Received: 7 June 2022 | Accepted: 2 August 2022
DOI: 10.1002/suco.202200555

ARTICLE

Repair of reinforced concrete bridge columns subjected to chloride-induced corrosion with ultra-high performance fiber reinforced concrete

Angelo Pelle[1] | Bruno Briseghella[2] | Gabriele Fiorentino[3] | Gian Felice Giaccu[4] | Davide Lavorato[1] | Giuseppe Quaranta[5] | Alessandro Rasulo[6] | Camillo Nuti[1]

[1]Department of Architecture, Roma Tre University, Rome, Italy
[2]College of Civil Engineering, Fuzhou University, Fuzhou, Fujian, China
[3]Department of Civil Engineering, University of Bristol, Bristol, UK
[4]Department of Architecture, Design and Urban Planning, University of Sassari, Alghero, Italy
[5]Department of Structural and Geotechnical Engineering, Sapienza University of Rome, Rome, Italy
[6]Department of Civil and Mechanical Engineering, University of Cassino and Southern Lazio, Cassino, Italy

Correspondence
Giuseppe Quaranta, Department of Structural and Geotechnical Engineering, Sapienza University of Rome, Via Eudossiana 18, 00184 Rome, Italy.
Email: giuseppe.quaranta@uniroma1.it

Funding information
National Natural Science Foundation of China, Grant/Award Number: 51778148; Sapienza Università di Roma, Grant/Award Number: RM120172B37F0628

Abstract
The rehabilitation of reinforced concrete (RC) bridge columns subjected to chloride-induced corrosion is addressed in the present paper. The proposed strategy is based on the replacement of the original external layer made of normal-strength concrete (NSC) with ultra-high performance fiber reinforced concrete (UHPFRC), and it additionally involves the substitution of the existing corroded longitudinal reinforcement with new machined steel rebars. This repair technique aims at restoring strength, stiffness, and ductility of the original column in a short time without altering its cross-section dimensions. Because of the high compactness of the UHPFRC, it also serves at improving its durability. The main contribution of the present work is a numerical investigation carried out in order to identify how the design decisions about the repair strategy influence the behavior of the restored column. The parametric investigation reveals that the length of the zone in which NSC is replaced by UHPFRC as well as the machined index (i.e., ratio between turned and original rebar cross-section area) must be properly selected to make the intervention effective. Numerical results also highlight that the main design issue to deal with is the relocation of the plastic hinge from the repaired zone towards the weak unrepaired part of the column. Practical design recommendations are finally formulated.

KEYWORDS
bridge column, machined steel rebars, pitting corrosion, reinforced concrete, repair, UHPFRC

1 | INTRODUCTION

Exposure to corrosive environments is one of the most common and detrimental sources of deterioration in

Discussion on this paper must be submitted within two months of the print publication. The discussion will then be published in print, along with the authors' closure, if any, approximately nine months after the print publication.

existing reinforced concrete (RC) structures. Particularly, existing RC bridges subjected to the risk of corrosion deserve careful consideration because this may have large negative impacts on safety, functionality, and resilience of the transportation network they belong to. Within this framework, special attention has been paid on the assessment of chloride-induced corrosion in RC bridges,[1–5] since the effects of the pitting corrosion that it causes can be more severe than those of the uniform corrosion due to carbonation.[6] In this perspective, apart from forecasting, monitoring, and assessing RC bridges subjected to corrosion, repair and retrofit are becoming relevant priorities in current transportation networks management policies. This is basically dictated by two main reasons. On the one hand, deputed authorities strive to extend the lifetime of existing RC bridges since rebuilding is costly whereas repair and retrofit are usually dubbed more convenient, at least if the structural reliability is not heavily jeopardized by deterioration phenomena. On the other hand, the preservation of existing RC bridges contributes to enhance the sustainability of the construction sector since it reduces the consumption of new building materials and the production of demolition wastes.

As regards repairing and retrofitting of corroded RC elements, intervention strategies mostly explored so far are based on the use of fiber-reinforced polymers (FRP).[7] For instance, Tastani and Pantazopoulou[8] as well as El Maaddawy and Soudki[9] investigated experimentally the effectiveness of FRP jackets in order to extend the lifetime of corroded RC members. Both glass FRP (GFRP) and carbon FRP (CFRP) jackets were considered by Tastani and Pantazopoulou[8] for repairing corroded RC columns with substandard detailing. They observed that jacket rupture in corroded RC columns under concentric compression originates within the corroded region and extends over the specimen followed by disintegration of the concrete cover and core, especially in the bottom area. El Maaddawy and Soudki[9] focused on corroded RC beams. Based on experimental evidences, they found that CFRP repair increases the ultimate strength of corroded RC beams (which resulted higher than the strength of the sound beam) while significantly reduces the deflection capacity. It has been pointed out that FRP jacketing may also serve for enhancing the durability of the restored RC column because external wrapping dramatically reduces the corrosion rate.[10]

The use of FRP jackets is indeed most common for restoring corroded RC elements, but alternative (even hybrid) approaches have been explored as well. For instance, Meda et al.[11] conducted a laboratory campaign for studying the effectiveness of high performance fiber RC (HPFRC) jacketing as a repair method for corroded RC columns. Farzad et al.[12] performed several laboratory tests on RC bridge columns with simulated corrosion-caused damage scenarios for evaluating the performance of ultra-high performance concrete (UHPC) as a repair material. Some applications of the ultra-high performance fiber RC (UHPFRC) jacketing for the rehabilitation of corrosion damage in concrete bridges have been reviewed by Bertola et al.[13] Similarly to FRP wrapping, the use of high and ultra-high performance concretes as repair material is also beneficial for enhancing the durability of RC members exposed to corrosive environments because of their high compactness.[11,14] Indeed, the diffusion coefficient of high and ultra-high performance concretes exposed to chloride is two and three orders of magnitude lower than that of normal-strength concrete (NSC),[15] respectively. Rajput et al.[16] performed experimental tests on corroded RC columns repaired by means of HPFRC jacketing, but they also considered GFRP wrapping to further improve the response in terms of strength and ductility. A similar hybrid repair approach has been employed within the experimental study by Rabehi et al.,[17] who explored the use of UHPFRC jacketing together with GFRP or CFRP wrapping. Bonded steel plate (BSP), ultra-high toughness cementitious composite (UHTCC) and high-performance ferrocement laminate (HPFL) are among the other solutions that have been investigated in the last years to repair and/or strengthen corroded RC members.[18–20] It is highlighted that repairing techniques also differ from each other in the strategies adopted regarding corroded rebars. For example, Hasan et al.[21] discuss a repair strategy for RC beams in which corroded bottom arms of stirrups are removed while corroded tensile reinforcement is replaced with stainless steel rebars, and CFRP sheets are finally attached.

Notably, the methodologies for repairing RC elements subjected to corrosion have been mostly investigated through experimental tests, while there is a lack of studies that address such issue by means of suitable structural models. Particularly, parametric simulations are useful to predict the behavior of the restored columns for a large variety of repair scenarios.

This paper presents a numerical study that aims at exploring the feasibility of a new repair strategy to extend the lifetime of existing RC bridge columns under chloride-induced corrosion. The discussed strategy exploits UHPFRC as repair material and involves the replacement of the corroded longitudinal reinforcement with new machined steel rebars. The considered technique is intended to restore the original capacity in terms of strength, stiffness, and ductility in a short time and without modifying the column dimensions. On the basis of the chloride-induced corrosion levels predicted from multiphysics simulations, nonlinear static analyses have been performed on the OpenSees platform for a real RC bridge column. This parametric investigation is meant at revealing the impact of key parameters on the performance of the restored RC bridge columns, such as

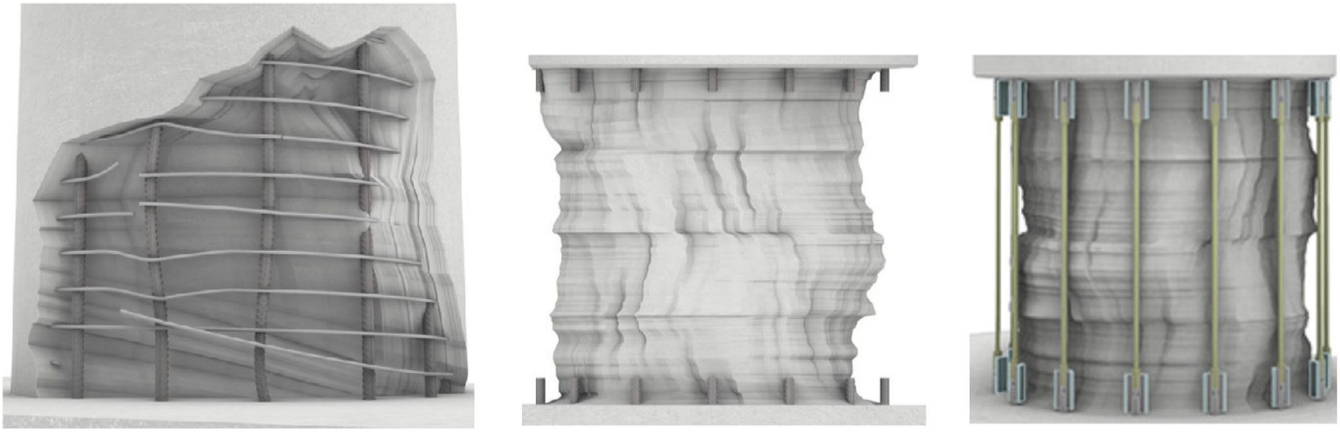

FIGURE 1 Some steps of the considered repair strategy based on ultra-high performance fiber reinforced concrete

intervention time and extension of the repaired area as well as the turning factor of the new machined longitudinal steel bars. Practical recommendations are finally formulated for repairing corroded RC bridge columns by means of UHPFRC.

2 | REPAIRING CORRODED RC BRIDGE COLUMNS WITH UHPFRC

The strategy herein considered for repairing RC bridge columns under chloride-induced corrosion is illustrated in Figure 1. It is implemented as follows.

- The existing external layer of concrete is initially removed from the intervention area. The repaired zone must extend along the column height and must go to depths beyond the backside of the original reinforcement in order to allow replacement of corroded longitudinal rebar parts as well as to prevent the corrosion of new steel rebars (height and depth of the intervention area are denoted as H_{int} and d_{int}, respectively). The repaired zone must also broaden into the foundation to properly distribute the tensions at the footing.
- Concrete core surface is prepared to improve the bond between existing and new concrete parts.
- Corroded longitudinal rebars are cut and replaced with new machined steel rebars (H_{mac} is the length of the zone in which machined steel rebars are employed while $\alpha = A_t/A_b$ denotes the turning factor, also known as a machined index, where A_m and A_s' are turned and original rebar cross-section area, respectively). This occurs in two steps.
  - New machined steel rebar segments are first aligned with the existing rebars whereas the couplers (i.e., steel equal angles) are placed on the backside.
  - Welding chords are made between rebar and coupler as well as between the rebars' end. This operation is carried out on the front side of the connection.
    Part of the original longitudinal reinforcement within the intervention area can be eventually replaced with new unmachined steel rebars ($H_{\text{int}} - H_{\text{mac}}$ is the length of the zone in which unmachined steel rebars are employed).
- Covering by means of HPFRC is thus performed. To this end, the formwork is installed and UHPFRC casting is completed. The formwork is removed once enough time is passed. Note that UHPFRC has a relatively early strength gain, which reduces the total time needed for completing the repair intervention (it takes 24–48 h).

It is highlighted that the very low diffusion coefficient of the UHPFRC essentially prevents chloride ingress in concrete and thus stops the corrosion of steel reinforcement near the repaired zone. It is also pointed out that the use of UHPFRC enhances significantly the shear capacity,[22] thereby allowing to remove without replacement the corroded arms of the transverse reinforcement in the repaired zone.

3 | NUMERICAL MODELING OF CORRODED RC BRIDGE COLUMNS REPAIRED WITH UHPFRC

3.1 | Finite element modeling

Numerical simulations based on the finite element (FE) method are performed in order to investigate the effectiveness of the considered repair technique for an RC bridge column with a circular cross-section subjected to chloride-induced corrosion.

Particularly, chloride ingress in the cross-section of the bridge column is simulated via multiphysics simulations, taking into account the effects of temperature, humidity, aging, and corrosion-induced cover cracking. The computer program COMSOL Multiphysics is employed to solve the governing partial differential equations. Once the corrosion current intensity is derived from the chloride concentration, the time-dependent reduction of the cross-section of the steel reinforcement is determined. The nonlinear model of the RC bridge column under chloride-induced corrosion has been developed into the OpenSees platform. The cross-sections of the column are discretized into several unidirectional steel and concrete fibers. The interested reader can refer to the recent work by Pelle et al.[5] for more details. In the current study, such nonlinear modeling of the RC bridge column has been revised to also account for the repair based on HPFRC covering and new machined steel rebars.

In the reference configuration, the proposed numerical model for the simulation of the repaired RC bridge column under chloride-induced corrosion is detailed in Figure 2. The whole column is divided into three regions. Element 1 is employed to model the cross-section repaired by means of machined steel rebars and UHPFRC in place of the original NSC. It is assumed that such a region extends over an assigned length equal to $H_{\text{mac}} = L_p$, where L_p is the plastic hinge length. Element 2 is considered to take into account the region of the RC bridge column where the repair is carried out by means of unmachined steel rebars and replacing the original NSC with UHPFRC. A variable length $H_{\text{int}} - H_{\text{mac}}$ is considered for such a region. It is assumed that no debonding occurs at the interface between the UHPFRC and core concrete. In the present study, L_p is determined according to Paulay and Priestley[23] considering the undamaged column. Finally, Element 3 represents the unrepaired part of the RC bridge column. While corrosion of steel rebars stops in Element 1 and Element 2 because of the very-low diffusivity of the UHPFRC, reinforcement continues to corrode in Element 3. The resulting discretized model employs force-based fiber elements, and the Gauss-Lobatto integration scheme is adopted.

A rigid link is introduced to connect the top of the column with the point where axial and lateral forces are applied. On the other side, a zero-length section element at the base of the column is introduced to simulate the strain penetration of the anchorage reinforcement in the footing. The stress–slip constitutive model developed by Zhao and Sritharan[24] is assigned to reinforcing steel bars. The anchorage is presumed to be protected against aggressive chemicals, and thus the reinforcement embedded in the foundation is not corroded. The stress–displacement relationship for concrete is obtained by multiplying the strain values of the Kent–Scott–Park strain–stress model[25,26] by an effective depth over which the compressive strain acts, which is taken equal to $0.3D$ following Kashani et al.[27] (D is the diameter of the RC bridge column). It is pointed out that a larger concrete cover is adopted for the zero-length section element at the base in order to prevent yielding since it is introduced only to account for the deformability due to strain penetration.

Strain–stress relationships for NSC, steel, and UHPFRC adopted in the FE model of the repaired RC bridge column are detailed hereafter.

3.2 | Strain–stress relationships for NSC and steel

The Kent–Scott–Park strain–stress relationship[25,26] with a parabolic curve in the pre-peak stage and a linear softening-type post-peak response is assumed to simulate the behavior of unconfined cover concrete. Conversely, the model proposed by Mander et al.[28] is adopted to account for the confinement due to transverse reinforcement on confined core concrete.

For the unrepaired region of the column (i.e., Element 3 in Figure 2), the effects of cracking and spalling on the strength of the cover concrete due to rust expansion are taken into account according to Coronelli and Gambarova.[29] The effect of transverse reinforcement corrosion on core concrete confinement is modeled by referring to the time-varying value of its corroded cross-section area.

It is known that the tensile strength of UHPFRC is higher than that of NSC mostly because of the fibers embedded into the concrete mix. This reflects in an increment of the effective lateral confining stress on the core concrete f'_ℓ. Hence, a uniform lateral pressure attributable to the UHPFRC $f'_{\ell,\text{UHPC}}$ must be considered together with the effective lateral confinement due to transverse reinforcement $f'_{\ell,w}$ calculated according to Mander et al.,[28] as it is shown in Figure 3.
It means that f'_ℓ is given by:

$$f'_\ell = f'_{\ell,w} + f'_{\ell,\text{UHPC}}. \tag{1}$$

Particularly, $f'_{\ell,\text{UHPC}}$ is herein evaluated as follows:

$$f'_{\ell,\text{UHPC}} = \frac{2\sigma_{cc} c_{rep}}{D'}, \tag{2}$$

where D' is the diameter of NSC confined by UHPFRC, c_{rep} is the thickness of the new UHPFRC cover, and σ_{cc} is the tensile strength of UHPFRC. This latter parameter is here calculated according to Willie et al.[30] as follows:

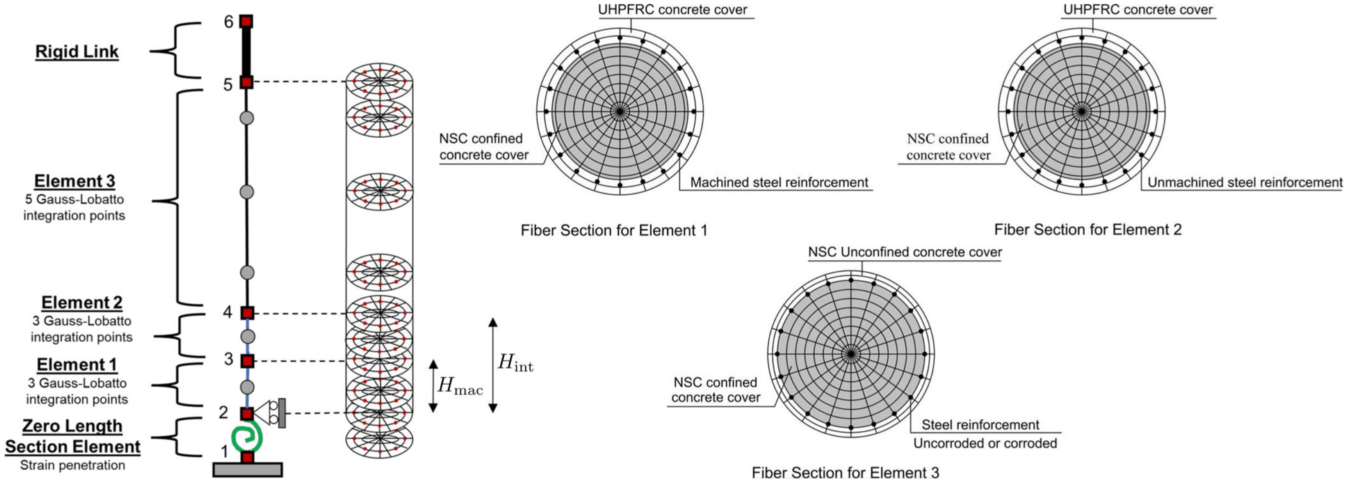

FIGURE 2 Structural FE model of the repaired RC bridge column and detail of the cross-section discretization (reference configuration). FE, finite element; NSC, normal-strength concrete; RC, reinforced concrete; UHPFRC, ultra-high performance fiber reinforced concrete

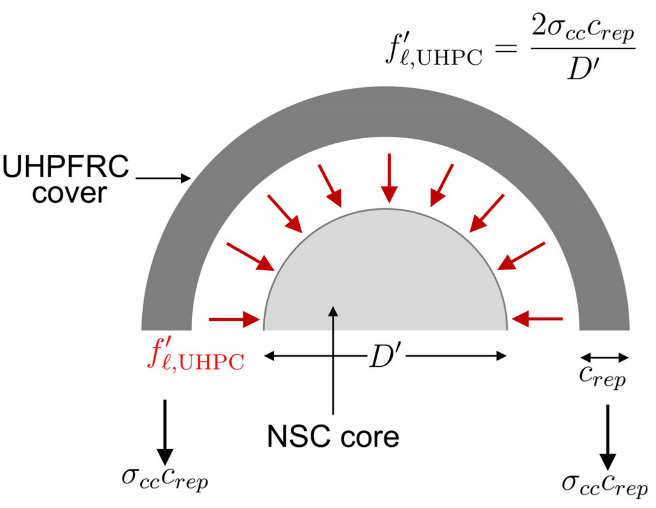

FIGURE 3 Evaluation of the effective lateral confining stress for the column regions repaired with ultra-high performance fiber reinforced concrete (UHPFRC)

$$\sigma_{cc} = -(v_f - 4)^2 + 14 \text{ MPa}, \tag{3}$$

where v_f is the volumetric ratio of steel fibers.

The Menegotto–Pinto strain–stress relationship is adopted in the present work for the steel rebars.[31] The strength reduction due to steel corrosion of the longitudinal reinforcement is modeled by referring to the time-varying value of its corroded cross-section area. The effect of corrosion on ductility is modeled by reducing the ultimate strain of corroded steel rebars as proposed by Imperatore et al.[32] It is pointed out that the reduced bond between concrete and machined steel rebars is not simulated in the current model.

3.3 | Strain–stress relationship for UHPFRC

UHPFRC has higher compressive strength, energy absorption capacity, and ductility than NSC due to its unique mix of design and embedded fibers. Recently, Naeimi and Moustafa[33] have developed a simple model for simulating the behavior of UHPFRC under compression based on a few parameters, namely unconfined compressive strength f'_{c0}, and volumetric ratio of steel fibers v_f, and volumetric ratio of transverse reinforcement ρ_s. The model was calibrated against a comprehensive experimental dataset, and its complete formulation has been reported by Naeimi and Moustafa.[34] For UHPFRC under compression, modulus of elasticity E_c, peak compressive strength f'_{cc}, strain at peak compressive strength ε'_{cc}, and the post-peak strain $\varepsilon_{cc,d}$ corresponding to the deteriorated strength $\eta_d f'_{cc}$ are thus estimated as follows:

$$E_c = 3400\sqrt{f'_{c0,v_f=0}} + 1310 v_f, \tag{4}$$

$$f'_{cc} = f'_{c0,v_f=0} + 6.26 v_f + 6.57 \rho_s, \tag{5}$$

$$\varepsilon'_{cc} = \varepsilon'_{c0,v_f=0} + 7.82 \times 10^{-5} v_f + 3.49 \times 10^{-4} \rho_s, \tag{6}$$

$$\eta_d = 0.289 + 0.004 v_f + 0.052 \rho_s, \tag{7}$$

where $f'_{c0,v_f=0}$ (MPa) and $\varepsilon'_{c0,v_f=0}$ are peak stress and strain values of the unconfined UHPC without fibers, respectively. The value of $\varepsilon_{cc,d}$ can be derived by equating to $\eta_d f'_{cc}$ the following Equation (8), and then solving for ε_{cc}:

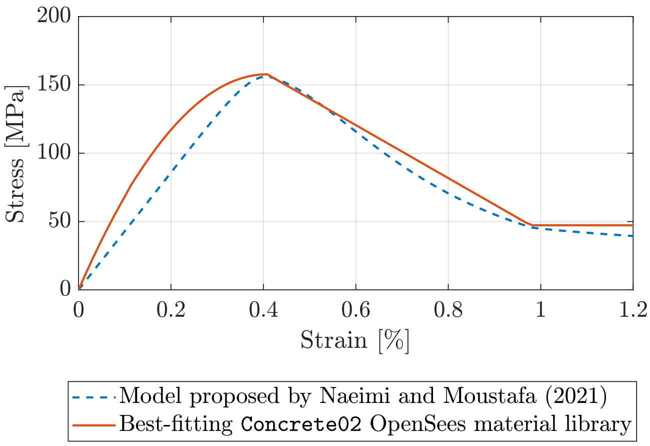

FIGURE 4 Strain–stress relationship for ultra-high performance fiber reinforced concrete under compression: comparison between the model proposed by Naeimi and Moustafa[34] and `Concrete02` after parameters tuning

$$f_c = f'_{cc} \frac{\beta_2 \left(\frac{\varepsilon_c}{\varepsilon'_{cc}}\right)}{\beta_2 - 1 + \left(\frac{\varepsilon_c}{\varepsilon'_{cc}}\right)^{\beta_3}}. \tag{8}$$

The material parameters β_2 and β_3 are calculated using these empirical formulations:

$$\beta_2 = 3.096 - 0.0941 v_f - 0.2073 \rho_s, \tag{9a}$$

$$\beta_3 = 3.793 - 0.2314 v_f - 0.0100 \rho_s. \tag{9b}$$

Since the strain–stress relationship for UHPFRC proposed by Naeimi and Moustafa[34] is not available into OpenSees, the existing material library for concrete under compression `Concrete02` is adapted to this end. Figure 4 demonstrates that the strain–stress relationship for UHPFRC under compression obtained by means of Concrete02 fairly well agrees with the model proposed by Naeimi and Moustafa[34] after parameters tuning. Following Zhang et al.,[35] the contribution of the UHPFRC in tension to the sectional strength is not taken into account, also to obtain a conservative prediction of the repaired column capacity. It is expected that such simplification has a modest influence on the final results, at least for the considered case study. In fact, the final results confirm that the major contribution of UHPFRC as a repair material for RC bridge columns in terms of sectional (flexural) strength is due to the increment of the lever arm of internal forces and the enhancement of the internal compressive force.

4 | NUMERICAL ANALYSIS

4.1 | Case study

The case study considered in the present numerical analysis is the RC bridge column of a real bridge located in Sardinia (Italy), which is illustrated in Figure 5. The column has a circular cross-section with a diameter equal to 1.2 m, whereas the height (up to the cap) is equal to 3.85 m. The longitudinal steel reinforcing bars inside the column are organized into a single concentric circular layer. The longitudinal reinforcement consists of 20 rebars with a diameter equal to 24 mm. Transverse reinforcement is provided in form of a spiral with a diameter and pitch equal to 12 mm and 250 mm, respectively. Concrete cover is equal to 40 mm and the axial load is estimated equal to 4500 kN.

The original RC bridge column is made of NSC with nominal compressive strength and corresponding strain equal to 30 MPa and 0.2%, respectively, whereas the softening branch reaches zero stress for a strain value equal to 0.4%. Yielding stress, ultimate stress, and corresponding strain of the reinforcing steel bars without corrosion are equal to 536 MPa, 649 MPa, and 11.6%. Pitting corrosion in the RC bridge column is simulated by means of multiphysics analysis over a time period equal to 100 years. A null initial chloride concentration is considered whereas the initial values of temperature and pore relative humidity are taken as 296.15 K and 0.65, respectively. A total surface chloride content of 7 kg/m^3 of concrete is assumed, which is representative of exposure conditions close to the Mediterranean coasts. Temperature and relative humidity on the boundary vary according to $296.15 - 15\sin(2\pi t/365)$ (K) and $h = 0.65 + 0.15\sin(\pi t/365)$, where t (days) is the time variable. A high pitting factor equal to 8 is considered to simulate severe corrosion conditions. Remaining data employed to simulate chloride ingress in NSC and reinforcement corrosion are taken equal to those previously adopted by Pelle et al.[5] (recall that no chloride flux through UHPFRC is assumed). The properties of the UHPFRC as repair material are the following: $f'_{c0,v_f=0} = 150$ MPa, $\varepsilon'_{c0,v_f=0} = 0.4\%$, $\rho_s = 0.0\%$ and $v_f = 1\%$.

4.2 | Parametric investigation

Figure 6 shows the time-dependent evolution of the pitting corrosion for, both, longitudinal and transverse reinforcement. It is pointed out that the shear capacity without considering the contribution due to the transverse reinforcement estimated according to Kowalsky

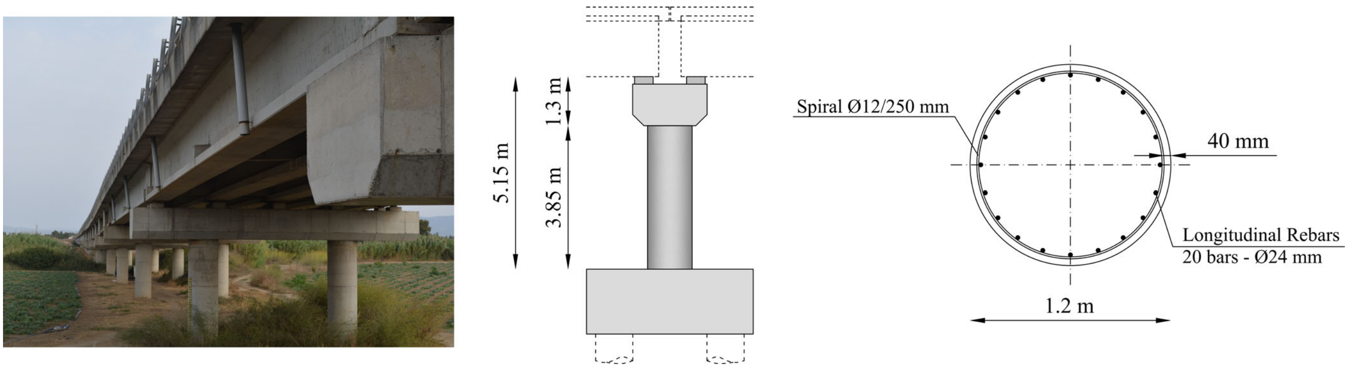

FIGURE 5 Picture of the reinforced concrete bridge selected as a case study together with data about geometry and reinforcement of the considered column

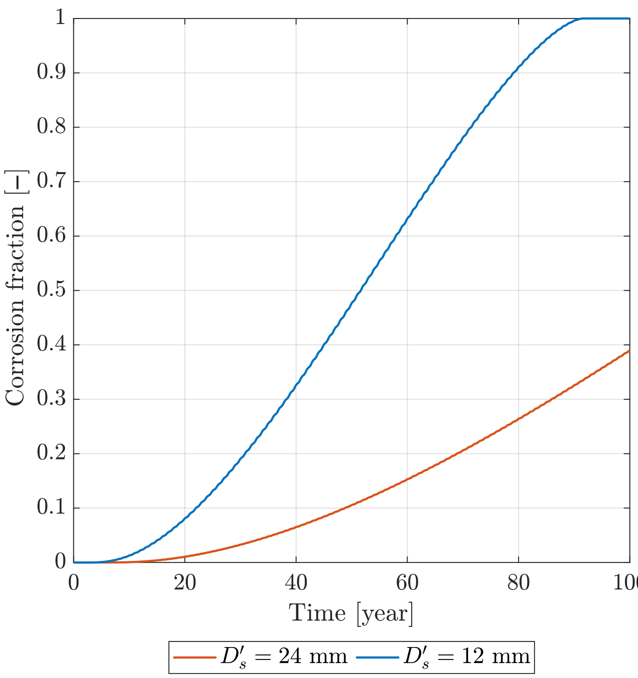

FIGURE 6 Time-dependent evolution of the pitting corrosion in longitudinal and transverse reinforcement of the reinforced concrete bridge column

and Priestley[36] was found always higher than the shear demand (even without considering the contribution due to the UHPFRC), thereby highlighting a flexural-dominated failure mode for the present RC column.

The parametric investigation aims at understanding the role of the intervention length H_{int} and that of the machined index α on the response of the repaired RC column under lateral forces, also considering the time passed since the corrosion started T_{int}. The variables considered for the present parametric investigation are listed in Table 1 together with the corresponding numerical values. It is recalled that H_{int} represents the length of the area in which NSC is replaced by UHPFRC, being $H_{\text{mac}} = L_p$ and

TABLE 1 Selected variables for the parametric investigation and corresponding numerical values

Variable	Values
Length of the intervention area, H_{int}	L_p, $2L_p$
Machined index, α	0.6, 0.8, 1.0
Time at which the column is repaired once corrosion started, T_{int}	50 years, 75 years, 100 years

$H_{\text{int}} - H_{\text{mac}}$ the length of the zones where corroded steel rebars are replaced by machined steel rebars and unmachined steel rebars, respectively (see Figure 2).

Figure 7 shows the monotonic response of the corroded RC column repaired with UHPFRC in terms of drift and base shear considering several turning factor values for the new machined longitudinal steel bars and two lengths of the repaired area. Figure 8 illustrates the moment–curvature relationships for the base section and for the first unrepaired section of the RC column. The response for the uncorroded RC column and that for the unrepaired RC column subjected to corrosion are also reported for a more comprehensive understanding of the effects of the repair.

It is evident from Figure 7 that repairing the corroded RC column with UHPFRC over a length $H_{\text{int}} = L_p$ is not enough to restore or even improve its response with respect to the undamaged scenario. In fact, except for the case where the repair is carried out at $T_{\text{int}} = 50$ years with a machined index $\alpha = 0.6$, the displacement ductility of the repaired column is lower than that of the undamaged column. If the column is repaired at $T_{\text{int}} = 100$ years, then a sudden drop of the capacity is observed due to failure in tension of corroded steel rebars, and the response of the repaired column fairly resembles that under corrosion without repair intervention. Therefore, a repair carried out at $T_{\text{int}} = 100$ years is basically useless. Conversely, Figure 7 demonstrates that extending the repair area to $H_{\text{int}} = 2L_p$

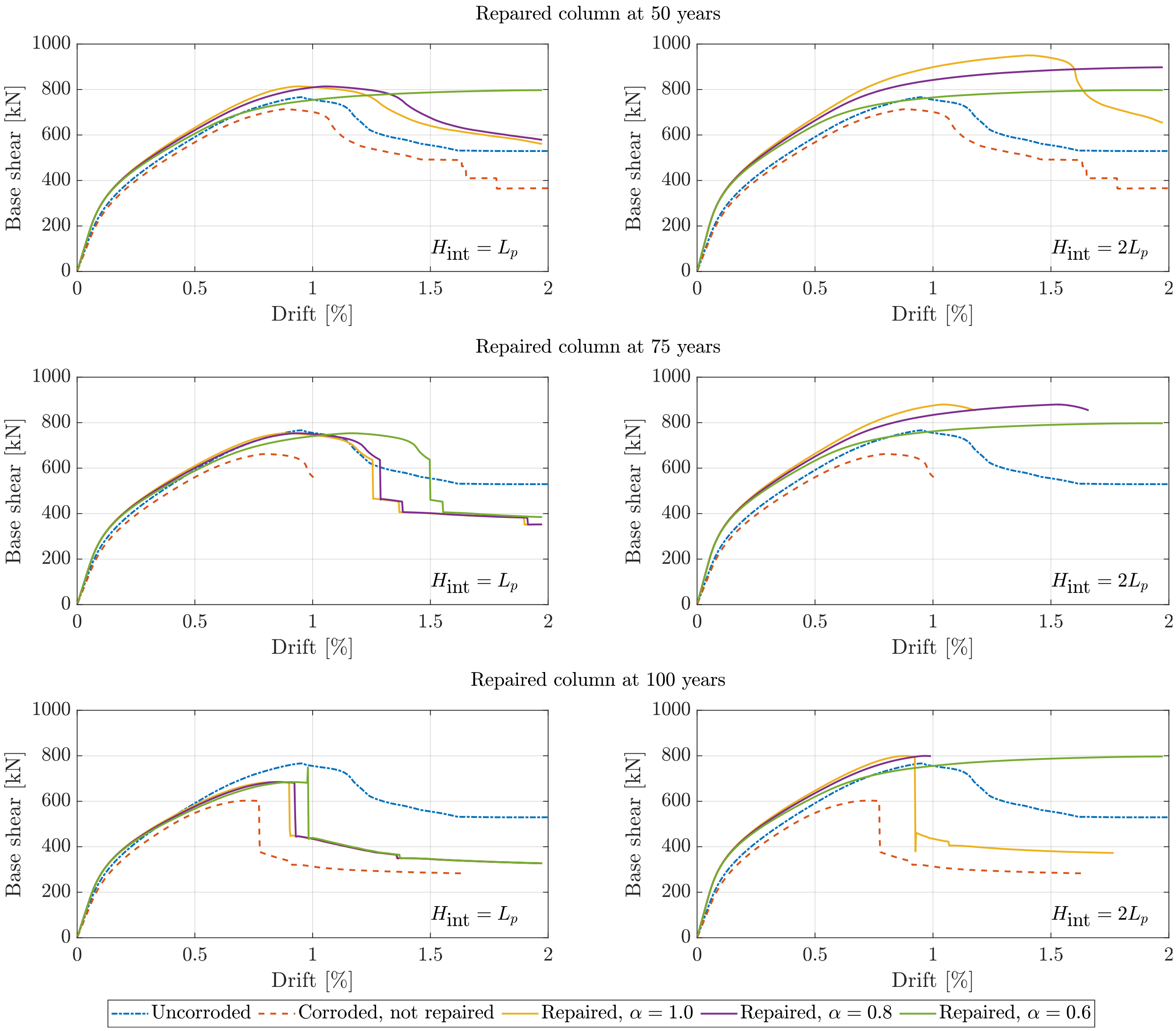

FIGURE 7 Pushover curves of the reinforced concrete (RC) bridge column under corrosion repaired with ultra-high performance fiber reinforced concrete considering several turning factor values for the new machined longitudinal steel bars and two lengths of the repaired area (pushover curves without corrosion and those for unrepaired RC bridge column under corrosion are also included)

allows to restore completely both capacity and displacement ductility regardless of the time at which the corroded RC column is repaired, provided that the cross-section area of the new machined steel rebars is 60% of the original value (i.e., $\alpha = 0.6$).

Results in Figure 7 can be also analyzed from a different perspective. Indeed, assuming that steel reinforcement corrodes in the unrepaired zone while does not corrode in the zone repaired with UHPFRC, the results at 75 years and 100 years also reflect the behavior of the repaired column once 25 years have passed since an intervention made at 50 years and 75 years, respectively. In this sense, repairing the column at $T_{\text{int}} = 50$ years over a length equal to $H_{\text{int}} = L_p$ using machined steel rebars with a machined index $\alpha = 0.6$ allows to restore its strength and ductility in the short-term, but it is not effective to extend its lifetime since the overall behavior degrades significantly when 25 years have passed. Conversely, if the RC bridge column is repaired over a larger length equal to $H_{\text{int}} = 2L_p$, then the use of machined steel rebars with a machined index $\alpha = 0.6$ always ensures the extension of its lifetime. Therefore, although repairing an RC bridge column over a smaller area may be attractive since this would result in quicker and easier operations, an invasive intervention may be more appropriate if the entire lifespan of the structure is considered, especially if its extension is a design goal.

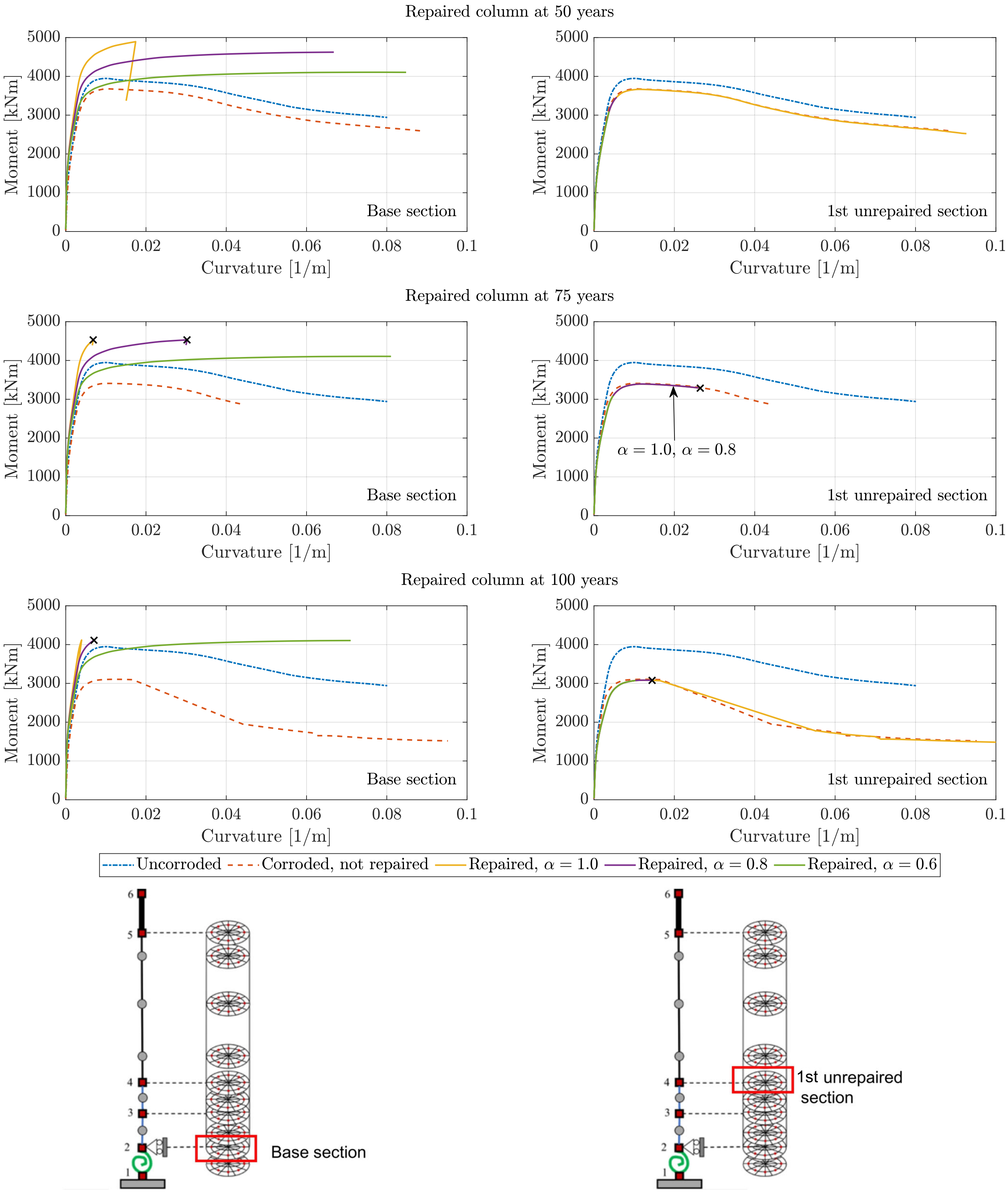

FIGURE 8 Moment–curvature curves for the base section and the first unrepaired section of the reinforced concrete (RC) bridge column under corrosion repaired with ultra-high performance fiber reinforced concrete considering several turning factor values for the new machined longitudinal steel bars and a length of the repaired area $H_{\text{int}} = 2L_p$ (moment–curvature curves without corrosion and those for unrepaired RC bridge column under corrosion are also included, the markers denote stopping by convergence issues)

Figure 8 is useful to explain why some design decisions about the length of the repaired area H_{int} and the machined index α may be not appropriate. In fact, it is evident that the higher strength of the repaired cross-section at the base as compared to the corroded unrepaired cross-section causes the relocation of the plastic hinge in the upper weak part of the column. The formation of the plastic hinge in the corroded zone dramatically reduces the displacement ductility of the column because of the higher cross-section curvature demand due to a lower shear span combined with a reduced ductility of the corroded steel rebars. Figure 8 also shows that the model has encountered convergence issues in some scenarios: nevertheless, the analysis of the strain–stress relationship demonstrates that a plastic hinge arises in the unrepaired part of the column also in such cases.

Taking into account the results of this parametric investigation, the reference configuration in Figure 2 has been revised to simulate the following two alternative repair scenarios.

- In order to evaluate the effects of a less invasive strategy, it is investigated the restoration of the original NSC with UHPFRC at the base over an assigned length equal to $H_{int} = 2L_p$ without replacing the original steel rebars.
- Moreover, it is considered the restoration of the original NSC with UHPFRC at the base over an assigned length equal to $H_{int} = 2L_p$ where half the length of the original reinforcement is replaced with machined steel rebars and the other half with unmachined ones. In such a case, in order to prevent the relocation of the plastic hinge, it is assumed that the original NSC above this region is replaced with UHPFRC over an assigned length equal to $H_{cap} = L_p$ without replacing the original steel rebars.

The monotonic response of the corroded RC column repaired according to these alternative scenarios is shown in Figure 9.

This last set of simulations demonstrates that repairing the column using UHPFRC without replacing the corroded steel rebars always allows to generate of the plastic hinge at the base, regardless of the time at which the intervention is made. However, if the corrosion level of the existing reinforcement is very high (e.g., repair after 75 years), then the displacement ductility of the column repaired with UHPFRC only will be limited by the reduced ductility of the corroded steel rebars. In such a scenario, the analysis of the strain–stress relationships shows that the failure is due to the rupture of corroded steel rebars in tension at the base section. If the column is repaired when the corrosion level of the existing reinforcement is not high (e.g., repair before 50 years), then it may be possible to restore or even improve the original performance in the short-term, but this strategy does not ensure the preservation of the performances throughout the lifespan.

Figure 9 also demonstrates that the relocation of the plastic hinge can be prevented by using UHPFRC in place of the NSC above the region where both original reinforcement and concrete are replaced. So doing, both capacity and displacement ductility of the original column are completely restored even in case of late intervention (i.e., high corrosion level of the existing reinforcement). Notably, this strategy can be implemented conveniently in order to enable the use of machined steel bars with a larger value of the turning factor (i.e., machined rebars with a lower reduction of the cross-section area).

5 | CONCLUSIONS

This work has addressed the repair of RC bridge columns subjected to chloride-induced corrosion by means of UHPFRC and machined steel rebars, with the aim of restoring the strength, stiffness, and ductility of the original column in a short time without changing its cross-section. Once the numerical model of the repaired column has been presented, a parametric investigation has been carried out to assess the role of the main design variables. Based on the obtained numerical results, the following design recommendations can be drawn.

- It is important to define properly the length of the area in which NSC is replaced by UHPFRC H_{int}, being H_{mac} and H_{int}–H_{mac} the length of the zones where existing corroded reinforcement is replaced by machined steel rebars and unmachined steel rebars, respectively. The numerical results have demonstrated that it must be carefully selected in combination with the machined index α. For the considered case study, it has been found that $H_{int} = L_p$ is not enough while $H_{int} = 2L_p$ always allows to restore the column performances provided that $\alpha = 0.6$ (with $H_{mac} = L_p$).
- The major design issue is the relocation of the plastic hinge from the repaired base zone of the column towards the unrepaired upper weak part, which can lead to a strong reduction of the displacement ductility. This can be effectively prevented by using UHPFRC in place of the NSC (with no need of substituting the original reinforcement) above the zone where the intervention is carried out by replacing both original reinforcement and concrete. Such a strategy can also

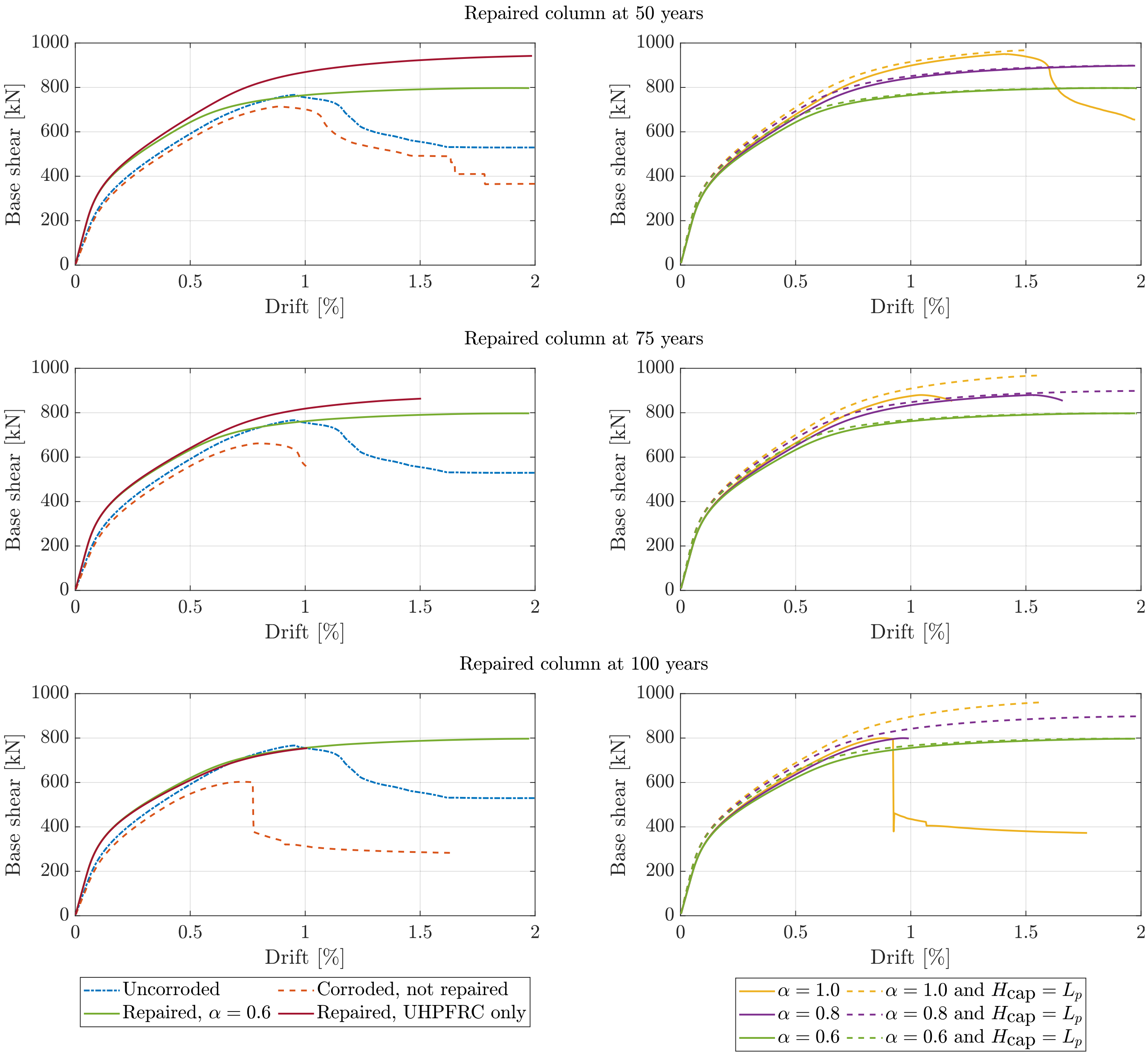

FIGURE 9 Pushover curves of the reinforced concrete bridge column under corrosion repaired according to two alternative scenarios: restoration of the original normal-strength concrete (NSC) with ultra-high performance fiber reinforced concrete (UHPFRC) only over an assigned length equal to $H_{\text{int}} = 2L_p$ without replacing the original steel rebars (left); replacement of original NSC and steel rebars over an assigned length equal to $H_{\text{int}} = 2L_p$, together with the use of UHPFRC only above this region (right)

be implemented in order to avoid a too large reduction of the cross-section area of the machined rebars inserted at the base.

- Repairing the RC bridge column by using UHPFRC without reinforcement replacement allows to generate the plastic hinge at the base. Although this strategy is less invasive and thus more attractive, it fails to ensure the long-term preservation of the restored column performances. In fact, the reduced ductility of the corroded steel rebars will limit the displacement ductility of the column repaired with UHPFRC only.
- It is also highlighted the need of designing the restoration of RC members subjected to corrosion taking into account the evolution of the repaired column performances throughout its lifetime. By restricting the attention to short-term benefits may hide long-term drawbacks, and thus can lead to improper design decisions.

ACKNOWLEDGMENTS

This work is supported by the National Natural Science Foundation of China (Grant No. 51778148). The work by Giuseppe Quaranta is framed within the research project

“Smart technologies and decision support tools for the assessment of deteriorating reinforced concrete infrastructures in seismic areas at territorial scale” (Grant No. RM120172B37F0628) funded by Sapienza Università di Roma. Open Access Funding provided by Universita degli Studi di Roma La Sapienza within the CRUI-CARE Agreement.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

ORCID

Giuseppe Quaranta https://orcid.org/0000-0001-8295-0912

Camillo Nuti https://orcid.org/0000-0002-0385-201X

REFERENCES

1. Alipour A, Shafei B, Shinozuka MS. Capacity loss evaluation of reinforced concrete bridges located in extreme chloride-laden environments. Struct Infrastruct Eng. 2013;9(1):8–27.
2. Yogalakshmi NJ, Balaji Rao K, Anoop MB. Safety assessment of in-service reinforced concrete T-girders of bridge decks. Struct Concr. 2017;18(5):733–46.
3. Osmolska MJ, Kanstad T, Hendriks MAN, Hornbostel K, Markeset G. Durability of pretensioned concrete girders in coastal climate bridges: basis for better maintenance and future design. Struct Concr. 2019;20(6):2256–71.
4. Marić MK, Ožbolt J, Balabanić G. Reinforced concrete bridge exposed to extreme maritime environmental conditions and mechanical damage: measurements and numerical simulation. Eng Struct. 2020;205:110078.
5. Pelle A, Briseghella B, Bergami AV, Fiorentino G, Giaccu GF, Lavorato D, et al. Time-dependent cyclic behavior of reinforced concrete bridge columns under chlorides-induced corrosion and rebars buckling. Struct Concr. 2022;23(1):81–103.
6. Val DV. Deterioration of strength of RC beams due to corrosion and its influence on beam reliability. J Struct Eng. 2007;133(9): 1297–306.
7. Sen R. Advances in the application of FRP for repairing corrosion damage. Prog Struct Eng Mater. 2003;5(2):99–113.
8. Tastani SP, Pantazopoulou SJ. Experimental evaluation of FRP jackets in upgrading RC corroded columns with substandard detailing. Eng Struct. 2004;26(6):817–29.
9. El Maaddawy T, Soudki K. Carbon-fiber-reinforced polymer repair to extend service life of corroded reinforced concrete beams. J Compos Constr. 2005;9(2):187–94.
10. Gadve S, Mukherjee A, Malhotra SN. Corrosion of steel reinforcements embedded in FRP wrapped concrete. Construct Build Mater. 2009;23(1):153–61.
11. Meda A, Mostosi S, Rinaldi Z, Riva P. Corroded RC columns repair and strengthening with high performance fiber reinforced concrete jacket. Mater Struct. 2016;49(5):1967–78.
12. Farzad M, Shafieifar M, Azizinamini A. Retrofitting of bridge columns using UHPC. J Bridge Eng. 2019;24(12):04019121.
13. Bertola N, Schiltz P, Denarié E, Brühwiler E. A review of the use of UHPFRC in bridge rehabilitation and new construction in Switzerland. Front Built Environ. 2021;7:769686.
14. Xue J, Briseghella B, Huang F, Nuti C, Tabatabai H, Chen B. Review of ultra-high performance concrete and its application in bridge engineering. Construct Build Mater. 2020;260:119844.
15. Sohail MG, Kahraman R, Al Nuaimi N, Gencturk B, Alnahhal W. Durability characteristics of high and ultra-high performance concretes. J Build Eng. 2021;33:101669.
16. Rajput AS, Sharma UK, Engineer K. Seismic retrofitting of corroded RC columns using advanced composite materials. Eng Struct. 2019;181:35–46.
17. Rabehi B, Ghernouti Y, Li A, Boumchedda K. Comparative behavior under compression of concrete columns repaired by fiber reinforced polymer (FRP) jacketing and ultra high-performance fiber reinforced concrete (UHPFRC). J Adhes Sci Technol. 2014;28(22–23):2327–46.
18. Peng J, Tang H, Zhang J. Structural behavior of corroded reinforced concrete beams strengthened with steel plate. J Perform Constr Facil. 2017;31(4):04017013.
19. Hou L, Wang J, Huang T, Shen C, Aslani F, Chen D. Flexural behaviour of corroded reinforced concrete beams repaired with ultra-high toughness cementitious composite. Construct Build Mater. 2019;211:1127–37.
20. Huang H, Huang M, Zhang W, Pospisil S, Wu T. Experimental investigation on rehabilitation of corroded RC columns with BSP and HPFL under combined loadings. J Struct Eng. 2020; 146(8):04020157.
21. Hasan MA, Akiyama M, Kashiwagi K, Kojima K, Peng L. Flexural behaviour of reinforced concrete beams repaired using a hybrid scheme with stainless steel rebars and CFRP sheets. Construct Build Mater. 2020;265:120296.
22. Xue J, Lavorato D, Bergami AV, Nuti C, Briseghella B, Marano GC, et al. Severely damaged reinforced concrete circular columns repaired by turned steel rebar and high-performance concrete jacketing with steel or polymer fibers. Appl Sci. 2018;8(9):1671.
23. Paulay T, Priestley MJN. Seismic design of reinforced concrete and masonry buildings. 1st ed. Hoboken: Wiley-Interscience; 1992.
24. Zhao J, Sritharan S. Modeling of strain penetration effects in fiber-based analysis of reinforced concrete structures. ACI Mater J. 2007;104(2):133.
25. Kent DC, Park R. Flexural members with confined concrete. J Struct Div. 1971;97(7):1969–90.
26. Scott BD, Park R, Priestley MJN. Stress–strain behavior of concrete confined by overlapping hoops at low and high strain rates. ACI J. 1982;79(1):13–27.
27. Kashani MM, Lowes LN, Crewe AJ, Alexander NA. Nonlinear fibre element modelling of RC bridge piers considering inelastic buckling of reinforcement. Eng Struct. 2016;116:163–77.
28. Mander JB, Priestley MJN, Park R. Theoretical stress-strain model for confined concrete. J Struct Eng. 1988;114(8): 1804–26.
29. Coronelli D, Gambarova P. Structural assessment of corroded reinforced concrete beams: modeling guidelines. J Struct Eng. 2004;130(8):1214–24.
30. Wille K, El-Tawil S, Naaman AE. Properties of strain hardening ultra high performance fiber reinforced concrete (UHPFRC) under direct tensile loading. Cem Concr Compos. 2014; 48:53–66.
31. Menegotto M, Pinto PE. Method of analysis for cyclically loaded RC plane frames including changes in geometry and non-elastic behavior of elements under combined normal force and bending. Prof. of IABSE symposium on resistance and

ultimate deformability of structures acted on by well defined repeated loads; 1973 (13). p. 15–22.
32. Imperatore S, Rinaldi Z, Drago C. Degradation relationships for the mechanical properties of corroded steel rebars. Construct Build Mater. 2017;148:219–30.
33. Naeimi N, Moustafa MA. Compressive behavior and stress–strain relationships of confined and unconfined UHPC. Construct Build Mater. 2021;272:121844.
34. Naeimi N, Moustafa MA. Analytical stress–strain model for steel spirals-confined UHPC. Composites C Open Access. 2021; 5:100130.
35. Zhang Y, Yang J, Li T, Deng M. Mechanical behavior of RC columns strengthened with thin UHPC jacket under cyclic loads. J Build Eng. 2022;49:104065.
36. Kowalsky MJ, Priestley MJN. Improved analytical model for shear strength of circular reinforced concrete columns in seismic regions. ACI Struct J. 2000;97(3):388–96.

AUTHOR BIOGRAPHIES

Angelo Pelle
Department of Architecture
Roma Tre University
Largo G. B. Marzi 10, 00153 Rome, Italy
angelo.pelle@uniroma3.it

Bruno Briseghella
College of Civil Engineering
Fuzhou University
No. 2 Xue Yuan Road, Fuzhou, 350108 Fujian, China
bruno@fzu.edu.cn

Gabriele Fiorentino
Department of Civil Engineering
University of Bristol
University Walk, BS8 1TR Bristol, UK
gabriele.fiorentino@bristol.ac.uk

Gian Felice Giaccu
Department of Architecture, Design and Urban Planning
University of Sassari
Palazzo del Pou Salit, Piazza Duomo 6, 07041 Alghero, Italy
gigiaccu@uniss.it

Davide Lavorato
Department of Architecture
Roma Tre University
Largo G. B. Marzi 10, 00153 Rome, Italy
davide.lavorato@uniroma3.it

Giuseppe Quaranta
Department of Structural and Geotechnical Engineering
Sapienza University of Rome
Via Eudossiana 18, 00184 Rome, Italy
giuseppe.quaranta@uniroma1.it

Alessandro Rasulo
Department of Civil and Mechanical Engineering
University of Cassino and Southern Lazio
Via G. Di Biasio 43, 03043 Cassino, Italy
a.rasulo@unicas.it

Camillo Nuti
Department of Architecture
Roma Tre University
Largo G. B. Marzi 10, 00153 Rome, Italy
camillo.nuti@uniroma3.it

How to cite this article: Pelle A, Briseghella B, Fiorentino G, Giaccu GF, Lavorato D, Quaranta G, et al. Repair of reinforced concrete bridge columns subjected to chloride-induced corrosion with ultra-high performance fiber reinforced concrete. Structural Concrete. 2022. https://doi.org/10.1002/suco.202200555