RC Column Repaired with HPFRCC and Confined with CFRP: Numerical Analyses to Evaluate the Column Section Capacity

D. Lavorato, J. Azeredo, A. V. Bergami, J. A. A. Salvador Filho, C. Nuti, S. Santini and B. Briseghella

Abstract This paper presents a numerical study to evaluate the behavior of reinforced concrete (RC) columns with circular section repaired and retrofitted by high-performance fiber-reinforced cement composites (HPFRCC) jackets and external carbon fiber-reinforced polymer (CFRP) wrapping. The column damage is due to degradation of concrete and steel rebars for effect of the corrosion. Different HPFRCC mix designs were considered to repair the column assuming different fiber types (polyethylene, stainless steel) and volume contents (1% or 2%). These HPFRCC concretes were developed and tested experimentally at the lab of the University of Roma Tre (Salvador Filho et al. in Mechanical properties of HPFRCC reinforced with different types and volumes of fibres [1]). The numerical analyses were conducted by means of fiber models using the software *OpenSees* (OpenSees structural software [computer software]. Pacific Earthquake Engineering Research Center, University of California, Berkeley, CA, [2]) applying a vertical load and a displacement history (section rotation). The analyzed sections represent the undamaged section, the section damaged for effect of rebar corrosion, and the repaired and retrofitted sections. The first numerical results about the section strength capacities for each type of repair material are discussed.

Keywords Repair · Confined section · Push-over analysis · Finite element method · HPFRCC

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B. Pradhan (ed.), *GCEC 2017*, Lecture Notes in Civil Engineering 9,
https://doi.org/10.1007/978-981-10-8016-6_2

1 Introduction

Many reinforced concrete (RC) structures built in aggressive environment present deterioration problems, both for the phenomena related to the maintenance and for the effects linked to aggressive agents of the atmosphere. The lack of proper maintenance of structures during their service life can originate pathological phenomena such as deterioration of concrete and steel, which manifest before the time provided in the structural design, often with serious consequences and great damage.

The reinforcement corrosion is one of the first direct consequences of reinforced concrete deterioration, which can cause a reduction of the structures' performance. Rehabilitation interventions on these structures, which aim to recover or increase structural capacity, can result difficult on construction site.

In this paper, repair techniques were considered to restore the concrete and steel rebar parts damaged by corrosion phenomena.

The nonlinear behavior of a circular RC column damaged by the corrosion of the steel reinforcement and then repaired and/or retrofitted by HPFRCC materials and CFRP wrapping was investigated by numerical analyses.

Different fiber section models were built in *OpenSees* [2] to study the behavior of the undamaged section before the corrosion: the section damaged by corrosion of the steel rebar, the section repaired by HPFRCC jacket which is used to restore the removed damaged concrete parts, and the section repaired by HPFRCC and retrofitted by an external CFRP wrapping. The HPFRCC materials with polyethylene or stainless steel fibers were considered to repair the damaged concrete parts. These HPFRCC concretes were developed and tested experimentally at the lab of the University of Roma Tre [1]. The first results of this numerical analysis about the section capacity are discussed to evaluate the effectiveness of the proposed interventions.

2 HPFRCC Materials

Plain concrete is a brittle material with low tensile strength but fibers may be added in the cementitious composite to improve its mechanical behavior. Besides the contribution in terms of tenacity, the fibers develop an important contribution for a better distribution of cracks in the concrete when this material is subjected to increasing loads until failure.

High-performance fiber-reinforced cementitious composites (HPFRCC) are a class of material characterized not only by high strength and low permeability but also by pseudo-ductility post-cracking behavior (consequently high deformability) and development of micro-cracks under tensile stress (Fig. 1). These characteristics are achieved due to the highly dense microstructure of cementitious matrix combined with use of microfibers that in adequate proportion can limit the width of the

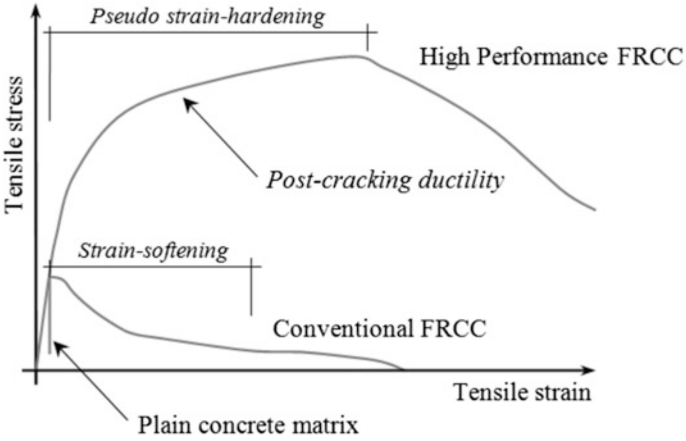


Fig. 1 Typical stress–strain curves (under tensile stress) for comparison between conventional FRCC (fiber-reinforced concrete) and high-performance FRCC behavior

cracks. These effects are described by several researches [3–6]. These materials are obtained by a combination of high-strength concrete and short fibers with an improved homogeneity, because traditional coarse aggregates are replaced with fine sand.

Pseudo strain-hardening behavior of HPFRCC under direct uniaxial tensile stress is an increase in tensile stress after first cracking (Fig. 1). On the other hand, conventional fiber-reinforced cementitious composites (FRCC) exhibit a decrease in tensile stress after first cracking that is called strain-softening, as generally seen in cement-based materials such as mortar and concrete.

An extensive experimental investigation was carried at Roma Tre University Lab to produce UHPFRCC with locally available materials and the effect of different volumes and types of fibers on mechanical properties. The main results from this study are shown in Table 1.

Table 1 Experimental tests results: mechanical properties of plain cementitious matrix and UHFRCC mixtures reinforced with polyethylene fibers and stainless steel fibers [1]

Mixtures	Plain matrix	Polyethylene		Stainless steel	
		1%	2%	1%	2 %
Compressive strength, R_{cm} (MPa)	65.34	45.67	45.13	83.60	88.15
Modulus of elasticity, E_{cm} (GPa)	25.99	–			
Flexural strength, f_{cfm} (MPa)	7.64	7.65	13.81	25.20	29.37
Axial tensile strength, f_{ctm} (MPa)	3.042	1.982	3.090	4.615	7.263

3 Case of Study: RC Cantilever Column

The numerical investigation was carried out considering a cantilever column tested experimentally before and after repair and retrofitting interventions by Lavorato et al. [7–18].

In this study, an RC cantilever column of 420 mm in diameter and 1170 mm in height represents a 1/6 scaled specimen of a bridge pier (Fig. 2). The steel reinforcement was composed of 12 bars with diameter $D_s = 12$ mm (longitudinal rebars), clear cover thickness of $C = 30$ mm, and transverse reinforcement with diameter $D_{st} = 6$ mm provided at 120 mm of spacing (Table 1). The mean compressive strength (f_{cm}), the modulus of elasticity (E_c), and the tensile strength ($\underline{f_{ctm}}$) of the undamaged column concrete are given in Table 2.

The yield strength of the longitudinal reinforcing steel (f_{ym}), the yield strength of the transverse reinforcing steel (f_{ytm}), and the rebar elastic modulus (E_s) are given in Table 2.

The damage due to corrosion assumed in the RC section is shown in Fig. 3 where it is evident: the concrete spalling due to rush expansion, the steel stirrups rupture, and the reduction of the longitudinal rebar diameter. The rebar mass loss is assumed equal to 10%, and the rebar steel characteristics were calculated by formulations presented in Kashani et al. [19, 20]: the reduced rebar diameter is 11.38 mm, the yield strength in tension is equal to 545.65 MPa, and the yield strength in compression is equal to 502.57 MPa.

Fig. 2 Case of study: AS built columns with corroded rebars

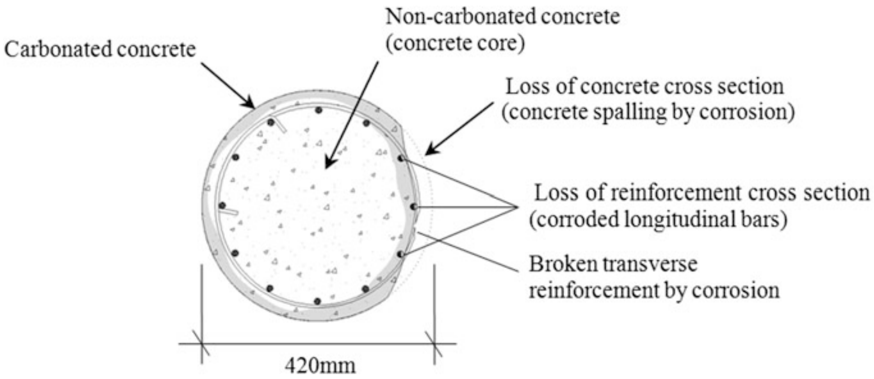


Fig. 3 Damage due to corrosion of the rebars assumed for the studied RC column section: damage of the concrete part and steel reinforcement

4 Numerical Investigation of the Behavior of Repaired and Retrofitted RC Sections

Some numerical simulations were performed to evaluate the bearing capacity of RC structural elements damaged by corrosion of the steel rebars and then repaired and retrofitted using HPFRCC materials. The numerical analyses were conducted considering: the undamaged column section, the column section damaged for effect of the rebar corrosion phenomena, the column section repaired by means of HPFRCC after the removing of the damaged concrete parts, and the column section repaired by HPFRCC and retrofitted by CFRP wrapping [17, 18, 21].

4.1 Numerical Models

The analysis about the nonlinear behavior of the circular reinforced concrete (RC) section of the column studied in [7–16, 22] was conducted by a fiber model using *OpenSees* software framework [2].

The fiber section (Fig. 4) was divided into several concrete and steel parts (fibers). The discretization of the section is illustrated in Fig. 4. Thirteen radial and 16/32 tangential divisions were employed for the concrete parts of the section whereas the longitudinal rebars are simulated by single steel fibers. This level of discretization is used to lead accurate results based on a convergence study not reported here.

To assess the performance level of the column base section, four numerical models were considered: the undamaged section before corrosion phenomena (Fig. 5), the damaged section with corroded steel rebars and degraded concrete parts due to corrosion (Fig. 6), the section repaired by HPFRCC to restore the

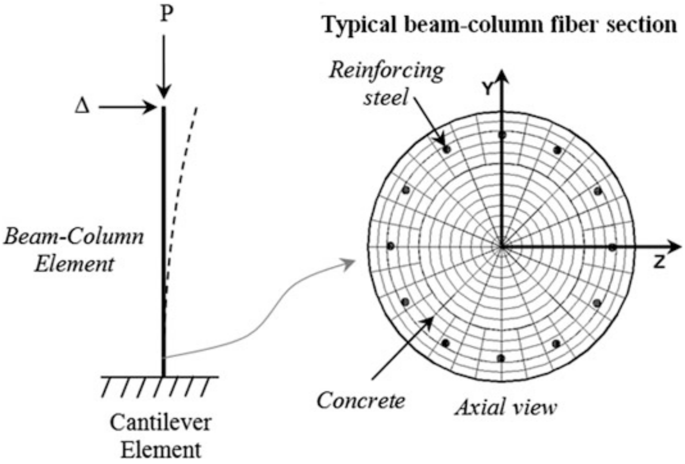


Fig. 4 Fiber model of the RC column section (FEM model in *OpenSees* [2])

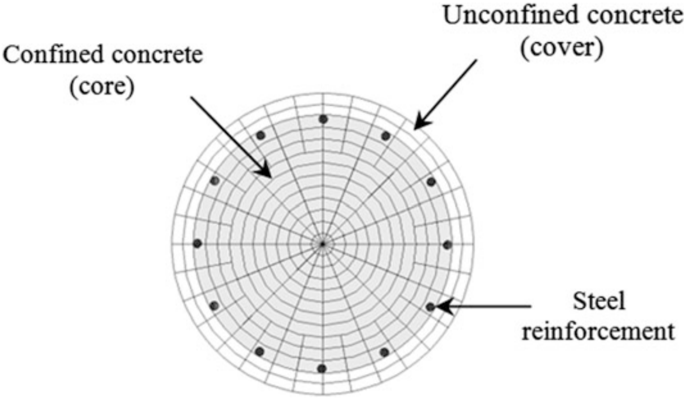


Fig. 5 Fiber section model in *OpenSees*: the undamaged base column section before corrosion phenomena

removed damaged concrete parts (Fig. 7), and the section repaired by HPFRCC and retrofitted by CFRP wrapping (Fig. 8).

The section model of the undamaged column had the geometries and steel reinforcement characteristics shown in §3.

The section model of the damaged column (Fig. 6) due to corrosion was built starting from the model of the undamaged section (Fig. 5):

- removing the deteriorated external part of the concrete section (Fig. 3),
- assuming no stirrup confinement effect on the section core concrete (broken stirrups),

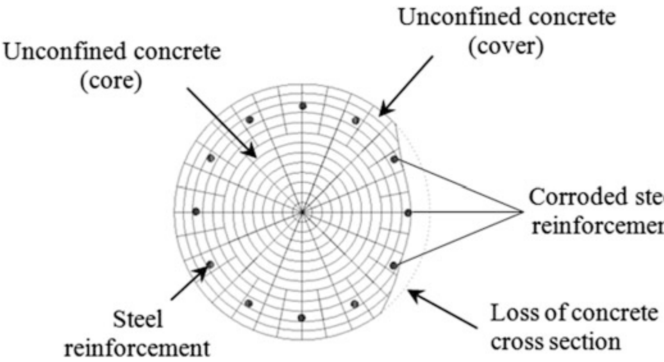


Fig. 6 Fiber section model in *OpenSees*: the damaged base column section due to corrosion phenomena

Fig. 7 Fiber section model in *OpenSees*: the repaired base column section by HPFRCC

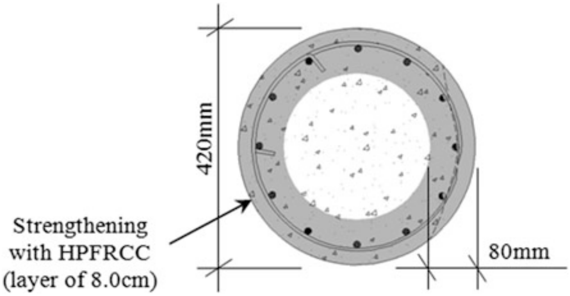
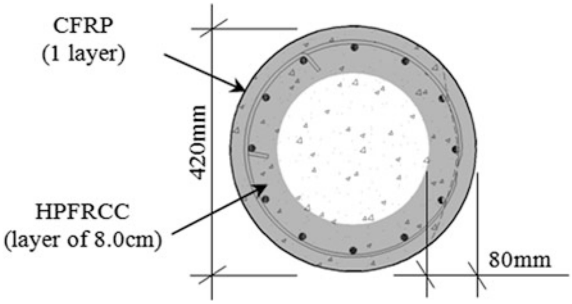


Fig. 8 Fiber section model in *OpenSees*: the repaired and retrofitted base column section by HPFRCC and CFRP wrapping



- reducing the longitudinal rebar diameter and the steel mechanical properties as in Kashani et al. [19, 20] considering a mass loss of 10% (§3).

The section model of the repaired column had an external part (8.0 cm, Fig. 7) built by HPFRCC to restore the damaged concrete parts removed along the external part of the RC section. Two HPFRCC mixtures were considered with polyethylene or stainless steel fibers and 1% or 2% of fiber content. These HPFRCC materials were tested experimentally in [1] to define the concrete characteristics.

The section model of the repaired and retrofitted column had an external part built by HPFRCC to restore the damaged concrete parts (8.0 cm, Fig. 8). The CFRP wrapping used to retrofit the column was not modeled but its confinement effect on the section core concrete was evaluated during the material properties definition. The mechanical characteristics of CFRP system were obtained from the commercial products specifications (f_{fk} = 4700 N/mm^2; E_f = 240000 N/mm^2; ε_f = 1.8%; t_f = 0.167 mm).

Proper concrete and steel material models (stress–strain relation) were associated with each fiber in the section considering the material properties given in §3. The mechanical characteristics of the corroded rebar were calculated by Kashani et al. model [19, 20] considering the residual capacity of the corroded rebars (§3). The model presented by Hosotani et al. [23, 24] simulated the behavior of the confined concrete by stirrups or CFRP.

The HPFRCC material behavior was defined considering the mechanical characteristics obtained from the experimental investigation explained in Salvador Filho et al. [1].

Each material model was simplified by a multilinear model to use the hysteretic material model available in *OpenSees* [2]. This approximation can be considered valid for the aims of these first analyses.

Nonlinear analyses were carried out applying a vertical load (266 kN) and a monotonic deformation history (section rotation) on the fiber section model to evaluate the corresponding moment–rotation behavior.

4.2 Numerical Results

The monotonic moment–rotation curves obtained by the numerical analysis in *OpenSees* for the undamaged, the damaged, the repaired, and the repaired and retrofitted sections are given in Figs. 9, 10 and 11. The comparison about the capacity curve for each type of section is given in Table 3 in terms of maximum moment ($\mathrm{M}_{\max}$) and performance factor (F_{p}) calculated by the ratio between the maximum moment of the section and the maximum moment of the undamaged section.

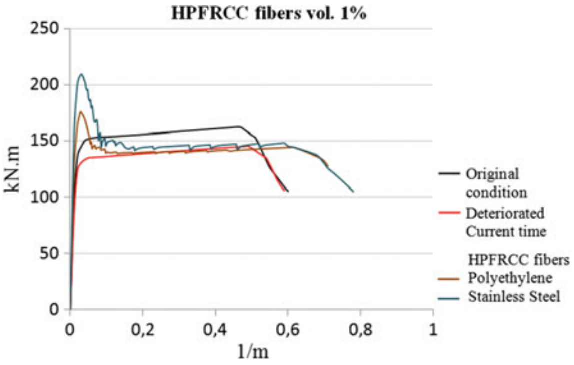


Fig. 9 Numerical moment–rotation capacity curve for the undamaged (original condition), the damaged (deteriorated current time), and the repaired by HPFRCC with polyethylene or stainless steel fiber using a fiber content of 1%

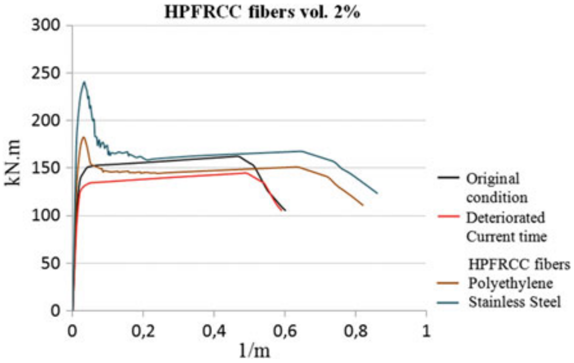


Fig. 10 Numerical moment–rotation capacity curve for the undamaged (original condition), the damaged (deteriorated current time), and the repaired by HPFRCC with polyethylene or stainless steel fiber using a fiber content of 2%

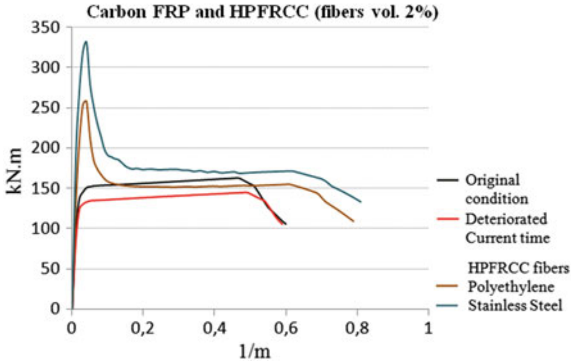


Fig. 11 Numerical moment–rotation capacity curve for the undamaged (original condition), the damaged (deteriorated current time), and the repaired by HPFRCC with polyethylene or stainless steel fiber using a fiber content of 2% and retrofitted by one layer of CFRP

5 Result Discussion and Conclusions

The nonlinear behavior of a circular RC column damaged by the corrosion of the steel reinforcement and then repaired and/or retrofitted by HPFRCC materials and CFRP wrapping was investigated by means of monotonic numerical analyses.

Table 2 Key information about the section geometries and the materials characteristics for the studied undamaged RC column

Concrete				
D	C	f_{cm}	f_{ctm}	E_{c}
(mm)	(mm)	(MPa)	(MPa)	(GPa)
420	30	20	2.21	22.36

Longitudinal bars				Transverse bars			
D_s		f_{ym}	E_{s}	D_{st}	s	f_{ytm}	E_{s}
(mm)	n	(MPa)	(GPa)	(mm)	(mm)	(MPa)	(GPa)
12	12	574.37	200	6	120	445.46	200

Note D = cross section diameter; C = concrete cover thickness; f_{cm} = concrete cylinder strength; f_{ctm} = concrete tension strength; E_{c} = elastic modulus of concrete; D_s = diameter of longitudinal bars; n = number of longitudinal steel bars; f_{ym},f_{ytm} = yield stress of steel bars; E_{s} = elastic modulus of steel; D_{st} = diameter of transverse steel bars; s = spacing of transverse steel bars

Table 3 Comparison between moment–rotation curves in terms of maximum moments (M_{max}) obtained for the undamaged (original condition), the damaged (deteriorated current time), the repaired by HPFRCC with polyethylene or stainless steel fiber, and the repaired and retrofitted by CFRP wrapping (one layer) and performance factor (F_{p})

Column section			M_{max} (kN m)	F_{p}
Original condition not damaged			163	1.00
Deteriorated current time			145	0.89
Repaired with HPFRCC	Polyethylene	(1%)	176	1.08
		(2%)	183	1.12
	Stainless steel	(1%)	209	1.28
		(2%)	241	1.48
Repaired and retrofitted CFRP and HPFRCC	Polyethylene	(2%)	258	1.58
	Stainless steel	(2%)	331	2.03

Note Fibre volume fraction (%) M_{max} = maximum moment; F_{p} = performance factor (in relation to the maximum moment of the original section—not damaged)

A detailed fiber section model was implemented in *OpenSees* program taking in account different section conditions: the undamaged section, the section damaged by corrosion of the steel rebar, the section repaired by HPFRCC jackets used to restore the removed damaged concrete, and the section repaired by HPFRCC and retrofitted by an external CFRP wrapping. HPFRCC materials with different fiber types (polyethylene, stainless steel) and volume contents (1% or 2%) studied during the experimental campaign in [1] were considered to repair the damaged concrete parts.

The first comparison of the results of the numerical analyses performed for each type of section in terms of maximum moment showed:

- The corrosion of the steel rebars reduces the section capacity. It is obvious because the longitudinal rebar diameter is reduced for effect of the corrosion and the damaged concrete part does not give contribution to the resistant moment capacity.
- The sections repaired by means of a modest layer of HPFRCC (8.0 cm) with polyethylene or stainless steel fibers after the damaged concrete removal showed an improved section capacity. The HPFRCC with polyethylene fiber can improve the section capacity of about 8% or 12% with respect to the one of the original undamaged sections using 1% or 2% of fiber content, respectively. The HPFRCC with stainless steel fiber can improve the section capacity of about 28% or 48% with respect to the one of the original undamaged sections using 1% or 2% of fiber content, respectively.
- The section repaired by means of a modest layer of HPFRCC (8 cm) with polyethylene or stainless steel fibers and retrofitted by one layer of CFRP wrapping can increase the section capacity. The HPFRCC with polyethylene fiber (2%) can improve about the 58% the resisting moment capacity of the section with respect to the one of the original undamaged sections. The HPFRCC with stainless steel fiber (2%) can improve about the 103% the resisting moment capacity of the section with respect to the one of the original undamaged sections.

One aspect considered relevant was the possibility of applying these techniques without changing the geometry of the elements and improving the durability of the structure, due to the presence of microfibers and the low porosity of the HPFRCC material. In this case, polyethylene fibers could be used in HPFRCC for the repair that requires a better distribution of finer cracks in the structure, consequently improving its resistance in relation to the entrance of aggressive agents. Proper anchorage of the new concrete jacket should be garanteed but it is not investigated here. This study is in progress and the anchorage problem will be discussed in a next paper.

Acknowledgements The authors wish to express their gratitude for the coordinating efforts used in this study provided by the *Laboratorio Prove e Ricerca su Strutture e Materiali* (PRiSMa) personnel of the Roma Tre University, and by the "Sustainable and Innovative Bridges Engineering Research Center, Fujian Province University" (SIBERC). This work was completed in part with resources provided by the Fuzhou University—Roma Tre University "Sino-Italian Center".

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