 | 1512 | 1600 | 5.81 | 0.75 |
| CP-4 | 1512 | 1688 | 11.62 | 0.78 |
| CP-5 | 1440 | 1527 | 6.05 | 0.72 |
| CP-6 | 1440 | 1615 | 12.15 | 0.76 |

## 4. Numerical results

Table 4 presents the numerical predictions of the design axial load capacity before $P_n$ and after confinement $P_{n,New}$, according to [16] and [14], respectively. The American code ACI 549.4R-13 [14] was selected to do these numerical predictions. The predictions were performed according to table 22.4.2.1 from [16] considering nonprestressed member concrete, thus, a limitation of the design axial strength to 80% of the nominal strength. For the calculation of the new design column axial strength $P_{nNew}$ only the contribution of concrete section and fibers are taken into consideration, according to [14]. Comparing the numerical results for $P_{nNew}$ with experimental results of $N_{max}$ it can be observed that the numerical results are very conservative. In average, there is a 25% reserve of axial capacity.

## 5. Conclusions

This paper presents the experimental results on short low-strength plain concrete columns confined by FRCM. Two columns were confined with one layer of FRCM, CP-3 and CP-5, two layers were used for CP-4 and CP-6, while no confinement was used for reference specimens CP-1 and CP-2. The results from the uniaxial tests on concrete material are also presented.

Adding one layer of FRCM provided the specimens CP-3 and CP-5 with an additional 13.17% capacity, relative to average capacity of reference specimens CP-1 and CP-2. A 14.53% capacity increase was obtained for two-layer specimens CP-4 and CP-6, relative to the reference average capacity. Similar results were obtained for the axial compressive strength.

It was observed that the use of FRCM system reduced the deformation of confined specimens for the same level of axial force, when compared to reference specimens. Also, using two layers of FRCM (CP- 4, CP-6) slightly reduced the deformation with respect to one-layer specimens (CP-3, CP-5).

The assessment of the failure mode of column specimens revealed that the failure mode of confined specimens was less brittle than the mode observed for unconfined specimens. Also, the failure of the confined specimens was observed at/near mid-height of the specimens. The failure starts as a crack at mid-height of specimen and vertically grows to extremities of the specimen until the failure occurs.

The numerical predictions revealed a 25% reserve of axial capacity.

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