Bridge pier corrosion in seismic areas: forecasting, future behavior and assessment

Camillo Nuti, Angelo Pelle, Giuseppe Quaranta, Alessandro V. Bergami, Bruno Briseghella, Davide Lavorato, Gabriele Fiorentino and Alessandro Rasulo

Department of Architecture,
Roma Tre University,
Largo G. B. Marzi 10, 00153 Rome, Italy

Abstract

The detrimental effect of steel corrosion on seismic response is investigated by non-linear analysis. A multiphysics FE model is used to evaluate the time-dependent chloride-induced corrosion. Different steel arrangements are considered. Results show that the greater is the diameter of the reinforcing bar, the lower is the degree of corrosion. Furthermore, numerical investigations of seismic response with IMPAb suggest that pitting corrosion may lead to different bar behavior, producing or avoiding premature bar buckling. Corrosion of transverse reinforcements results to be more severe than for longitudinal ones leading to probable shear failure.

1 Introduction

Reinforced Concrete (RC) bridges are of crucial importance for any transportation networks, and their serviceability should be guaranteed, in some cases, also after a strong earthquake. Frequently, RC bridges are exposed to aggressive environments, such as marine environments, so that may suffer from material aging. Corrosion of steel reinforcement is undoubtedly the most important degradation phenomenon for RC bridges piers, and more generally for all RC structures, in fact, many considerations can be easily extended to buildings. In this work, we refer mainly to RC columns as the deck degradation, less relevant for seismic issues, is usually dealt with for non-seismic situations.

Uniform and/or localized corrosion phenomena are widely recognized as the most common corrosion morphologies. The former is mainly due to carbonation-induced corrosion and involves the full length of steel bars reducing equally the diameter, while the latter occurs under chloride ions penetration in concrete, and reinforcing surface is characterized by local cavities and notches, known as pits. Pitting corrosion may appear in a heterogeneous way along the length of the reinforcement resulting in a more severe attack than a uniform one. Localized cavities, in fact, not only reduce the strength of the reinforcing bars but also their ductility. If the steel bar is stretched by a tensile force, the deformation will be concentrated in deeper notches. Thus, the overall elongation will be developed in small zones and, consequently, the average strain will be less at failure compared to an uncorroded bar. Different studies have been proposed to address tensile [1,2] as well as compressive behaviours [3,4] of both bare and embedded corroded bars.

Corrosion directly affects the mechanical properties (strength and ductility) of RC elements. Meda et al. [5] found a reduction of about 30% and 50% of ultimate lateral resistance and displacement, respectively in a corroded column with respect to the uncorroded one.

Longitudinal bars under compression in RC members, if not properly retained by transversal reinforcement, may exhibit large transverse deformation, known as buckling. Lavorato et al. [6] observe that corrosion may increase the likelihood of premature bar buckling since reduces average bar diameter and increases the longitudinal reinforcement buckling length, also for the deteriorated stirrup retaining contribution. In addition, the compressive response of the longitudinal bars may be strongly affected by pitting morphologies. The position of cavities along the steel surface as well as the loss cross-section area in these zones may create very different behaviours, as detected in [3,7]. Eventually, it has been shown in [7] that pitting corrosion may even reduce the probability of rebar buckling if two pits only create within the stirrup pitch where buckling usually develops. Moreover, transversal reinforcements, because of their minor concrete cover, are affected by a greater degree of corrosion than longitudinal ones, making easier local and global bar buckling. In certain circumstances, a strong reduction of the transversal rebars cross-section area associated with a decrease of its strength and ductility may facilitate shear failure, a brittle mechanism.

In the RC bridge pier immersed in the sea can be distinguished different zones along the height of the column: submerged zone, tidal and splash zone, and atmospheric zone. In the submerged zone the corrosion is modest or even absent, contrary, the tidal and splash zone is the worst one because cyclic wetting and drying may cause accumulation of chloride which facilitates corrosion initiation and propagation. Hence, a different spatial variability of corrosion along the elevation of the piers may create a weaker section, not at the base, but close to the mid-level. Similar mid-height corrosion concentration may also happen in piers where, for example, trees or bushes exist at the base, protecting from rain, sunshine, and freeze. During a strong seismic action, the plastic hinge may form at a higher level, with respect to the base section, increasing the local ductility demand (i.e. curvature ductility) due to shorter distance from plastic hinge to pier top, while displacement demand remains unchanged, therefore decreasing column displacement ductility.

Nowadays, the modern codes, such as the Eurocodes, have introduced specific requirements to reduce serious material aging issues for RC structures during the design working life [8], adopting higher concrete strength and larger cover. Bergami et al. [9] showed that Eurocode requirements result in a sharp reduction of the degree of reinforcement corrosion. This fact avoids strength and ductility reduction. Buckling of compressed reinforcement is avoided in new structures thank to a limited spiral pitch, while aging does not affect transverse reinforcement, avoiding possible buckling due to corrosion. Unfortunately, most of the existing RC bridges have been built prior to the adoption of the modern codes and lack of adequate provision to prevent reinforcement corrosion and avoid premature bar buckling which strongly contributes to column failure.

Hence, there is the need for fragility evaluation techniques that allow accounting for the huge uncertainties related to corrosion processes to produce a reliable seismic assessment, without disproportionate calculation efforts. To account for the non-linear seismic response the scientific community, in a recent period, is oriented to use pushover-based procedure specifically developed for buildings or bridges [10]. This approach is oriented to avoid non-linear dynamic analysis (is now popular the use of Incremental Dynamic Analysis (IDA) [11,12]) since those can be time-consuming and the time histories selection and scaling is a controversial point. The adoption of adequate time histories in the fields of the rare records complying with specific site conditions and high intensities is not always possible; this difficulty adds to the cumbersome treatment of the great uncertainties associated with corrosion. To this end, the authors have proposed the use of IMPAβ (Incremental Modal Pushover Analysis for bridges [13]), a method specifically for bridges, developed as an evolution of Incremental Modal Pushover [14,15] originally proposed for buildings; IMPAβ allows to reduce computational time with respect to IDA without losing the accuracy of the fragility evaluation, especially in case of corrosion [9].

In this paper, we discuss the cited items considering as case study a continuous bridge with piers of different height and so classified as irregular, according to modern codes [16]. The following three hypotheses are made: a) designed according to Eurocode 8 with slightly excessive stirrup pitch; b) like in the previous case but with smaller longitudinal diameters and with stirrup pitch compliant with Eurocode, c) under-designed bridge with 1/3 of case b) reinforcement. In all three cases, cover provisions for corrosion seem to be respected. The aim of the proposed numerical investigations, for which the results are reported in §3, is to show the effect of uniform and pit type corrosion, of both longitudinal and transversal reinforcement, on seismic performances as a consequence of different steel arrangements. Finally, conclusions are drawn.

2 Numerical Investigation

2.1 Case studies

The RC pier selected for the present numerical investigation, with a diameter of 2.5 m and height of 7.0 m, is the central one of a four-span irregular bridge studied in many previous works [9,13,17], considering three different reinforcements as shown in Table 1 and in Fig. 1. The steel rebars have yield strength equal to 450 MPa and the ultimate strain for uncorroded rebars is assumed to be equal to 7.5 %.

Table 1 Pier Geometry and reinforcement arrangements

Case	Longitudinal Reinforcement	Transverse Reinforcement
A	210ϕ30 – on 2 layers	2 ϕ18 mm spiral /200
B	330ϕ24 – on 3 layers (2nd and 3rd in adherence)	2 ϕ12 mm spiral /100
C	110ϕ24 – on 1 layer	ϕ12 mm spiral /100

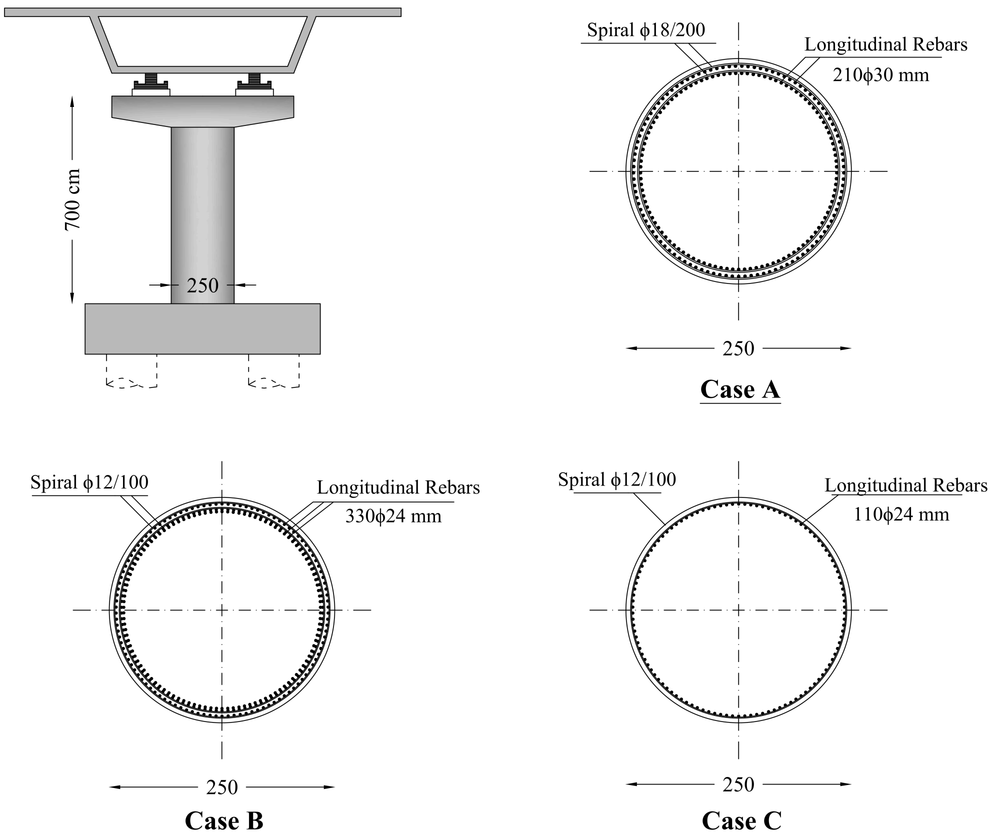

Fig. 1 RC pier bridge geometry and reinforcements: Case A) 210ϕ30 mm longitudinal rebars and spiral ϕ30/200 mm, Case B) 330ϕ24 mm longitudinal rebars and spiral ϕ12/100 mm and Case C) 110ϕ24 mm longitudinal rebars and spiral ϕ12/100 mm.

For all these section configurations, the concrete cover was assumed to be 50 mm from the external surface to the centroid of spiral reinforcement. The longitudinal reinforcement ratio ρ_l for the first two reinforcement configuration is about ρ_l=3.0%, while the third one has a longitudinal reinforcement ratio of about ρ_l=1.0 %. Resulting in an over reinforced section for arrangements A and *B* and in an under reinforced section for arrangement *C*. The axial load ratio is about ν=15.0 % (P=13936.7 kN).

Cases A and B result from design in Reggio Calabria (Italy), where PgA (peak ground acceleration) is 0.35g. Details of the design response spectrum are given in [9].

2.2 Numerical modelling

2.2.1 Effects of chloride-induced corrosion

In this work, a multiphysics FE model to evaluate the effect of chloride-induced corrosion for the different section arrangements is adopted. The ingress of chloride ions inside concrete cover is simulated as a diffusion process adopting the Fick's second law to evaluate the spatial variability of total chloride concentration C_{tc} at the time t. The effects of temperature, humidity, cover cracking, and concrete age on the chloride diffusion coefficient are considered.

Corrosion current density i_{corr} is evaluated as a function of total chloride concentration C_{tc} by the equation proposed in [18] and, assuming that pitting corrosion dominates the loss of reinforcing steel bar cross-section, the model proposed by Val. [19] can be used to evaluate the residual cross-section area at the time t. More details on the multiphysics FE model can be found in [9].

Fig. 2 shows the time-dependent cross-section of transversal and longitudinal reinforcement area losses for the considered steel arrangements. Initial conditions are: a null chloride concentration, the values of temperature and humidity equal to 296.15 K and 0.65, respectively. Furthermore, a total surface chloride content of 7 kg/m^3 of concrete has been assumed, which is representative of exposure conditions close to the Mediterranean coasts.

2.2.2 Finite element model of RC bridge pier

The finite element model adopted in this research is developed according to Kashani et al. [20] using OpenSEES. It is based on a two-component approach, in which the following coexisting behavioural mechanisms are separately accounted for flexure and bonding, as schematically depicted in Fig. 3.

The flexural behavior is modelled using a nonlinear force-based beam-column element available in OpenSEES. The first element, in the proximity of the plastic hinge zone, is modelled using three Gauss-Lobatto integration points and its length is 6 times the longitudinal steel buckling length L_b (herein assumed equal to the spiral pitch). Instead, the second element is modelled as a force-based element with five integration points (Fig. 3a). The behavior of the beam-column is obtained through the integration of the responses obtained at the section level. The element cross-sections are discretized in fibres (Fig. 3b).

Since it is expected that bar buckling will occur on the first critical section of the column, modified Monti and Nuti with corrosion stress-strain law (SteelMN implemented in OpenSEES by the authors), which is able to account for bar buckling, is employed to represent the response of the steel bars in the element 1. More details on this constitutive model are available in [6,7,21,22]. The softening ratio b_{0-}, superposition length γ_s, and curvature control parameter in compression R_{0-} have been specifically evaluated through a FE micro model of the steel bar. Instead, the constitutive model by Menegotto and Pinto (Steel02) is adopted for the bars in the 2nd element. Variations of steel bar mechanical proprieties due to corrosion are considered only for the outermost layer on the base of corrosion diffusion results. To account for the effect of strain concentration due to pitting corrosion which reduces the reinforcements ductility, the method proposed by Imperatore et al. [23] is employed. The greater slenderness ratio ($\lambda=L/D$, where L is the spiral pitch and D is the diameter of the longitudinal reinforcement) of the corroded longitudinal rebars under compression is accounted for as suggests in [6].

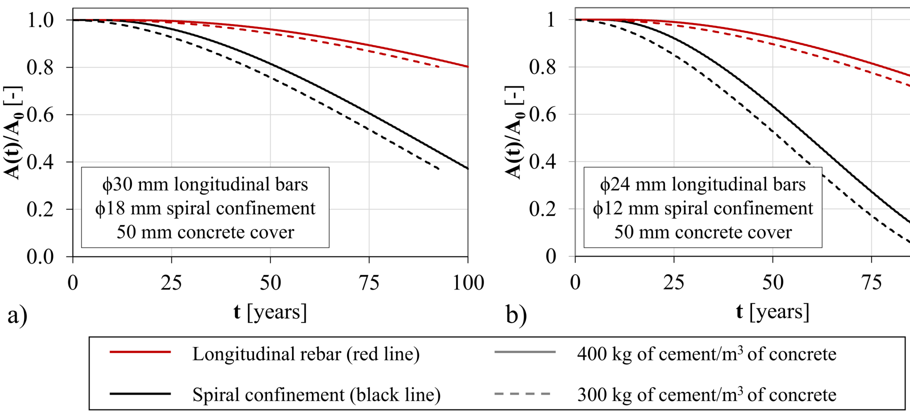

Fig. 2 Loss of cross-section area for transversal and longitudinal reinforcement with 50 mm of concrete cover. a) 30 mm diameter longitudinal rebars and 18 mm diameter spiral confinement, b) 24 mm diameter longitudinal rebars and 12 mm diameter spiral confinement.

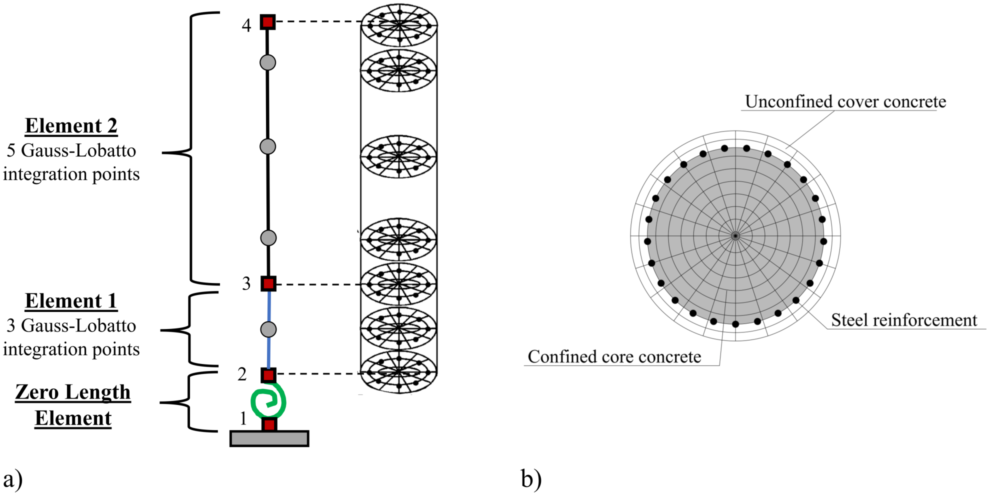

Fig. 3 Model implemented in OpenSEES: a) element configuration, b) fibre section.

The concrete is modelled using the Concrete04 uniaxial material which is based on the Popovics law. The concrete on the section cover is considered unconfined, whilst the concrete in the section core is considered as confined, using the Mander et al. model. The effect of concrete cover cracking and spalling due to rust expansion is also taken into account reducing the strength of the cover concrete as suggest by Coronelli and Gamabrova [24], no variations of mechanical proprieties of the confined concrete core are considered since internal spiral confinement is expected to be uncorroded.

The bonding is responsible for the extra displacement due to the slippage of the longitudinal reinforcing bars in the anchoring concrete. This is accounted for through a rotational slip spring at the bottom of the column with a linear constitutive relationship [25].

3 Results and discussion

Table 2 reports a general overview of the numerical investigations considered in the present paper, for Case A and B they are named as, for example, *A.0* where the letter specifies the section case considered and the following number represents the time of exposure (0 means uncorroded case). Instead, for Case C, the numerical results are named as, for example, *C.0.5a* where the first two characters have the same meaning of the previous cases while the following number indicates the slenderness ratio of the longitudinal bars since, only for Case C, two slenderness ratios are considered, adding to the usual as in case B of about 5.0 also a slenderness ratio equal to 8.0, while the last letter indicates the pit morphologies, *a* for three pits configuration (Fig. 6a) and *b* for two pits (Fig. 6b).

Fig. 4 shows: a) the displacements Vs Peak Ground Acceleration (PgA) obtained in [9] for the central column of the bridge, and b) the cyclic history imposed to the column at different drifts to have an understanding of the seismic behavior at such large deformations.

Table 2 Cases considered in the present numerical investigation

Case	Time [years]	Longitudinal bar $A(t)/A_0$ [%]	Spiral confinement $A(t)/A_0$ [%]
A.0, B.0 and C.0.*x*	0.00	100.0	100.0
A.68	68.0	89.3	60.5
B.68, C.68.*x*a and C.68.*x*b	68.0	81.5	27.2

Note: x in C.0.x, C.68.xa or C.68.xb is equal to 5 or 8, the slenderness ratios considered.

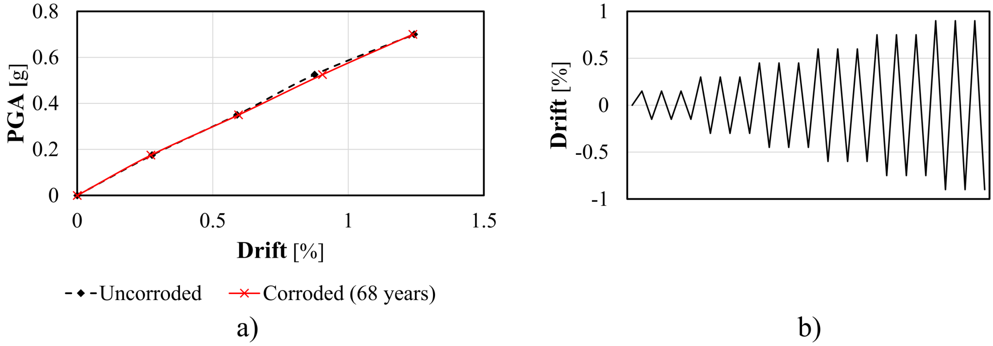

Fig. 4 a) Displacement of the central column Vs PgA in [9]; b) cyclic displacements applied to OpenSees model, in Fig.3.

In Fig. 5 the pier shear-drift behaviours for the uncorroded and corroded cases are compared. For Case A (Fig. 5a) there are slight differences between the uncorroded and corroded responses. This may be attributed to the modest loss cross-section area of the longitudinal reinforcement due to pitting corrosion. In fact, there is a loss of about 10% at 68 years of exposure in the external circumference while the internal remains uncorroded. Similar conclusions can be drawn for Case B (Fig. 5b), despite a greater loss cross-section area (about 20% at 68 years of exposure for the external layer) only one-third of longitudinal rebars are expected to be corroded.

It is important to underline that the external spiral reinforcements are heavily affected by larger corrosion with respect to longitudinal reinforcement. Therefore, the pier may undergo a shear failure in the elastic branch or immediately after the formation of the plastic hinge [26]. The FE model developed herein is not able to directly account for shear behavior. However, the shear strengths for the corroded pier evaluated with the model of Priestley [27] and with a truss model (*θ=45°*) are reported in Fig. 5.

The latter model is quite conservative than the former one. It is evident that in Case B the failure may be in shear, while in Case A the shear strength is higher than shear demand yet. This is due to the different transverse arrangements; the greater is the spiral reinforcement diameter (18 Vs 12), the lower is the damage due to pitting corrosion.

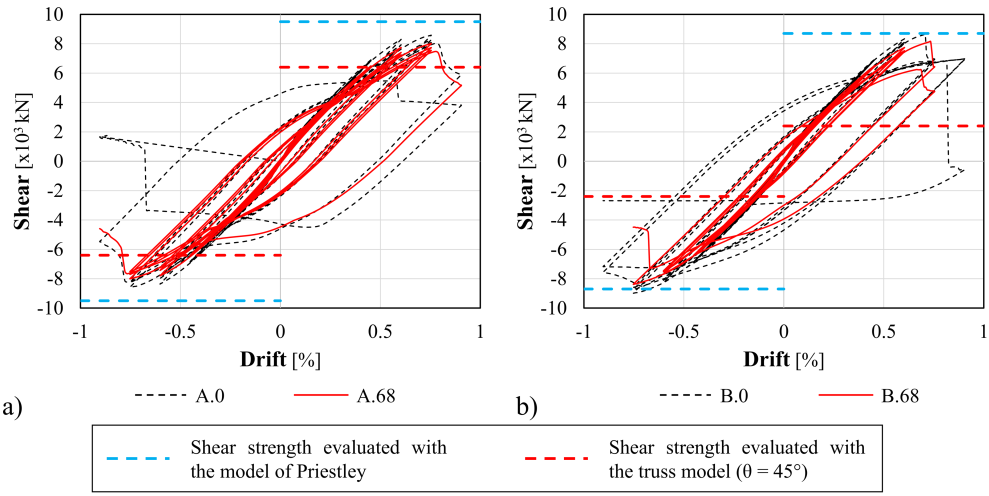

Fig. 5 Comparison between uncorroded and corroded behaviours. a) pier shear-drift responses for Case A, b) pier shear-drift responses for Case B. Shear strength is evaluated only for corroded cases.

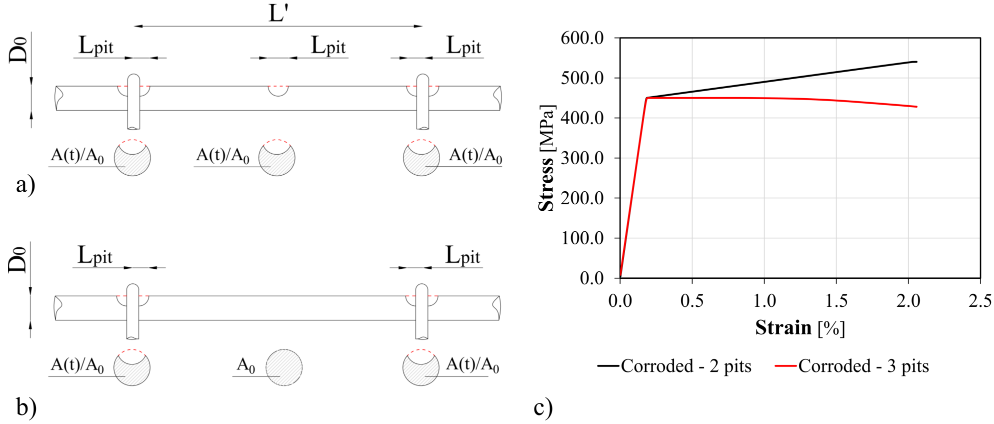

Fig. 6 Adopted scheme for pit corrosion: a) case with three pits at the spiral level, b) case with two pits, c) compressive stress-strain behaviour for case *a* (red line) and *b* (black line) for a slenderness ratio equal to 5.1.

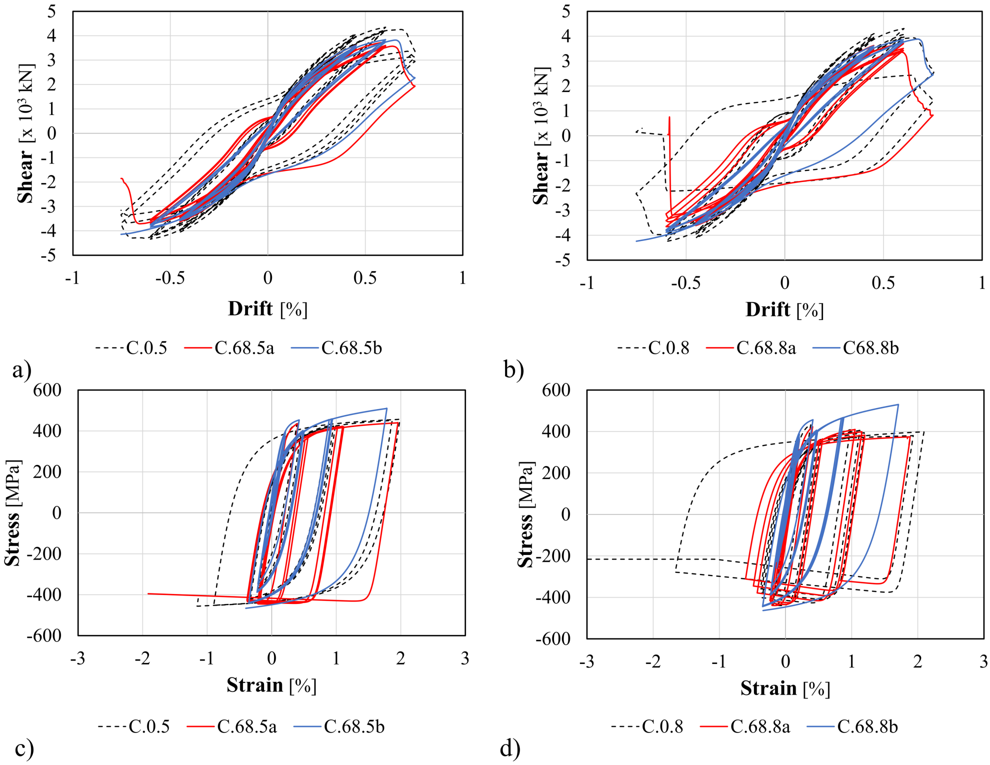

Fig. 7 Comparison between uncorroded and corroded behaviours with and without bar buckling. In a) and c) pier shear-drift and rebar stress-strain responses, respectively, with a slenderness ratio of the longitudinal bars equal to 5 are reported. In b) and d) are reported the same quantities with a slenderness ratio equal to 8.0.

In Fig. 6c the responses for two distinct pits morphologies (Fig. 6a and Fig.6b), obtained through a FE micro model of the compressive longitudinal bar, are reported. Buckling may or may not happen whether the middle pit creates or not and according to the amount of loss cross-section area in the two pits near the spiral level, which usually happen first. Namely, in the case of two pits and a cross-section area reduction corresponding to 68 years of exposure, buckling cannot arise, contrary to the case with three pits. This topic deserves further investigations.

In this paper, the modified Monti and Nuti stress-strain law parameters have resulted from the FE micro model of the compressive longitudinal steel bar. For Case C the effects of different pit morphologies, shown in Fig. 6, on column response and longitudinal rebars at the base of the column, are reported in Fig. 7. In Fig 7a and c, pier shear-drift responses and stress-strain laws of longitudinal rebars, respectively, with a slenderness ratio equal to about 5 are plotted, in Fig 7b and d the same quantities are plotted for the slenderness ratio equal to 8. For both, pits morphology *b* impedes buckling.

Case with slenderness 5 has no buckling at time 0, while has buckling for time 68 years and morphology *a* (Fig. 6a). On the other hands, case with slenderness 8 has buckling at time 0 too and even larger for time 68 years and morphology *a*. Buckling cannot happen for morphology *b* (Fig. 6b).

4 Conclusion

The cases of bridge columns with code complying for design for corrosion are investigated at time 0 (zero) and after 68 years. Corrosion may happen in different ways: uniform, pitting and in the latter case with different morphologies. The following conclusions can be drawn:

- Pushover allows the determination of seismic response, resulting fast and efficient.
- It has been shown that transverse reinforcement has larger corrosion with respect to longitudinal.
- Large diameter adoption reduces the amount of corrosion.
- Buckling of corroded longitudinal rebars usually happens also in cases of original design complying with provision given to avoid this drawback.
- Eventually, pit corrosion may lead to avoid buckling thanks to the reduction of two sections per spiral pitch. This may result in a stronger column in bending but leads more easily to shear failure.

References

[1] Du, Y.G., Clark L.A., and Chan A.H.C. 2005. "Residual capacity of corroded reinforcing bars." *Magazine of Concrete Research* 57:135–47.

[2] Du, Y.G., Clark L.A., and Chan A.H.C. 2005. "Effect of corrosion on ductility of reinforcing bars." *Magazine of Concrete Research* 57(7):407–419.

[3] Kashani, Mohammad M., Crewe A.J., and Alexander N.A. 2013. "Nonlinear stress–strain behaviour of corrosion-damaged reinforcing bars including inelastic buckling." *Engineering Structures* 48:417–429.

[4] Imperatore, Stefania, and Rinaldi Zila. 2019. "Experimental behavior and analytical modeling of corroded steel rebars under compression." *Construction and Building Materials* 226:126–138.

[5] Meda, Alberto, Mostosi S., Rinaldi Z., and Riva P. 2014. "Experimental evaluation of the corrosion influence on the cyclic behaviour of RC columns." *Engineering Structures* 76:112–123.

[6] Lavorato, Davide, Fiorentino G., Pelle A., Rasulo A., Bergami A.V., Briseghella B., and Nuti C. 2019. "A corrosion model for the interpretation of cyclic behavior of reinforced concrete sections." *Structural Concrete* 21(5):1732-1746. Accessed December 30, 2019. https://doi.org/10.1002/suco.201900232.

[7] fib. "Modelling of structural performance of existing concrete structures." *Fédération Internationale du béton / International Federation for Structural Concrete*; 2020. In Press

[8] European Committee for Standardization. 2005. "Eurocode – Basis of structural design." *European Committee for Standardization*: Brussels, Belgium.

[9] Bergami, Alessandro V., Pelle A., Fiorentino G., Lavorato D., Giaccu G.F., Quaranta G., Briseghella B., and Nuti C. 2020. "Seismic assessment of corroded RC bridges through incremental modal pushover analysis." *SUBMITTED*

[10] Kappos, Andreas. J., Saiidi M.S., Aydinoğlu M.N., and Isaković T. 2012. *Seismic Design and Assessment of Bridges: Inelastic Methods of Analysis and Case Studies.* Springer Science & Business Media
[11] Alipour, Azadeh, Shafei B., Shinozuka M. 2011. "Performance Evaluation of Deteriorating Highway Bridges Located in High Seismic Areas." *Journal of Bridge Engineering* 16(5):597–611..
[12] Dizaj Ebrahim A., and Kashani M.M. 2020. "Numerical investigation of the influence of cross-sectional shape and corrosion damage on failure mechanisms of RC bridge piers under earthquake loading." *Bulletin of Earthquake Engineering* 18:4939–4961. Accessed August 2020. https://doi.org/10.1007/s10518-020-00883-3.
[13] Bergami Alessandro V., Nuti C., Lavorato D., Fiorentino G., and Briseghella B. 2020. "IMPAβ: Incremental modal pushover analysis for bridges." *Applied Science* 10(12): 4287. Accessed June 22, 2020. https://doi.org/10.3390/app10124287.
[14] Bergami Alessandro V, Nuti C., and Liu X. 2015. "Proposal and application of the Incremental Modal Pushover Analysis (IMPA)." Paper presented at the IABSE conference–structural engineering: providing solutions to global challenges. Rep 2015:1695–700. https://doi.org/10.2749/222137815818359104.
[15] Bergami Alessandro V., Forte A., Lavorato D., and Nuti C. 2017. "Proposal of a Incremental Modal Pushover Analysis (IMPA)." *Earthq. Struct* 13(6):539–549. https://doi.org/10.12989/eas.2017.13.6.539.
[16] European Committee for Standardization. 2005. "Eurocode 8 – Design of Structures for Earthquake Resistance – Part 2: Bridges." *European Committee for Standardization:* Brussels, Belgium.
[17] Bergami Alessandro V., Fiorentino G., Lavorato D., Briseghella B., and Nuti C. 2020. "Application of the Incremental Modal Pushover Analysis to Bridges Subjected to Near-Fault Ground Motions." *Applied Science* 10(19):6738. Accessed September 26, 2020. https://doi.org/10.3390/app10196738.
[18] Liu T., and Weyers R.W. 1998. "Modeling the Dynamic Corrosion Process in Chloride." *Cement and Concrete research* 28(3):365–379.
[19] Val, Dimitri V. 2007. "Deterioration of Strength of RC Beams due to Corrosion and Its Influence on Beam Reliability." *Journal of Structural Engineering* 133(9):1297-1306.
[20] Kashani Mohammad M., Lowes L.N., Crewe A.J., and Alexander N.A. 2016. "Nonlinear fibre element modelling of RC bridge piers considering inelastic buckling of reinforcement." *Engineering Structures* 116:163-177.
[21] Monti, Giorgio, and Nuti C. 1992. "Nonlinear cyclic behavior of reinforcing bars including buckling." *Journal of Structural Engineering* 118(12):3268-3284.
[22] Zhou, Zhiao, Lavorato D., Nuti C., Marano G.C. 2015. "A model for carbon and stainless steel reinforcing bars including inelastic buckling for evaluation of capacity of existing structures." Paper presented at the COMPDYN 2015 - 5th ECCOMAS Thematic Conference on Computational Methods in Structural Dynamics and Earthquake Engineering 2015:876–86. https://doi.org/10.7712/120115.3436.1636.
[23] Imperatore, Stefania, Rinaldi Z., Drago C. 2017. "Degradation relationships for the mechanical properties of corroded steel rebars." *Construction and Building Materials* 148:219–230.
[24] Coronelli, Dario, Gambarova P. 2004. "Structural Assessment of Corroded Reinforced Concrete Beams: Modeling Guidelines." *Journal of structural engineering* 130(8):1214–1224.
[25] Elwood, Kenneth J., Moehle J.P. 2004. "Shake Table Tests and Analytical Studies on the Gravity Load Collapse of Reinforced Concrete Frames." PEER 2003/01, November 2003.
[26] Rasulo, Alessandro, Pelle A., Lavorato D., Fiorentino G., Nuti C., and Briseghella B. 2020. "Finite element analysis of reinforced concrete bridge piers including a flexure-shear interaction model." *Applied Science* 10(7):2209. Accessed March 25, 2020. https://doi.org/10.3390/app10072209.
[27] Kowalsky Mervyn J., Priestley M.J.N. 2000. "Improved Analytical Model for Shear Strength of Circular Reinforced Improved Analytical Model for Shear Strength of Circular Reinforced Concrete Columns in Seismic Regions." *Structural Journal* 97(3):338-396.

Aknowledgements:DPC-ReLUIS RP 2014-2018 and 2019-2021, NSF of China (Grant No. 51778148), Federbeton (Italy) partial support for "Seismic Behaviour of Integral Bridges"