Flexural performance of RC columns with FRCC jacketing

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Abstract. A new repair technique consisting on a light jacketing with Fibre Reinforced Cementitious Composites (FRCC) for existing reinforced concrete (RC) buildings has been recently proposed to reduce durability problems of RC members and enhance their capacity. In this work, the effects of FRCC jacketing on the flexural capacity of existing RC columns, with and without a pre-damage, has been evaluated of full-scale specimens under cyclic loading. Digital Imagine Correlation (DIC) was also adopted for understanding the strain distribution in the FRCC jacket. The results shown that the FRCC jacket without a proper anchorage slightly enhanced the flexural capacity of the column. The strengthened column experienced a low damage with respect to control column, but occurrence of premature failures did not allow the achievement of high levels of deformation capacity and ductility.

1. Introduction

FRCC jacketing technique for repair and retrofit purposes is rather innovative in this field and still under investigation. FRCCs are cement-based materials with very small aggregates, which contain high strength discrete micro steel fibres and a minimum water/cement ratio. The main advantage of this kind of material is the possibility of partially replacing conventional steel reinforcement with the short steel fibres embedded in the cementitious matrix, improving the tensile capacity as well as the durability of the structural element, especially in coastal area. Moreover, the traditional RC jacketing can be replaced by the FRCC jacketing, avoiding the cross-section enlargement required by the traditional RC jacketing technique. Indeed, in addition to unique tensile capacity and high compressive strengths, FRCCs have also favourable flow properties (as Self Compacting Concrete that can be poured into narrow gaps between formworks and existing element) that make them ideal candidates for creating thin layers of external high-performance jacketing.

Generally, FRCCs are characterized by high compressive strengths (ranging between 120 and 150 MPa), residual tensile strengths and a softening post-cracking behaviour. A further improvement of FRCC material properties has been achieved with High Performance FRCCs (HPFRCCs) or Ultra High Performance FRCCs (UHPFRCCs), characterized by a fibre content greater than 3% in volume, which allows a post-cracking

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strain hardening behaviour under traction due to the bridging action provided by the steel fibres.

Successfully applications of cast in-place HPFRCC jackets for retrofitting RC bridge piers affected by lap splice failure [1] and for RC columns with poor materials quality [2] or corroded bars [3] can be found in literature. However, the effectiveness of such retrofit solution for increasing the poor capacity of existing RC members under seismic loading [4-6] remains to be studied.

Similar retrofit applications with cast in place FRCC jacketing for seismic retrofit of RC columns can be found in [7] for the repair of a full-scale column subjected to cyclic lateral load and in [8-10] for the confinement of scaled and full-scale columns under axial compression. In [11], prefabricated FRCC panels were used for providing external confinement to RC columns. As the research about the use of FRCCs for seismic retrofit is still in an early stage, more experimental work is needed to corroborate and further understanding the validity of this technique.

2. Methods

Three experimental tests on full-scale RC columns were performed in order to evaluate the effectiveness of two different FRCC jacketing solutions; the experimental data were analysed by using DIC technique. In the following, the geometrical and mechanical properties of materials and specimens are described along with the testing procedure and the adopted DIC technique.

2.1. FRCCs mechanical properties

Two different FRCC materials, named FRCC_a and FRCC_b, were adopted in the present experimental program as jacketing system applied to RC columns non-conforming to modern codes. The two materials had very similar mechanical properties in both tension and compression but were slightly different in terms of concrete matrix mix design and fibre geometry.

In both cases, FRCCs were made of a cement-based matrix with small aggregates and short fibres in a volumetric ratio lower than 2%. In particular, FRCC_a had plain steel fibres (fibre diameter 0.21 mm, fibre length 13 mm), as shown in Figure 1a. Conversely, FRCC_b had waved steel fibres (fibre diameter 0.25 mm, fibre length 18 mm), as shown in Figure 1b.

The uniaxial compressive and tensile strength were determined by means of cylindrical specimens of 150 mm x 300 mm and 100 mm x 200 mm dimensions (diameter x height), respectively. Tensile tests were performed on notched specimens using an in-house direct tensile setup. The average compressive strength, elastic modulus and tensile peak stress derived for both FRCC materials were summarized in Table 2. Although the very different composition of two composite materials, they exhibited a quite close response in terms of peak capacity in compression and tension.

(a)

(b)

Fig. 1. FRCC materials: plain steel fibers (a) and waved steel fibers (b).

Table 1. FRCCs mechanical properties.

Mechanical properties	**FRCC_a**	**FRCC_b**
f_c (MPa)	104.3	121.0
E_c (GPa)	31.3	37.0
f_t (MPa)	4.3	3.8

2.2. Specimens details

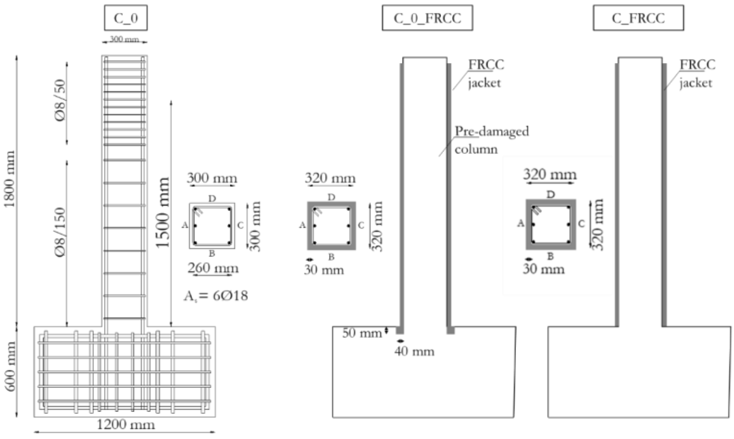
Each specimen had a square cross-section 300 x 300 mm reinforced with six 18 mm diameter deformed rebars (longitudinal geometrical reinforcement ratio, $\rho = A_s/bh = 1.7\%$ with A_s total area of longitudinal steel reinforcement and b,h, cross section dimensions). The cyclic lateral load was applied at a distance of 1,500 mm from the foundation block. The specimens were subjected to a constant axial load ratio of 0.1 and an incremental lateral cyclic loading under displacements control. A further description of specimens details and test set-up can be found in [7].

The specimens were cast with a poor-quality concrete, with mean compressive strength about 15 MPa. The steel used for the columns had an average yielding strength of 531 MPa for longitudinal reinforcement and of 525 MPa for transverse reinforcement, derived from tensile tests carried out on coupon bars.

The strengthening technique consisted in applying a thin layer of FRCC (total thickness of 30 mm) to the full-scale RC columns after the complete removal of the concrete cover (20 mm of thickness) from the existing concrete surface, slightly enlarging the cross-section about 20 mm per side. The resulting cross section dimension was 320 mm x 320 mm. The jacketing procedure consisted of different steps: after complete concrete cover removal, the concrete surface was wetted up to complete saturation; then, a wooden formwork was constructed around the perimeter and along the full length of the column in order to allow fresh FRCC pouring. Given the highly performing bond properties of both FRCC materials, no bonding agent or primer was employed at the FRCC-inner concrete interface.

2.3. Experimental program

The experimental program consisted of two full-scale RC columns investigated under three configurations: (i) bare RC column, named C_0; (ii) repaired RC column with FRCC_a jacketing after pre-damage, named C_0_FRCC; (iii) strengthened RC column with FRCC_b jacketing without pre-damage, named C_FRCC. A summary of the experimental campaign is reported in Figure 2. A further distinguishing feature among C_0_FRCC and C_FRCC specimen configurations is the jacketing anchorage to the foundation block. Indeed, in the case of C_0_FRCC the jacketing is anchored to the foundation by means of a socket in the foundation that increased the bond surface, as visible in Figure 2b. Conversely, in the other specimen, no anchorage was provided between jacket and foundation, as depicted in Figure 2c.



(a) (b) (c)

Fig. 2. Specimens grometry and strengthening configurations for C_0_FRCC (b) and C_FRCC (c).

2.3. DIC system

To fully understand the effect of composite jacketing on the structural behaviour of RC columns and its variability with regard to the different configurations adopted, DIC technique was used to monitor FRCC strains throughout the cyclic tests. The DIC records were elaborated for evaluating the strain field along the longitudinal axis of the specimens (i.e. longitudinal strain) and the strain filed along the transverse direction of the specimen (i.e. transverse strain). The post-processing of DIC-derived longitudinal strains evaluated at increasing distance from the base-section allowed the definition of the experimental cross-sectional curvature along the member length.

3. Results and discussion

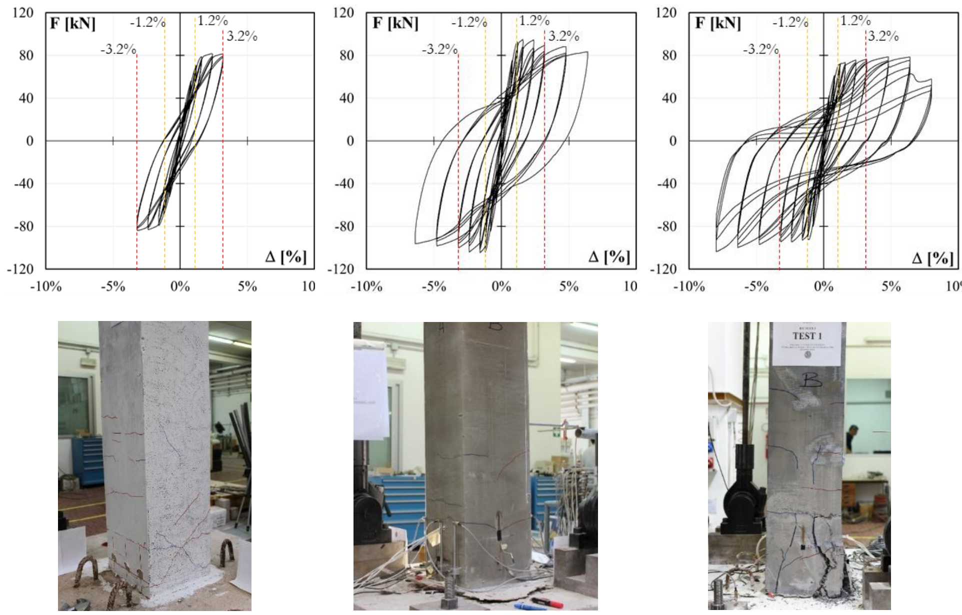
The lateral force-drift relationships, F-Δ, derived from the experimental tests for the three configurations investigated are reported in Figure 3, along with the damage pattern at failure. Results for C_= and C_0_FRCC were already presented in [7].

As aforementioned, the test of specimen C_0 was stopped at a drift ratio of 3.2%, to allow the repair of the specimen (Figure 3a). At this level of drift, the specimen achieved the flexural yielding, but no failure mechanisms were observed up to the end of the test.

The pre-damaged and repaired specimen, C_0_FRCC, had a flexural behaviour up to a drift ratio of 6.4%. Then, the test was arrested for safety reasons and the conventional failure, defined as a strength degradation up to 80% of peak force, was not achieved (Figure 3b). The anchorage system induced a rigid rocking behaviour, activating a sliding surface inside the foundation block. At the end of the test, the FRCC jacket was lightly damaged, with very small and isolated flexural and shear cracks. However, the anchorage system provided also a slight increase of strength and stiffness with respect to bare specimen C_0, working as flexural strengthening.

Conversely, the specimen C_FRCC achieved a sudden drop of lateral capacity for a drift ratio of 6.4% (Figure 3c). This was related to the crushing of the FRCC jacket that caused the overall failure of the specimen. In this case, the absence of anchorage between the jacket and the foundation block did not allowed significant increase of lateral capacity. The failure of the jacket and the observed asymmetric response of the specimen in the positive and negative load directions were probably related to small asymmetries of the jacket thickness developed during the casting process.

The two investigated jacketing configurations leaded to completely different damage patterns of the FRCC and relative strain field distributions that can be difficulty interpreted with local measures. Thus, the DIC results are fundamental for fully understanding the FRCC behaviour.



(a) (b) (c)

Fig. 3. Experimental behavior of specimens C_0 (a), C_0_FRCC (b) and C_FRCC (c).

2.3 Strain fields distribution

The knowledge of the strain field distributions at each drift allowed a complete knowledge about the mechanisms of stress propagation in full-scale RC members before and after the seismic retrofit with FRCC, considering also the influence of different strengthening configurations on stress/strain distribution and cyclic damage accumulation. Furthermore, the development of cracks can be detected since the beginning just monitoring the tensile strains concentrations over the surface of the specimen.

The longitudinal strain fields recorded by using the DIC at drift ratios of 1.2% (i.e. yielding) and of 3.2% were reported in Figure 4 for the three configurations investigated for both positive and negative load directions.

The plot of longitudinal strains was helpful for understanding the behaviour and the resisting mechanisms of the specimens. Looking at bare specimen C_0, the compressive struts involved in the resisting mechanism to shear were clearly visible at a drift ratio of 1.2%. Tensile strains (i.e. yellow in legend) were distributed along inclined lines, according the truss analogy resisting mechanism for shear actions, defining the compressive struts. It’s interesting to note how the strain distribution resulted different among the three different configurations at this drift level. The bare RC column exhibited multiple tensile strain concentration lines along the height, remaining below a threshold of 0.1%. FRCC strengthened specimens seem to spread the tensile strains in wider areas of the specimen with just two main concentration zones. Among these, a higher level of tensile strain appeared in the specimen C_FRCC at a height of 300mm from the base section in the positive load direction.

The aforementioned tensile zones developed in flexural cracks for greater drift ratios, as visible in Figure 4 for a drift ratio of 3.2%. In the positive load directions, where the tensile strains overcame the concrete/FRCC tensile capacity (i.e. red in legend), cracks developed following the principle tensile direction.

In the case of C_0_FRCC, the magnitude of strains concentration is definitely lower with respect to C_0, with tensile strains lower than 1.5%. The tensile strains aligned along the tensile principal direction were still visible, but the strain value was reduced due to the rocking behaviour developed by the jacketed specimen that probably caused a strain release. By this, the most part of the deformation was related to the rigid rotation along the sliding surface inside the foundation block. Very few small cracks were developed on the FRCC jacket.

Conversely, a single large crack opened in the positive direction on specimen C_FRCC, due to the strain-softening tensile behavior FRCCs which dissipated energy by a single macro-crack, leading to a very limited damage if compared to C_0. Similarly to specimen C_0_FRCC, the magnitude of strains was slightly lower than that recorded for C_0 as well as the damage distribution, due to the strain release caused by the rocking behaviour at the base-section.

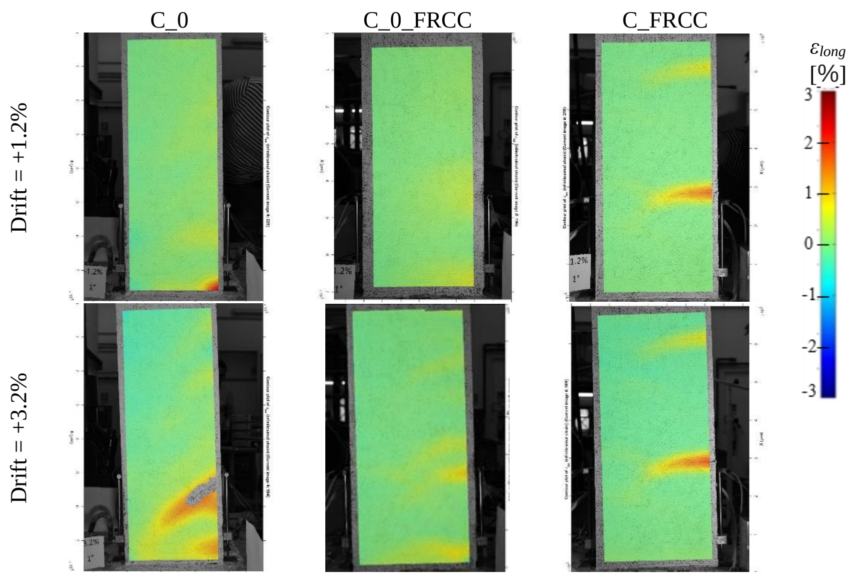


Fig. 4. Longitudinal strain fields from DIC (positive strain values correspond to tensile strains).

4. Conclusions

Two full-scale RC columns were tested under cyclic loading and three configurations were investigated: (i) bare column; (ii) repaired column with FRCC jacketing after pre-damage; (iii) strengthened column with FRCC jacketing without pre-damage. Digital Imagine Correlation (DIC) technique was adopted for improving the knowledge about the experimental behaviour of full-scale RC columns seismic retrofitted with FRCC jacketing.
The following conclusions can be outlined:

- specimens jacketed with FRCC experienced low damage with respect to the bare specimen, where large cracks were detected, and this was partly due to the activation of the rocking behaviour that moved the damage concentration at the interface between column and foundation block;
- the partial anchorage between the FRCC jacket and the foundation block in C_0_FRCC configuration allowed the achievement of a slight strength increase and of small flexural deformations of the specimen before the activation of the rocking behaviour. Conversely, the FRCC jacketing without anchorage in C_FRCC configuration caused a rigid rocking behaviour since the beginning of the test;
- the FRCC jacketing was able to restore the capacity of the predamaged specimen but without a proper anchorage system it was not able to enhance the flexural capacity, due to the activation of rigid rocking behavior,
- DIC is a suitable technique for monitoring the strain fields distribution over a large region (300 x 800 mm^2) for the specimens during cyclic loading. The strain fields recorded on the external surface of specimens allowed to understand the resting mechanism and the damage propagation in both bare and FRCC jacketed specimens.

The authors acknowledge Mapei S.p.A. and Italcementi S.p.A. for the financial and technical support.

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