Response of rc columns strengthened with composite materials

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Abstract. The use of High Performance Fiber Reinforced Cementitious Composite (FRCC) systems as a repair/strengthening of RC columns is an innovative technique for increasing their capacity and preventing brittle failures when a seismic event occurs. This study presents and discusses the results of an experimental program carried out on nine scaled RC columns under compressive axial load. In particular, six columns were strengthened with FRCC, two columns were confined with uniaxial carbon fibres (CFRP) and one unstrengthened column was used as control specimen. The strengthening with FRCC consisted of the total replacing of the existing concrete cover with a thin layer of FRCC for the entire length of the specimen. The behaviour of columns strengthened with FRCC is compared with the two columns confined by using CFRP. The effectiveness of the FRCC repair/strengthening technique was investigated by means of comparisons with the response of the control specimen and columns confined with CFRP. The specimens’ response has been analysed in terms of failure modes and strength/deformation capacity.

1. Introduction

The use of High Performance Fiber Reinforced Cementitious Composite (FRCC) is an innovative repair/strengthening technique for improving the seismic performance and the damage tolerance of existing RC columns. The FRCCs selected in this work are a class of fibre cement composites with fine aggregates that exhibit a strain-softening behavior both in tension after first cracking (i.e. quasi-brittle behavior) and in compression.

Some authors recently investigated the effectiveness of using different fibre cement composites systems for the repair and seismic retrofit of obsolete RC members under flexure or shear [1-10]. However, to the best knowledge of the authors, the behavior of RC columns with FRCC jacketing under pure compressive axial load has not been extensively investigated.

This work presents the results of an experimental program carried out on nine scaled RC columns subjected to monotonic compressive axial load. Six columns were strengthened with FRCC system, two with CFRP uniaxial sheets and one was used as control specimen. The experimental program allowed a preliminary comparison between the response of columns strengthened by using different composite systems.
2. Experimental program

Nine scaled RC columns were designed with geometrical properties and reinforcement detailing as reported in Figure 1. Each specimen had a square cross-section 200 x 200 mm reinforced with four 10 mm diameter deformed rebars (longitudinal geometrical reinforcement ratio, $\rho = A_s/bh = 0.8\%$ with $A_s$ total area of longitudinal steel reinforcement and $b,h$ cross section dimensions).

![Figure 1. Geometry of specimens (dimensions in mm)](image)

Transverse reinforcement was made of 6 mm diameter ties, spaced at 100 mm apart in the central zone (a reduced spacing has been adopted on columns ends; this to avoid damage where the location of load application). The clear length of columns was 800 mm. The experimental average concrete compressive strain was 18.6 MPa.

Six specimens were strengthened with FRCC system. The existing concrete cover was removed and replaced with a layer of FRCC. In particular, three specimens (named FRCC _20_01, FRCC _20_02 and FRCC _20_03) were strengthened with a 20 mm thick layer of FRCC and the other three with a 40 mm thick layer (named FRCC _40_01, FRCC _40_02 and FRCC _40_03). The experimental mechanical properties derived for the FRCC by manufacturer were: compressive strength 130 MPa and tensile strength 8 MPa.

The experimental behaviour of columns strengthened with FRCC was compared with that of a control column (named C_0) and those of two specimens (named CFRP_01 and CFRP_02) confined with continuous carbon fibres (CFRP) uniaxial sheets. The CFRP unit weight was 300g/m² (thickness of dry fibres 0.16 mm). Mechanical properties of carbon fibres given by the manufacturer were elastic modulus 252 GPa and ultimate axial strain 1.9%.
The specimens were subjected to monotonic displacement controlled compressive axial load up to failure with a displacement rate of 0.015 mm/s. In case of strengthening with FRCC system, the displacement was applied to the original concrete core only, so that the external reinforcement was not directly loaded and it worked due to the bond action and for confinement.

3. Discussion of experimental results

Failure modes

Damage patterns observed at failure are reported for all specimens in Figure 2. The control specimen C_0 exhibited a classical failure mode under pure compression, with lateral dilatation and spalling of concrete.

All the three specimens strengthened with a 20 mm thick FRCC layer showed a very similar failure mode. Vertical cracks were detected at corners of top end of columns after the peak load.

Conversely, the three columns strengthened with a 40 mm thick layer of FRCC showed vertical cracks at both top (specimen HFRC_40_01) and bottom (HFRC_40_02 and HFRCC_40_03) ends.

Both specimens strengthened with CFRP achieved a brittle failure governed by the fibres tensile rupture just after the peak load, due to stress concentrations at corners.
Axial stress-strain relationships

The axial load-displacement relationships are reported in Figure 3 for all specimens. The main test results (i.e. maximum axial load $F_{\text{max}}$, displacement at maximum axial load $D_{\text{Fmax}}$, displacement at conventional failure assumed as a strength degradation of 20% of maximum load, $D_{0.8F_{\text{max}}}$) are summarized in Table 1. A quite similar response was observed for the three specimens strengthened with a 40 mm thick layer of FRCC (FRCC_40_01, FRCC_40_02 and FRCC_40_03) and the two specimens strengthened with CFRP (CFRP_01 and CFRP_02), see Figure 3. Conversely, a large variability was observed on the three specimens strengthened with a 20 mm layer of FRCC (FRCC_20_01, FRCC_20_02 and FRCC_20_03).

In terms of axial load capacity, the three specimens strengthened with a 20 mm thick layer of FRCC achieved a very slight increase of axial capacity with respect to the unstrengthened specimens C_0 (in a range between +3% and +9%). Conversely, a more significant increase of axial load capacity (+13-19%) and elastic stiffness was observed for specimens strengthened with a 40 mm layer of FRCC. Specimens strengthened with CFRP uniaxial sheets achieved greater axial load capacity with respect to both control column and columns strengthened with FRCC (+ 27-28%).

In post-peak phase, all specimens showed a fast decrease of axial capacity, due to the formation of vertical crack in the FRCC jacketing or the CFRP rupture. In terms of $D_{0.8F_{\text{max}}}/D_{\text{Fmax}}$ ratio, the two strengthening systems slightly increased the specimens’ deformation capacity.

![Figure 3. Experimental load-displacement relationships.](image)

| Specimen | $F_{\text{max}}$ [kN] | $D_{\text{Fmax}}$ [mm] | $D_{0.8F_{\text{max}}}$ [mm] | $D_{0.8F_{\text{max}}}/D_{\text{Fmax}}$ [-] |
|----------|----------------|----------------|----------------|----------------|
| C_0      | 1000          | 3.1            | 4.6            | 1.5            |
| CFRP_01  | 1280          | 3.1            | 4.6            | 1.5            |
| CFRP_02  | 1273          | 5.6            | 8.5            | 1.5            |
| FRCC_20_01 | 1044          | 2.8            | 6.4            | 2.3            |
| FRCC_20_02 | 1094          | 3.9            | 5.8            | 1.5            |

Table 1. Test results
4. Conclusions
The present work focused on the behavior of RC columns strengthened with high performance Fiber Reinforced Cementitious Composite (FRCC) under pure compression.

The results of an experimental program carried out on nine RC columns subjected to monotonic compressive axial load have been presented and discussed. Six columns were strengthened with FRCC system (three with a 20 mm layer thickness and three with 40 mm). The experimental response of these specimens was compared with two specimens strengthened with CFRP and with an unstrengthened control specimen.

The failure mode of specimens strengthened with FRCC was governed by the formation of vertical cracks in the FRCC layer starting from the corners of the columns ends (both top and bottom) just after the achievement of the peak load.

The strengthening system with a 20 mm layer of FRCC slightly increased the axial strength of the columns with respect to the control specimen (+3%–9%). The use of a thicker layer of FRCC (40 mm instead of 20 mm) leads to a greater increase of axial load capacity (+13–19%). However, the comparison between specimens strengthened with FRCC and with CFRP showed that specimens strengthened with CFRP attained the maximum increase of axial load capacity (+28–29%).

In terms of ductility, specimens strengthened with FRCC (both with 20 and 40 mm thick layer) did not show a sensitive increase of deformation capacity in the post peak phase, due to the formation of vertical crack in the FRCC layer just after the peak load.

Acknowledgements
This study was performed in the framework of PE 2014–2018 joint program DPC-ReL UIS. The authors thank Mapei S.p.A., producer of the composite materials adopted in this research, for the financial and technical support.

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