Durability analysis and environmental impact of ultra-high performance fibre reinforced concrete (UHPFRC) for bridge applications

Camillo Nuti[1], Angelo Pelle[1], Giuseppe Quaranta[3], Alessandro V. Bergami[1], Bruno Briseghella[4], Gabriele Fiorentino[2], Davide Lavorato[1], Alessandro Rasulo[5],

[1] *Department of Architecture, Roma Tre University, Rome, Italy*

[2] *Department of Civil Engineering, University of Bristol, Bristol, UK*

[3] *Department of Structural and Geotechnical Engineering, Sapienza University of Rome, Rome, Italy*

[4] *College of Civil Engineering, Fuzhou University, Fuzhou, China*

[4] *Department of Civil and Mechanical Engineering, University of Cassino and Southern Lazio, Cassino, Italy*

1 Introduction

Durability evaluation of reinforced concrete (RC) bridges in aggressive environments imposes special attention to the evaluation of corrosion of reinforcing steel bars since it impacts significantly on the direct and indirect costs in existing RC structures. Bridges can experience sudden failures, even under ordinary loading conditions, if suitable actions are not implemented on time.

On the other hand, in the context of structural rehabilitation, adequate innovations in design with regard to materials and geometries as well as choice of time for the intervention, should be accurately investigated in next few years. Efforts towards new best practice in design may have an even greater and certainly faster environmental impact on reducing harmful carbon dioxide emissions, but also raw materials consumption, than limiting to push towards technological advances in cement production .

Different interventions of repairing or retrofitting of RC bridge column damaged by seismic action have been previously proposed. Among these, repair the columns through a jacket of concrete, steel or FRP, with or without substitution of damaged longitudinal rebars, have received great interest. A comprehensive review of these technique is proposed in [1]. In addition, the authors of the present paper also proposed a rehabilitation technique which is reported in [2],[3][4]. In this perspective, ultra-high performance fibre reinforced concrete (UHPFRC) can be a viable solution to deal with durability and sustainability issues. Thanks to its very low permeability [5], [6], UHPFRC is especially attractive to lengthen the lifetime of new structures or to extend that of existing constructions when used as retrofitting material.

Hence, the present work aims to investigate numerically the possible replacement of normal strength concrete (NSC) of the cover, damaged by reinforcement corrosion, with one in UHPFRC, also considering the possibility to replace corroded longitudinal steel rebars. The simple substitution of the cover with NSC is also presented for comparison.

2 Numerical modelling

The effects of chloride-induced corrosion are evaluated by a multiphysics approach which accounts for temperature, pore relative humidity, cover crack width, and concrete age [7].

The numerical model to evaluate the mechanical capacity of the column has been developed into OpenSEES platform, with reference to [7]-[9], adopts force-based elements, cross-sections discretized into fibers. A zero-length element at the base accounts for the strain penetration.

The uniaxial material Concrete01 available in the OpenSEES material library is adopted to simulate the response of the unconfined NSC of the cover. Instead, the uniaxial material Concrete04 is employed to simulate the response of the confined core concrete. The effect of the transverse reinforcement corrosion on core confinement is modelled by referring to the corroded cross-section area. The confining pressure on the core concrete due to tensile strength of UHPFRC is also considered.

The uniaxial materials Concrete01 and Hysteretic are adopted for the compressive and tensile responses of UHPFRC, [10] and [11].

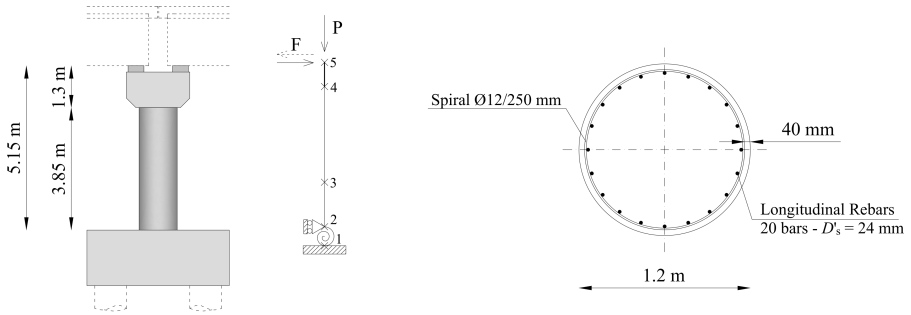
Menegotto-Pinto relation is adopted for the longitudinal reinforcement, as the monotonic behaviour is investigated, bar buckling and other features relevant for cyclic behaviour [6] are neglected.

3 Numerical investigation

The column bridge configuration is a real RC bridge considered in [7]. Column dimensions and reinforcement quantities are shown in Fig. 1. The concrete cover is 40 mm, and the axial load is P = 4500 kN.

The unconfined concrete strength is f'_c = 30 MPa. Uncorroded steel properties are f'_{sy} = 536 MPa, f'_{su} = 649 MPa and ε'_{su} = 11.6%.

To assess the time evolution of the pitting corrosion in the original RC bridge column cross-section by means of Multiphysics simulation, a null initial chloride concentration is considered within the cross-section whereas the initial value of temperature and pore relative humidity are taken as 296.15 K (23 °C) and 0.65m, respectively. A total surface content of 7 kg/m3 of concrete is assumed, which is representative of exposure conditions close to the Mediterranean coasts.



a) Prespective view **b) Cross-Section of the pier**

Fig. 1 Layout of the case study

Table 1 Investigated cases

Case	New cover type	Length of new cover	Rebar substitution	Time of intervention (years): T_i
NSC_COR	NSC	L_p	No	50, 75, 100
UHPC_Cor_1.5lp_50	UHPFRC	$1.5 \cdot L_p$	No	50
UHPC_Cor_1.5lp_75	UHPFRC	$1.5 \cdot L_p$	No	75
UHPFRC_UC_1lp	UHPFRC	$1.0 \cdot L_p$	Yes	50, 75, 100
UHPFRC_UC_1.5lp	UHPFRC	$1.5 \cdot L_p$	Yes	50, 75, 100
UHPFRC_UC_2lp	UHPFRC	$2.0 \cdot L_p$	Yes	50, 75, 100

The repair technique consists in substituting the cover at the base, for different lengths: L_p – 1.5 L_p – 2 L_p (L_p is the estimated plastic hinge length) with a new one in UHPFRC or NSC, with/without substitution of the corroded reinforcement. Table 1 shows the investigated cases. Uncorroded (UC) and corroded (Cor) responses are reported as reference. Interventions cases are reported in Table 1.

4 Results and discussion

In Fig. 2 one can see the uncorroded capacity compared to the corroded at T_i. At 50 years corrosion is active since few years, there is a reduction in strength about 10% and drift (the value at which 20% of maximum strength is lost) of about 10%. In case we leave the reinforcement and substitute the cover with NSC there is no practical improvement in strength and displacement capacity. Note the abrupt strength reduction at 75 years (1% Drift) and 100 years (0.75% Drift), due to failure of corroded bars. If UHPFRC is used, we may note an increase in strength, due to its tensile contribution. The intervention at 50 Years without rebar substitution leads the same behaviour, we have failure a 1.3% of drift. Indeed, shear increases as the plastic hinge move above the intervention zone. This negative characteristic is triggered delaying the time of intervention. We note that at 75 and 100 year we have in fact the same behaviour if we substitute or not the corroded rebars in the plastic hinge zone. Outside the intervention zone, bending capacity reduces and demand in the repaired zone cannot overtake capacity even without corroded rebar substitution. The intervention zone must be extended. With 1.5 lp we have an improvement at 100 years, but not at 75.

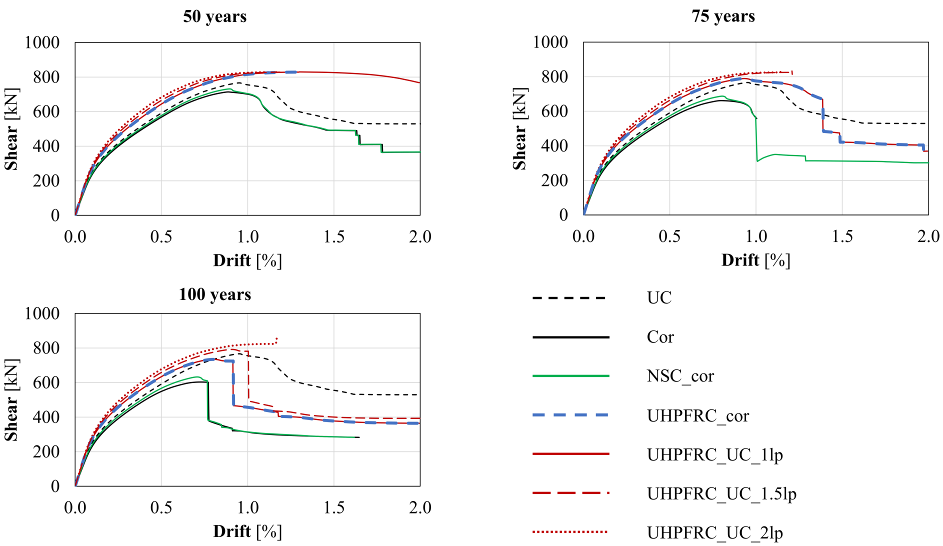


Fig. 2 Drift vs base shear at three different time of intervention T_i = {50, 75, 100}

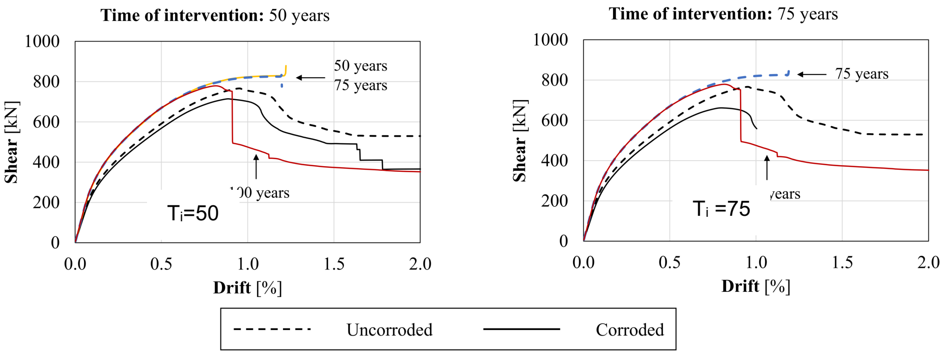


Fig. 3 Drift vs shear without rebar substitution, intervention height 1.5 lp.

The effect of time after intervention at 50 and 75 years, Fig 3, shows that the former maintains it characteristics at 75 years, as yielding happens at the base. Within the repaired zone with UHPFRC there is no corrosion, and maximum moment distribution along the column remain the same. Eventually failure at 100 years happens at 1.5 L_p, where corrosion reduces section strength below bending request. The maximum available drift reduces from 1.2% to 0,85%.

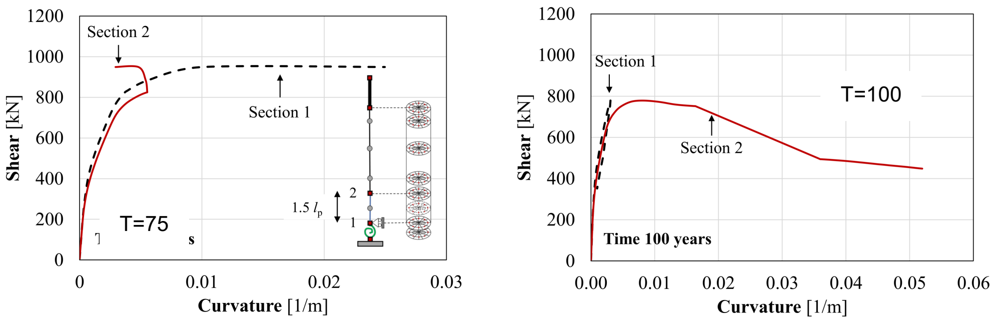


Fig. 4 Base Curvature (section 1 and 2) vs shear. T_i=75 years, with UHPFRC, without rebar substitution, intervention height 1.5 lp.

With reference to Fig.4. we may note for T_i=75 that we have yielding in the repaired zone, while section 2 remains quite elastic, at 100 years we have yielding in section 2, with a reduction in shear from 970kN to less than 800kN due to rebar corrosion, while base section (1) remains elastic. Rebar substitution would be useless or even negative, a careful evaluation of repair length is essential.

References

[1] He, R., Yang, Y., & Sneed, L. H. 2015. “Seismic repair of reinforced concrete bridge columns: Review of research findings.” *Journal of Bridge Engineering* 20(12), 04015015.

[2] Lavorato, D., A. V. Bergami, C. Nuti, B. Briseghella, J. Q. Xue, A. M. Tarantino, G. C. Marano, and S. Santini. 2017. “Ultra-high-performance fibre-reinforced concrete jacket for the repair and the seismic retrofitting of Italian and Chinese RC bridges.” In *COMPDYN - Proc. Int. Conf. Comput. Methods Struct. Dyn. Earthq. Eng.*, 2149–2160. Athens: National Technical University of Athens.

[3] Xue, J., Lavorato, D., Bergami, A., Nuti, C., Briseghella, B., Marano, G., ... & Santini, S. (2018). Severely Damaged Reinforced Concrete Circular Columns Repaired by Turned Steel Rebar and High-Performance Concrete Jacketing with Steel or Polymer Fibers. Applied Sciences, 8(9), 1671.

[4] Xue J., Lavorato, D., Bergami, A.V., Tarantino, A.M., Briseghella, B., Nuti, C. 2021. “Reinforcing Bar Replacement in Damaged RC Bridge Column Plastic Hinges: Design Criteria and Experimental Investigation”. *Journal of Structural Engineering* (Under review).

[5] Farzad, M., Sadeghnejad, A., Rastkar, S., Moshkforoush, A., Azizinamini, A. 2020. “A theoretical analysis of mechanical and durability enhancement of circular reinforced concrete columns repaired with UHPC.” *Engineering Structures* 209, 109928.

[6] Xue, J., Briseghella, B., Huang, F., Nuti, C., Tabatabai, H., & Chen, B. 2020. “Review of ultra-high performance concrete and its application in bridge engineering.” *Construction and Building Materials* 260, 119844.

[7] Pelle A, Briseghella B, Bergami AV, Fiorentino G, Giaccu GF, Lavorato D, et al. 2021. “Time-dependent cyclic behavior of reinforced concrete bridge columns under chlorides-induced corrosion and rebars buckling.” *Structural Concrete* 1–23.

[8] Kashani MM, Lowes LN, Crewe AJ, Alexander NA. 2016. “Nonlinear fibre element modelling of RC bridge piers considering inelastic buckling of reinforcement.” *Eng Struct.* 116:163–77.

[9] Berry MP, Eberhard MO. 2006. “Performance modeling strategies for modern reinforced concrete bridge columns.” *PEER Report 2007/07: Pacific Earthquake Engineering Research Center*.

[10] Naeimi, N., Moustafa, M. A. 2021. “Analytical Stress–Strain model for steel spirals-confined UHPC.” *Composites Part C: Open Access*, 5, 100130.

[11] 8 Wille, K., El-Tawil, S., & Naaman, A. E. 2014. “Properties of strain hardening ultra high performance fiber reinforced concrete (UHP-FRC) under direct tensile loading.” Cement and Concrete Composites, 48, 53-66