2019 SECED Conference
Earthquake risk and engineering towards a resilient world
9-10 September 2019, Greenwich, London

CRITICAL REVIEW OF MODELS FOR THE ASSESSMENT OF THE DEGRADATION OF REINFORCED CONCRETE STRUCTURES EXPOSED TO CORROSION

Luigi DI SARNO[1] & Francesco PUGLIESE[2]

Abstract: *Exposure to aggressive environments is one of the main causes of reinforced concrete (RC) civil infrastructure degradation and damage, which can become critical if such structures are unprotected, as in the case of bridges, and even more crucial if subjected to seismic loading. This paper aims at analysing the models and approaches currently used for the assessment of RC structures exposed to different levels of corrosion. Furthermore, a specific section will be devoted to the evaluation of ageing on the seismic performance of bridges. A few numerical and analytical models of aged reinforced concrete structures have been chosen among thousands the proposed in the literature based on chronological time criteria. The methodological approach consists in comparing the results provided in the literature, based on experimental tests, with the outputs of Finite Element. These analyses were conducted by changing the mechanical properties of both concrete and steel rebars at different corrosion rates, which affect concrete strength, yielding stress, ultimate stress and stiffness of embedded steel rebars, and thus, bearing-capacity and seismic performance. New relationships for concrete strength and steel properties according to the level of corrosion are given. The results confirm the pivotal role and evolutionary nature of the impact of corrosion on the lifecycle of concrete structures*

Keywords: Corrosion; Earthquake Engineering; Structural Modelling; Numerical Simulations.

Introduction

Corrosion of steel rebars is one of the leading causes of premature degradation and ageing of reinforced concrete (RC) infrastructures. Although the process of corrosion has been studied by many authours, it is still challenging to analyse and predict its evolution since it is time-dependent. Typically, when reinforcement bars leave the factory, they are covered with a layer of mill scale which oxidizes according to the so-called “atmospheric corrosion.” Potentially, this porous and uniform layer protects steel reinforcements from early corrosion, which could compromise their purpose in the concrete elements, and assists the formation of the passive layer when concrete is poured [1]. As a result, concrete provides a high alkaline environment (typically PH>13) for steel rebars and ensures a direct physical barrier to the attack of aggressive agents through the cover.

Despite numerous changes in Standards and Codes over the years, small concrete-cover thickness and low-strength concrete remain prevalent. As a result of this, aggressive agents can easily penetrate through the concrete and de-passivate the layer of film lying uniformly on the surface of steel rebars. Chemical and physical processes cause various damage processes and alter the mechanical properties of both the steel reinforcement bars and the concrete. Accordingly, mass loss and cross-section reduction of steel reinforcement bars and concrete cover cracking, as well as reduced concrete compressive strength and effectiveness of confined concrete summarise the main consequences of corrosion. The broad context of environmental deterioration and environmental risk assessment is directly related to structural performance and its serviceability. Evidence from experimental results (Rodriguez et al. 1996 [2], Uomoto and Misra (1988) [3], Revathy et al.(2009) [4]) seems to confirm how corrosion decreases the overall

---

[1] Senior Lecturer in Structural Design, Civil Engineering and Industrial Design, University of Liverpool, Liverpool, United Kingdom, Luigi.Di-Sarno@liverpool.ac.uk; Assistant Professor in Earthquake Engineering, Engineering Department, University of Sannio, Benevento, Italy

[2] PhD Student, Institute for Risk and Uncertainty and Civil Engineering and Industrial Design Department, University of Liverpool, Liverpool, United Kingdom

ultimate capacity of RC elements owing to the substantial decay of the mechanical properties of both concrete and steel rebars, which can affect both seismic and non-seismic prone zonas.
Many unprotected civil infrastructures, such as bridges, even in non-seismic zonas (i.e. UK) , show deficient conditions due to ageing and, often poor or non-existent inspection-ratings are available to assess and plan risk mitigation. When inspection-ratings are available, they usually yield an overestimation of repair costs. An investigation carried out by RAC Foundation (The Royal Automobile Club Foundation) with the help of the National Bridges Group of ADEPT (The Association of Directors of Environment, Economy, Planning and Transport) found that 2434 out of 50561 (5%) bridges in the UK are in poor conditions and cannot carry the loading of more than one lorry driving through. As a result, all these bridges are categorised as “substandard”. Therefore, actions are required to recover those bridges, and further investigations have revealed that bills will hit more than £6.7 billion [5].

Since there are no clear standards for evaluating deteriorated RC elements, especially in seismic prone-areas, this paper aims to provide a better understanding of the performance of ageing RC structures and proposes to develop a new Interaction Surface M-N for the evaluation of the remaining capacity of RC piers, which can be used as a new inspection-rating. The proposed approach will help to reduce excessively conservative solutions and, increase and preserve the safety of all RC structures. An extended state-of-art and literature review will also be presented to cover all the parameters related to the mechanical behaviour of corroded concrete and steel reinforcements, and a section on the seismic performance through a Finite Element approach for a deteriorated RC bridge is given.

Research Significance

To evaluate the condition of corroded RC structures, the actual performance has to be determined. New corrosion-related inspection-ratings have to be established to plan maintenance, new cost-effective strategies and risk mitigation. To meet all these goals, this study proposes a new method based on the cross-sectional analysis of RC elements subjected to different degrees of corrosion. Accordingly, numerical validation has been provided to demonstrate the effectiveness of this method.

Literature Review

Reinforced Concrete civil infrastructures are among the primary concerns for many worldwide governments due to their economic and social importance. A certain amount of deterioration is accounted for in the design of RC structures. However, over the last few years, it has become evident that having a better idea of the rate at which such deterioration occurs is a technical challenge of crucial importance. Moreover, such deterioration does not affect only the capacity of RC structures to withstand load bearing capacity, but also the mechanism of failure from ductile to brittle type [4], with severe implications for the seismic behaviour of RC civil infrastructures.
Marine exposure, salts de-icing, sulphate and carbonate attacks have increased the annual costs of the maintenance. Many efforts have been made to investigate and develop technical solutions. The purpose of this review is to evaluate the effects of corrosion on concrete and steel reinforcements.

Figure 1. a) Bridge Collapse in Ohio due to corrosion, Public Domain; b) A bridge in Monroeville, Pennsylvania, shows signs of embedded steel rebar corrosion, photo of Anil Patnaik (http://corrdefense.nace.org); c) Bridge piers show sign of corrosion [34]

Concrete

The contact with aggressive agents deteriorates the concrete leading to cover-cracking and microcracking within the confined concrete core. As a result, concrete becomes more permeable, and the attack may have disastrous consequences. Usually, there are two different kinds of exposure: direct, such as sea splashes and de-icing salts, and indirect such as sulphate-carbonate-chloride based accelerants. While for direct exposure, chlorides and sulphates can penetrate through concrete from external sources, the indirect exposure could eventually happen because of the presence of some previously mentioned agents in the cement paste. In particular, in the winter season, these accelerants provide a high hydration heating, which allows concrete to reach high compressive strength after few days. The deterioration of concrete depends upon numerous factors, such as:

- Environmental conditions, the presence of aggressive agents which induce deterioration both in concrete and steel reinforcement;
- Climate, the particular exposure of RC structures;
- The composition of the cement paste that can influence the permeability of the concrete and its diffusion;
- The geometry of reinforced concrete elements which is a crucial component for the deterioration of concrete due to corrosion.

There are two chemical processes that cause the deterioration of the concrete:

- Sulphate attacks;
- Alkali-aggregate reactions.

The sulphate attacks can be external and internal. External attacks happen when some sulphates (in solution) penetrate the concrete, while the internal attack is mainly due to some soluble sulphate during the mixing of concrete [6]. Instead, alkali-aggregate reactions are responsible for expansive cracking occurring in the later ages of the concrete. Alkalis including free potassium (K, sodium (Na^+) and hydroxyl (OH^-), react with some aggregates in the concrete and result in a deleterious expansion and thus, strong internal stress concentrations [7].

Impact of Corrosion on the concrete properties

Sulphate attacks and Alkali-Aggregate reactions generate cracks, the spoiling of concrete cover and a decrease in concrete's compressive strength, stiffness and ductility. The decline of the compressive strength is the leading cause of damaged concrete. Coronelli and Gambarova [8] proposed a method to evaluate the corroded compressive strength of concrete based on the numerical modelling of RC beams. Notably, the relationship proposed is an adaptive of the equation given by Vecchio and Collins [9] who carried out an experimental campaign on RC panels.

$$\beta = \frac{f_c^*}{f_c} = \frac{1}{1 + K\,\frac{2\pi X n_{bars}}{b\varepsilon_{c2}}} \tag{1}$$

where f_c^* represents the corroded compressive strength, f_c the uncorroded compressive strength, K a constant equal to 0.1 for medium rebar, X the corrosion penetration, b the width of the cross-section, ε_{c2} strain at the peak and n_{bars} the number of steel reinforcement in the compressive zone. In Coronelli and Gambarova [8], nbars represents the number of reinforcements in the top layer (compressive zone) and f_c^* applied on the entire section, but, the reduction of the concrete's compressive strength should be only considered on the side of the attack and applied only on the area really exposed to corrosion; otherwise, the reduction will be excessively high and the ultimate capacity underestimated.

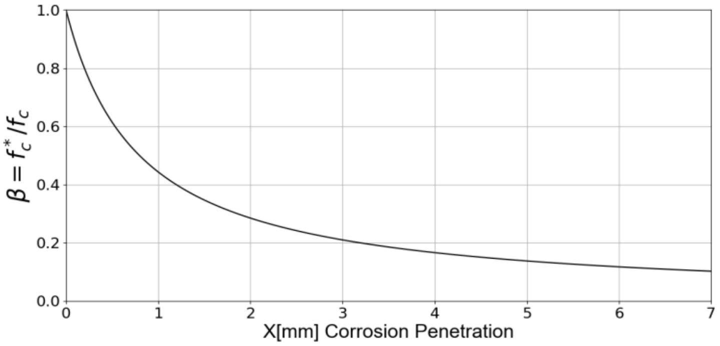


Figure 2. Reduction Coefficient for concrete compressive strength

Corrosion does affect two other main properties of plain concrete, such as ductility, which is the capacity of the concrete to undergo extensive plastic deformation without failing, and stiffness, which is the ability of the concrete to resist deformation when a force is applied. Figure 3 shows how the stiffness goes down by 12% while the strength decreases by 22% with a level of corrosion of 10%. Although the reduction of stiffness and ductility depend upon the reduced concrete's compressive strength, by contrast, future works should bridge this gap, especially for plain concrete.

According to Eurocode 2 Part 1-1 [10], the stress-strain relation of concrete will be approximated by a parabola-rectangle diagram, which is convenient to use in analytical studies as it is continuous up to the strain at maximum strength and flat until the ultimate strain:

$$f = \begin{cases} f_c\left[1-\left(1-\frac{\varepsilon_c}{\varepsilon_{c2}}\right)^n\right] & 0 \le \varepsilon_c \le \varepsilon_{c2} \\ f_c & \varepsilon_{c2} \le \varepsilon_c \le \varepsilon_{cu} \end{cases} \tag{2}$$

where:

$$n = \begin{cases} 2.0 & 0\,MPa \le f_c \le 50MPa \\ 1.4 + 23.4\left(\frac{90-f_c}{100}\right)^4 & 50MPa \le f_c \le 90MPa \end{cases} \tag{3}$$

$$\varepsilon_{c2}[‰] = \begin{cases} 2.0 & 0\,Mpa \le f_c \le 50MPa \\ 2.0 + 0.085(f_c-50)^{0.53} & 50MPa \le f_c \le 90MPa \end{cases} \tag{4}$$

$$\varepsilon_{cu}[‰] = \begin{cases} 3.5 & 0\,Mpa \le f_c \le 50MPa \\ 2.6 + 35\left(\frac{90-f_c}{100}\right)^4 & 50MPa \le f_c \le 90MPa \end{cases} \tag{5}$$

The typical stress-strain curve of concrete is shown in Figure 3:

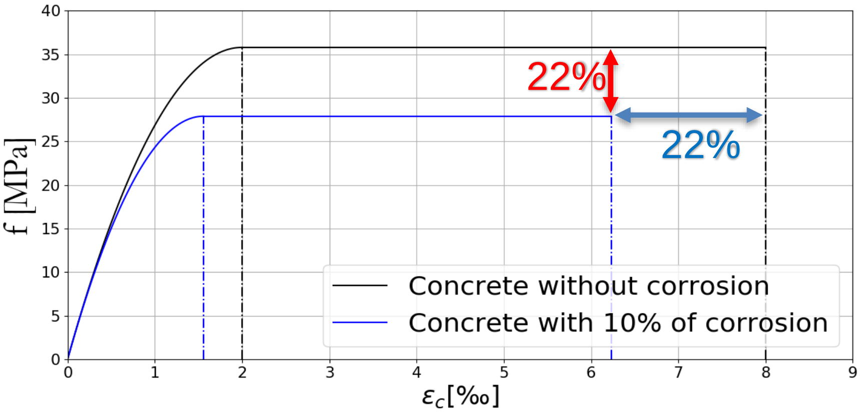


Figure 3. Stress-Strain for Concrete without/with corrosion

Model of damaged steel

Corrosion is the central aspect of the degradation of reinforcement bars embedded into the concrete. Usually, the corrosion penetration can be measured in-situ in mm/year, as follows:

$$(t) = \int_{t_i}^{ti+t_p} r_{corr} dt \tag{6}$$

where r_{corr} is the still corrosion rate, t_p represents the propagation time and t_i the initiation time (it does not correspond to zero). The reduction of the cross-section reinforcement area can be computed through a coefficient, as follows:

$$\gamma = \frac{x(t)}{\varphi_0} \tag{7}$$

where γ reduction coefficient for steel rebars [0;1], $x(t)$ corrosion penetration in mm φ_0 initial diameter of the steel reinforcement [24]. However, the definition of this coefficient depends upon the type of corrosion, uniform and localised (pitting) respectively. If corrosion is a result of carbonation, the attack is more likely to be uniform along the bar, while if corrosion is a result of pitting due to chlorides, then the attack is more likely to be localised along the bar. As a result, two models are available for corrosion on steel reinforcements, uniform and pitting. Carbonation and low chlorides contents lead to a steady reduction of embedded reinforcement (Uniform Corrosion), while high chloride contents lead to a localised reduction of steel rebars (Localised Corrosion).

Yielding stress reduction

Several researchers have carried out experimental tests to investigate how steel rebars behave when exposed to corrosion. Mostly, these experimental campaigns were set up on deformed bars. According to these experimental tests, researchers ended up with linear relationships between the yielding stress reduction and mass loss due to corrosion. The general equations have the same shape, i.e.:

$$f_y^* = (1 - \beta CR[\%])f_y \tag{8}$$

where f_y^* is the corroded yielding stress, f_y the un-corroded yielding stress, β the experimental coefficient and $CR[\%] = \frac{M_0 - M_C}{M_0}$ the mass loss based on mass before (M_0) and after corrosion (M_C). Table 1 provides coefficients for different experimental tests:

Author	Type	Exposure	Corrosion rate [%]	β
Du [11]	Bare Rebar	Accelerated	0-25	0.0140
Du [11]	Embedded Rebar	Accelerated	0-18	0.0150
Morinaga et al. [12]	Embedded Rebar	Service-Chlorides	0-25	0.0170
Zhang et al. [13]	Embedded Rebar	Service-Carbonation	0-67	0.0100
Andrade et al. [14]	Bare rebar	Accelerated	0-11	0.0150
Clark et al. [15]	Embedded Rebar	Accelerated	0-28	0.0130
Lee et al. [16]	Embedded Rebar	Accelerated	0-25	0.0120
Cairns et al. [17]	Embedded Rebar	Accelerated	0-3	0.0120
Du et al. [18]	Embedded Rebar	Accelerated	0-18	0.0050
Wang and Liu [19]	Embedded Rebar	Accelerated	0-10	**
Imperatore et al. [20]	Both	Accelerated	0-40	**

Table1. Empirical Coefficient for reduced steel yielding strength,
*** The value is different depending on whether it is uniform or pitting corrosion as it is explained in Table 2*

Wang et al. [19] and Imperatore et al. [20] provided empirical coefficients for both uniform and pitting corrosion, which make these studies more reliable compared with the other ones. Furthermore, Parson's coefficient factor, which is the measure of the strength of a linear association between two variables, is almost one in the Imperatore and Wang's experimental campaigns as shown in Table 2.

Author	Type of Corrosion	β	Correlation Factor
Wang and Liu [19]	Uniform	0.0124	0.7800
	Pitting	0.0198	0.9200
Imperatore et al. [20]	Uniform	0.0151	0.9263
	Pitting	0.0199	0.9234

Table 2. The correlation coefficient for uniform and pitting corrosion

The study in Imperatore et al. [20] includes many experimental results provided in the literature and are more consistent with all uncertainties related to the corrosion impact on reinforcements embedded into the concrete. Figure 4a shows the relationship, for uniform and pitting corrosion, between yielding stress and mass loss in Imperatore et al. [20].

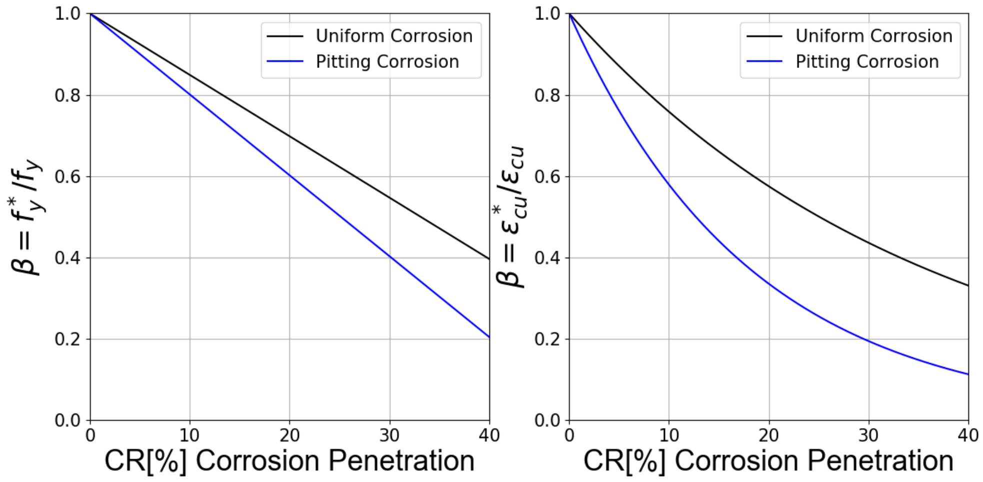


Figure 4. a) Relations for reduced yielding stress and b) ultimate strain of corroded steel reinforcement [adapted by Imperatore et al.[20]]

Ductility degradation of steel rebar

Ductility is a critical factor for steel reinforcement and represents the capacity of the rebar to undergo plastic deformation. Experimental tests have shown that even for low corrosion level the behaviour shifts from ductile to brittle (especially for highly corroded rebars). Based on experimental results, Kobayashi (2006) [21] proposed a relationship for an ultimate residual strain[24]:

$$\frac{\varepsilon_{su}^*}{\varepsilon_{su}}[\%] = 100 - 18.1x[\%] \tag{9}$$

where x represents the cross-sectional reduction. This relationship was based on experimental results with low corrosion level, so it becomes useful for 3-4 % of the mass loss. Coronelli and Gambarova (2004) [8] proposed a new relationship to account for pitting as well:

$$\varepsilon_{su}^{*} = \varepsilon_{sy} + \left(\varepsilon_{su} - \varepsilon_{sy}\right)\left(1 - \frac{\alpha_{pit}}{\alpha_{pit,max}}\right) \tag{10}$$

where ε_{sy} is the steel strain at yielding, α_{pit} and $\alpha_{pit,max}$ are respectively the depth and maximum depth of the pitting attack. The last two parameters are difficult to determine, especially for existing structures. Biondini (2011) [22] proposed a new function for the ultimate strain based on the experimental results of Apostopoulos (2008) [23], as follows:

$$\varepsilon_{su}^{*} = \begin{cases} \varepsilon_{su} & 0 \leq CR[\%] \leq 1.16 \\ 0.1521\ CR^{-0.4583}\varepsilon_{su} & 1.6 \leq CR[\%] \leq 100 \end{cases} \tag{11}$$

The relationship (7) is based on a single experimental campaign. Imperatore et al. also include the ultimate strain for corroded steel reinforcements in their studies which include experimental results and literature review. Again, they came up with two relationships for uniform and localised corrosion, as follows:

$$\begin{cases} \varepsilon_{su,pitting}^{*} & = \varepsilon_{su} e^{0.0547 CR[\%]} \\ \varepsilon_{su,uniform}^{*} & = \varepsilon_{su} e^{0.0277 CR[\%]} \end{cases} \tag{12}$$

All the experimental results carried out on the steel bars have confirmed that the elasticity modulus does not change because of corrosion [25].

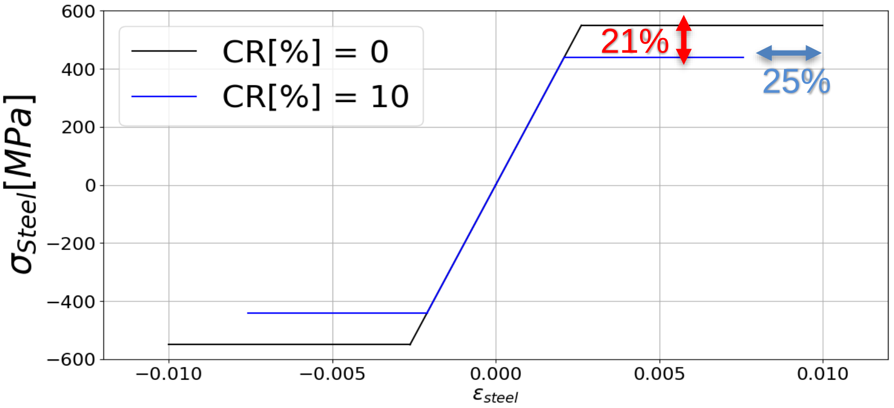


Figure 6. Steel Reinforcement bars with/without Corrosion

Bond Deterioration

One of the most important features of the RC elements is the excellent bond between concrete and steel reinforcement bars. However, due to the lack of maintenance, corrosion is allowed to propagate in the concrete, increasing local stresses and generating cracking, which compromises the bond between the concrete and rebars. As a result, elastic and inelastic buckling and the spoiling of concrete cover are among the main causes of the bond reduction that decreases significantly the performance and the safety of RC structures. Although, many experimental campaigns, through pull-out tests, have been carried out to investigate the residual bond between concrete and steel reinforcements due to corrosion, none has produced reliable models to evaluate bond deterioration. Some results are outlined in Table 3:

Author	Model	Correlation Coefficient
Cabrera et al. [30]	$\frac{\tau(CR)}{\tau(0)} = 1 - 5.6CR$	$R^2 = 0.326$
Bhargava et al. [31]	$\frac{\tau(CR)}{\tau(0)} = e^{-11.7(CR[\%]-1.5\%)}$	$R^2 = 0.370$
Lin and Zhao [32]	$\frac{\tau(CR)}{\tau(0)} = e^{\delta(CR[\%]-1.5\%)}$	$R^2 = 0.456$
Jiang et al. [33]	$\frac{\tau(CR)}{\tau(0)} = f(CR)$	$R^2 = 0.410$

Table 3. Bond Deterioration Models

Despite the new experimental campaigns, no significant headway has been made as the bond deterioration is still a complex problem. Particularly, the correlation factor between corrosion and bond stress remains unreliable compared with the other parameters studied so far.

Proposed Method

The proposed method is based on the construction of the interaction surface Moment-Axial forces using deteriorated concrete and steel reinforcement properties. The actual material properties will be modified by the above-mentioned deterioration functions. The method consists in dividing the RC cross-section into three concrete blocks containing the concrete cover, the un-effective confined core and the effective enclosed core. The concrete cover represents the clear cover (CC) until the transverse reinforcement, while the un-effective (UCC) and effective (ECC) confined concrete are respectively the area twice the diameter of longitudinal reinforcement bars and the remaining uncorroded area of the concrete (Figure 6). Once corrosion occurs, only the compressive strength of the concrete cover and un-effective confined concrete will be reduced by the use of the coefficient β in Eq. (1). The reason for the different blocks for concrete is to simulate the real behaviour of the RC members.

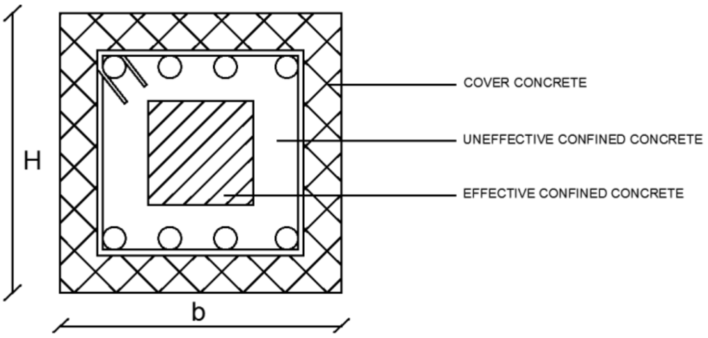


Figure 7. Concrete blocks

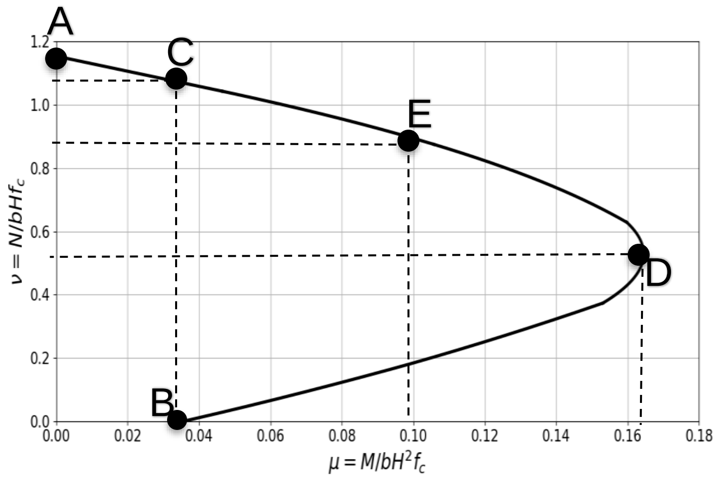
Accordingly:

$$f_c^* = \frac{\beta f_c A_{CC} + \beta f_{cc} A_{UCC} + f_{cc} A_{ECC}}{A_{CC} + A_{UCC} + A_{ECC}} \tag{13}$$

where f_{cc} is the confined compressive strength. The confined compressive strength has been calculated according to the method proposed by Razvi and Saatcioglu (1999) [26] based on an extensive experimental campaign and using different RC cross-sections and reinforcement configurations. The elastic-perfect plastic curve is used for corroded steel reinforcement bars and the parabola-rectangle for corroded concrete as in Figure 6 and Figure 3. The proposed method allows to obtain continuous interaction surfaces M-N for corroded RC members.

Interaction Surface Moment-Axial loads (M-N) for corroded Reinforced Concrete elements

The interaction diagram M-N for RC columns is a reliable method to assess the capacity of RC structural components both in design and verification and represents the geometric locus of M-N pairs that define the limit state of RC elements under combined compression-bending loading as shown in Figure 8.



A-Pure Compression

B-Pure Bending Moment

C – Combined Pure Moment-axial force

E- generic point of combined bending moment-axial load

D – Balanced failure

Figure 8. Generic Interaction Domain M-N

Potentially, this useful tool may help engineers in designing effective repairing solutions for damaged RC elements. The interaction surfaces are computed by assuming a series of strain distributions, which correspond to a different M-N pair on the domain. The ultimate compressive strain for concrete and steel is set at the ultimate value of confined concrete [26] and 0.01 respectively. Based on the strain distributions, the stresses and the location of the neutral axis are determined. The forces for each layer are computed multiplying the stress by the area on which they act. Finally, the axial force P is calculated by summing all the individual forces acting on the cross-section, while the bending moment multiplying these forces by their distance to the plastic centroid [33].

Numerical Validation

As model validation, experimental results by Rodriguez (1996) [2] for the ultimate bearing capacity of RC columns will be herein used. The proposed method will account for the corrosion rate and reduction of all the mechanical properties both for concrete and steel. The tested columns were poured with an additional solution of Calcium Chloride to target the accelerated corrosion, while impressed current was used to corrode the samples. An incremental displacement was applied to the column to reach failure. Geometrical properties as follows:

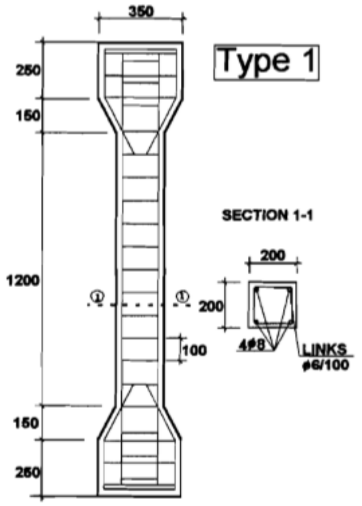


Figure 9. Geometrical properties of the RC column tested by Rodriguez et al. (1996) [2]

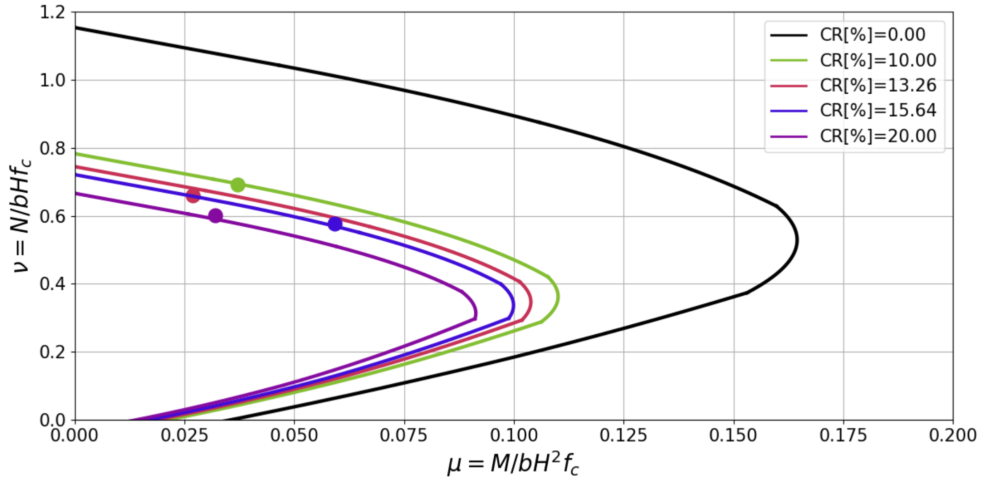
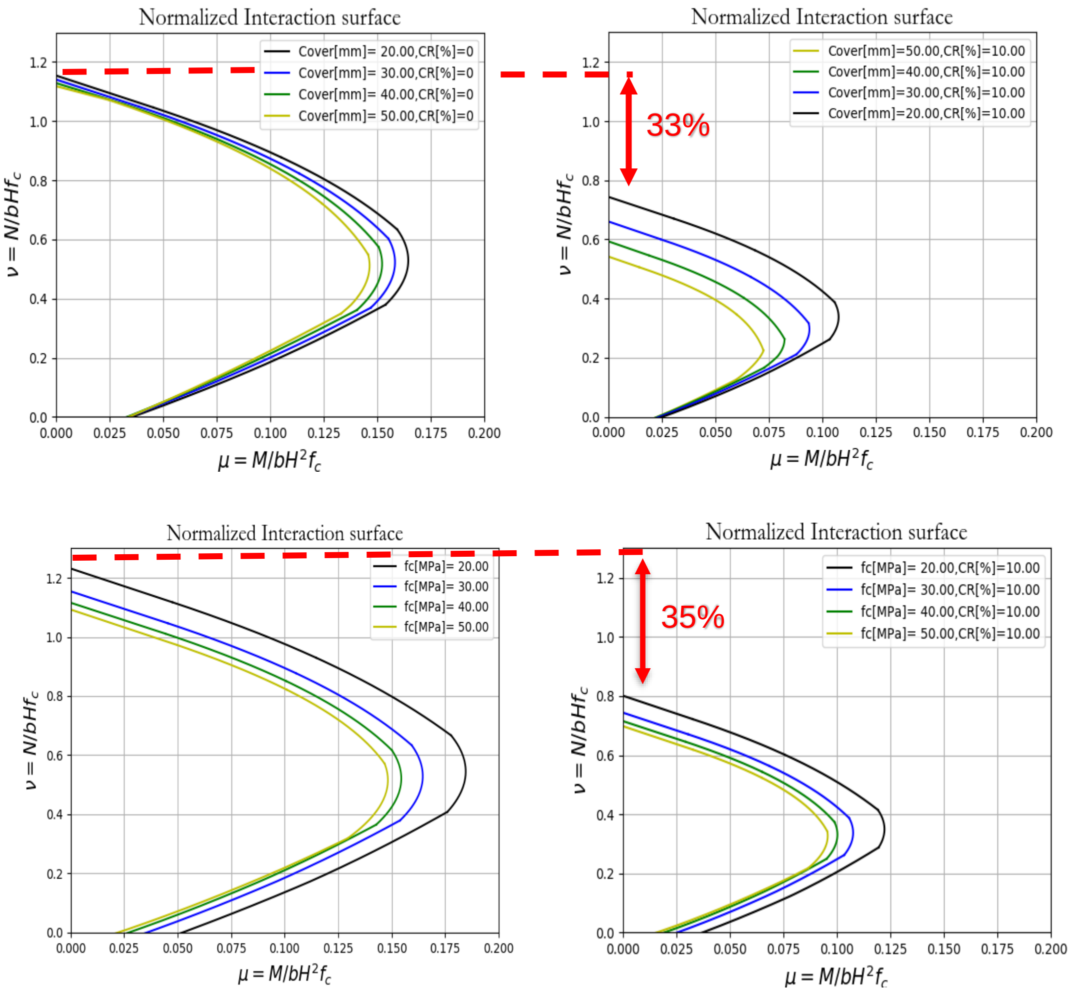


Figure 10. Numerical Validation of the proposed method

The results of the proposed method show an excellent agreement with the experimental campaign for RC columns exposed to corrosion (the points in Figure 10 represent the ultimate capacity of the tested RC columns). A further description and examination (Parametric Study) of relationships between parameters is also given to analyzing the performance of the proposed method within different parameter sets such as the depth of the concrete cover, the geometric reinforcement ratio and the concrete's compressive strength.



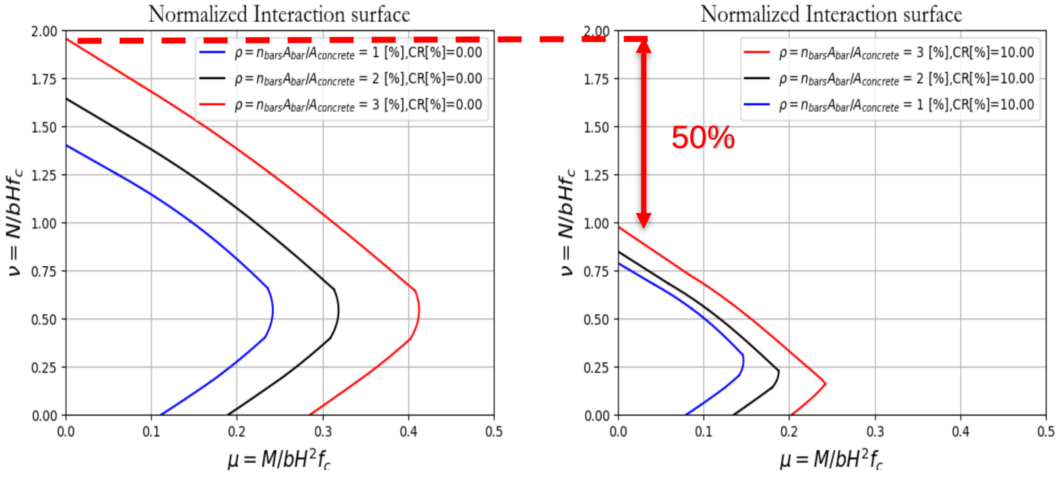


Figure 11. a) Parametric study for clear cover with/without corrosion; b) Parametric study for compressive strength with/without corrosion; c) Parametric study for geometric reinforcement ratio with/without corrosion

The parametric study shows how the impact of corrosion reduces the capacity of RC members. In particular, the geometric reinforcement ratio seems to be the worst condition for deteriorated structural RC members as there is a strong reduction both for bending moment and axial load. However, the concrete cover and the concrete compressive strength also influence the residual capacity of aged RC structures, 33% and 35% respectively, but the impact is less destructive than the geometric reinforcement ratio.

Seismic assessment of an aged RC Bridge

Since many RC bridges are declared to be “substandard”, the structural condition assessment of RC bridges has become extremely important. The evaluation of the structural conditions is extensively based on visual inspections and subjective rating-indices. As a result, it is crucial to develop a methodology that it is able to evaluate RC bridges status. This approach requires the development of a reliable structural analysis that is capable of assessing the deterioration of the critical RC elements over the years. SeismoStruct 2019, a general finite element software developed by [27], was selected as the platform for this study. SeismoStruct is a business software capable of running linear and non-linear analyses and giving reliable results for RC structures. The reference RC bridge was chosen from one of the examples given by the SeismoSoft company, which is a 7-span RC Bridge modelled by Dr Timothy E. Huff of Tennessee Tech University(Figure 14). Corrosion has been applied only to columns, which were modelled by using the Mander [28] model for concrete and the elastic-perfect plastic model for steel reinforcement bars. Three different analyses have been executed: Modal Analysis, Non-Linear Static Analysis or Pushover Analysis and the time-history analysis. The modal analysis is an elastic method that allows the user to extract the modal parameters such as the natural frequencies and modal constants. The Pushover analysis is the most common non-linear method used for evaluating the response of RC structures under seismic loads. Non-linear elements are often implemented using either plastic hinges at the edge of RC members, which represent the lumped plasticity or fiber layers, which describe the spread plasticity. Finally, the time-history analysis is a step-by-step analysis that gives the dynamics response of an RC structure subjected to a specified load that may vary with time. This approach is often used to determine the seismic response of a structure under a dynamic load of a representative earthquake. Table 4, Figure 12 and Figure 13 show the outcome of the modal analysis, pushover analysis and the time-history analysis respectively. Furthermore, the maximum values of the axial load and bending moment at the base of a group of the piers are given in Figures 15.

		MASS PARTICIPATION FACTOR [%]					
CR[%]	T[sec]	[Ux]	[Uy]	[Uz]	[Rx]	[Ry]	[Rz]
0	1,783	38,73	32,06	0,00	-8,79	10,10	25,06
	1,606	33,60	-38,11	0,00	10,34	8,73	-27,58
	1,095	0,03	0,81	0,00	-0,22	0,01	-2.434,11
10	1,828	30,94	37,75	0,00	-9,93	8,04	23,18
	1,632	-39,22	30,67	0,00	-8,02	-10,16	17,16
	1,101	0,03	0,62	0,00	-0,18	0,01	-2.374,97
20	1,836	30,35	38,21	0,00	-10,06	7,89	23,04
	1,636	-39,69	30,09	0,00	-7,88	-10,28	16,49
	1,103	0,03	0,61	0,00	-0,18	0,01	-2.374,98
30	1,857	28,79	39,35	0,00	-10,35	7,48	22,58
	1,646	-40,83	28,60	0,00	-7,47	-10,56	14,78
	1,109	0,03	0,58	0,00	-0,17	0,01	-2.374,94

Table 4. Parameters of the Modal Analysis

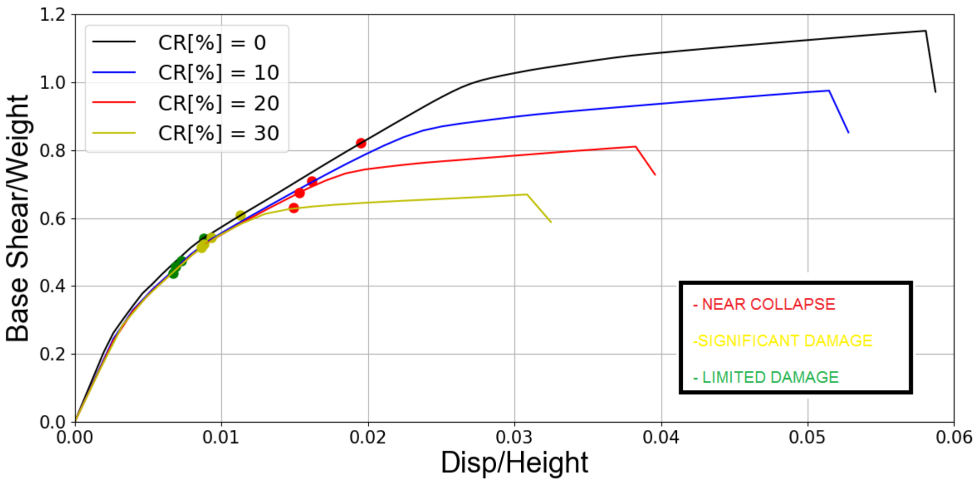


Figure 12. Pushover Curve with/without corrosion

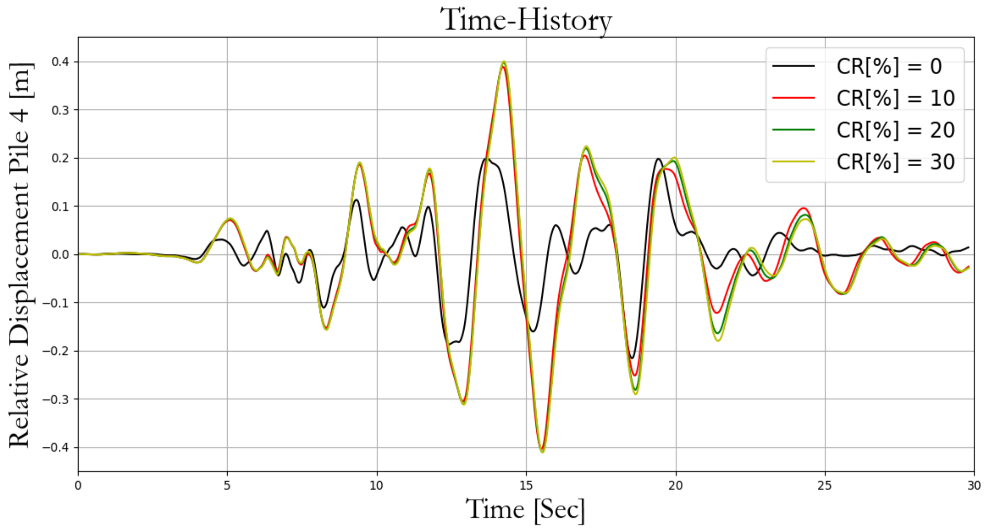


Figure 13. Time-History Curves with/without Corrosion (Earthquake, Loma San Francisco, US, Magnitude 6.9)

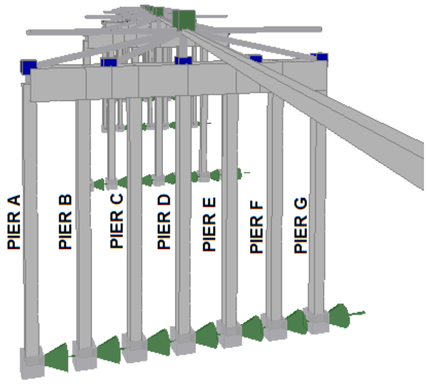


Figure 14. Seismostruct model

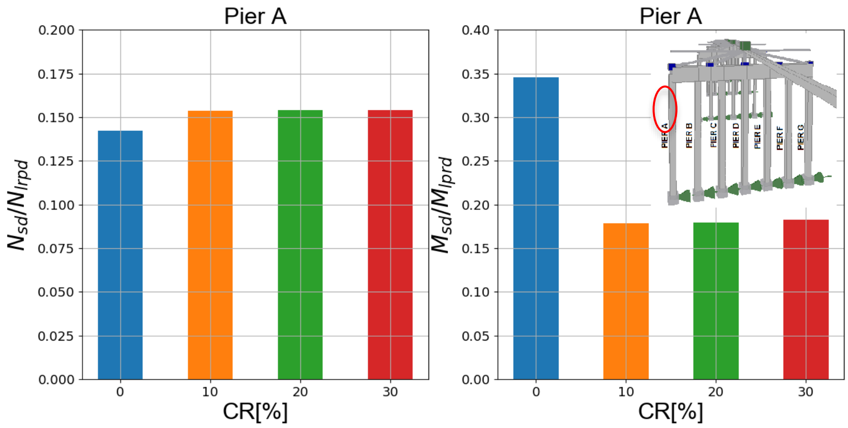


Figure 15. a) Impact of Corrosion on the Maximum values of the axial load and the bending moment of the Pier A

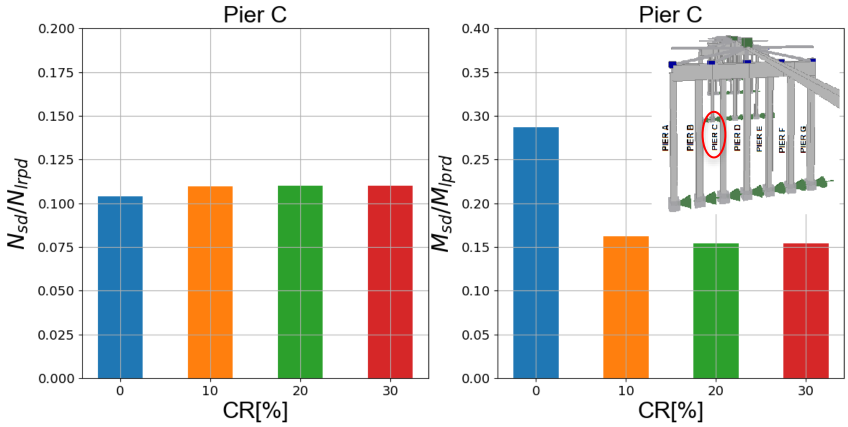


Figure 15. b) Impact of Corrosion on the Maximum values of the axial load and the bending moment of the Pier C

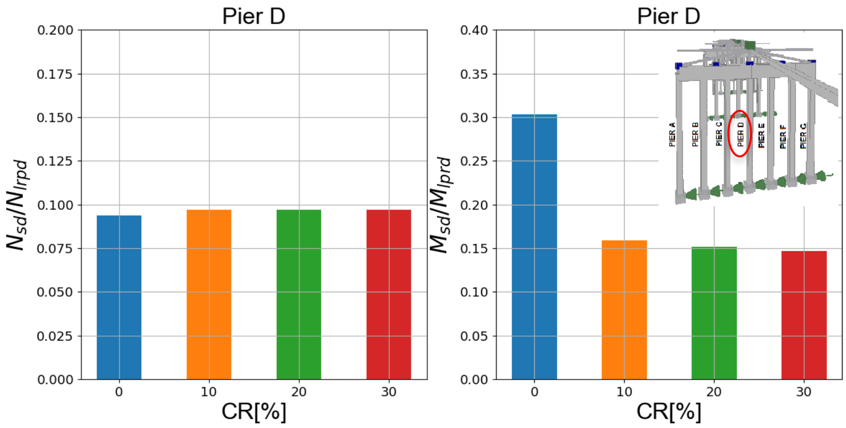


Figure 15. c) Impact of Corrosion on the Maximum values of the axial load and the bending moment of the Pier D

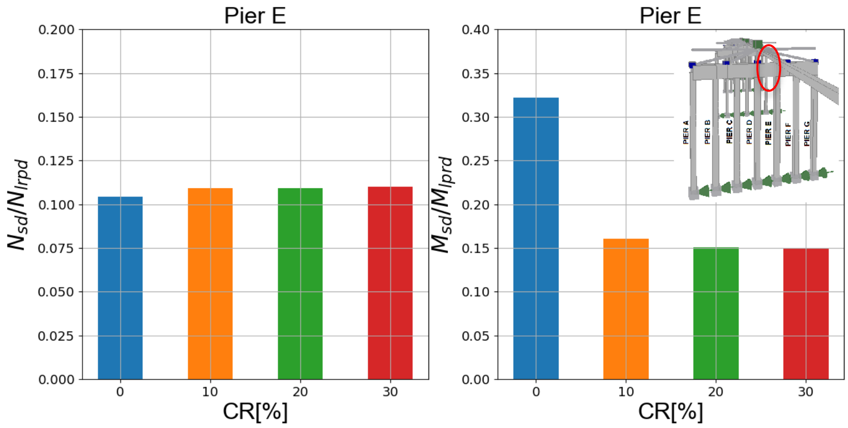


Figure 15. d) Impact of Corrosion on the Maximum values of the axial load and the bending moment of the Pier E

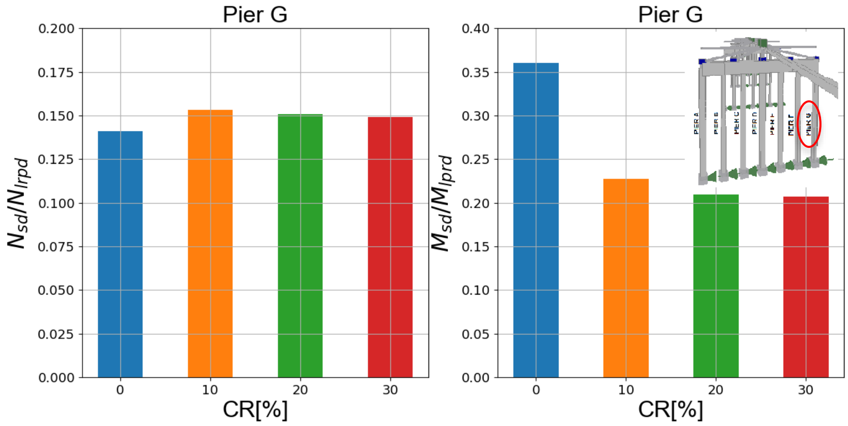


Figure 15. e) Impact of Corrosion on the Maximum values of the axial load and the bending moment of the Pier G

Conclusions

Structural effects of corrosion on the residual capacity of RC elements are here examined under a different level of corrosion by constructing the interaction surface M-N using a modified procedure that consists of dividing the cross-section into three different concrete blocks accounting for confined and unconfined concrete. A numerical validation has been presented to represent the excellent agreement of the proposed method with the experimental results in the literature. Moreover, a parametric study has been given to show how different parameters sets are affected by corrosion. The results have demonstrated that the geometric reinforcement ratio has a greater impact on the reduction of the residual capacity of RC cross-section compared with the concrete cover and the concrete's compressive strength. A Finite Element approach using the SeismoStruct software has been used to investigate the impact of corrosion on some common structural analyses such as the Modal Analysis, Push-Over Analysis and the Time-History Analysis. Particularly, these analyses highlighted how the corrosion reduces both the load-bearing and the seismic capacity of RC structures. The modal analysis has shown an increase of the natural frequency when corrosion occurs, while the Pushover curve shows a reduction in the ductility, that is the capacity to resist large plastic deformation, and in the base shear-force, which is the capacity to withstand seismic loads. Moreover, the time-history analysis suggested that for deteriorated RC columns the displacement increases over time and it is twice the displacement of the RC bridge without corrosion. In addition, the impact of corrosion is relevant also for the axial forces at the base of each piers shifting the failure mode from ductile to brittle.

To conclude, this study has shown the importance of the impact of corrosion on the behaviour of RC structures, especially bridges that are unprotected and expose to aggressive environments. Further investigations should be considered to bridge the gaps that remain unsolved, such as the different location and exposure of RC elements to corrosion both for unprotected (Bridges) and protected structures (Buildings), the phenomena of elastic and inelastic buckling for high level of corrosion, as well as the corrosion for RC beams that play an essential role in RC structures.

Acknowledgment

The authors would like to acknowledge the gracious support of this work through the EPSRC and ESRC Centre for Doctoral Training on Quantification and Management of Risk and Uncertainty in Complex Systems Environments Grant No. (EP/L015927/1)

References

[1] Raoul François, Stéphane Laurens and Fabrice Deby (2018), Corrosion and its Consequences for Reinforced Concrete Structures, ISTE Press - Elsevier, 232 pages, ISBN 978-1-78548-234-2

[2] J. Rodriguez, L.M. Ortega, J. Casal (1996), Load Bearing Capacity of Concrete Columns with corroded reinforcement, ACI Journal, Issued 208 Vol. 49 pg. 49-62

[3] T. Uomoto and S. Misra (1988), Behavior of Concrete Beams and Columns in Marine Environment When Corrosion of Reinforcing Bars Takes Place, ACI Journal, Vol. 109 pg. 127-146

[4] J. Revathy, K. Suguna and P.N. Raghunath (2009), Effect of Corrosion Damage on the Ductility Performance of Concrete Columns, American J. of Engineering and Applied Sciences 2: 324-327, ISSN 1941-7020

[5] RAC Foundation & UK Department for Transport (2019), Council bridge maintenance backlog grows, Annually Website Publication, "https://www.racfoundation.org/completed-collaborations"

[6] Rundong Gao, Qingbin Li and Shunbo Zhao (2013), Concrete Deterioration Mechanisms under Combined Sulfate Attack and Flexural Loading, ASCE Journal Vol. 25

[7] Mark E. Williams, Dilip Choudhuri and Mike Perez (2009), Managing Premature Concrete Deterioration in Bridges, ASCE Journal, Structures 2009 pg. 485-490

[8] Coronelli and Gambarova (2004), Structural Assessment of Corroded Reinforced Concrete Beams: Modeling Guidelines, ASCE J. of Structural Engineering VOL 130 Issue 8

[9] Vecchio and Collins (1986) The Modified Compression-Field Theory for Reinforced Concrete Elements Subjected to Shear, ACI Journal 83-22

[10] EN 1992-1-1 Eurocode 2: Design of concrete structures - Part 1-1 : General rules and rules for buildings

[11] Du,Y,(2001) Effect of Reinforcement Corrosion on Structural Concrete Ductility, PhD Thesis, University of Birmingham,UK, 320 pg.

[12] Morinaga,S. (1996), Remaining Life of Reinforced Concrete Structures after Corrosion Cracking, Durability of Building Materials and Components, C. Sjostrom, ed., E&FN Spon, London 1996, pp. 127-137

[13] Zhang,P. S., Lu, M. and Li, X. (1995), The Mechanical Behaviour of Corroded Bar, Journal of Industrial Buildings, Vol. 25, N°257. pg. 41-44

[14] Andrade, C., Alonso, C., Garcia, F and Rodriguez, J. (1991), Remaining Lifetime of Reinforced Concrete Structures: Effect of Corrosion in the Mechanical Properties of the Steel, Life Prediction of Corrodible Structures, NACE, Cambridge, UK; pg. 12/1-12/11

[15] Clark, L. A. and Saifullah,M. (1994), Effect of Corrosion Rate on the Bond Strength of Corroded Reinforcement, Corrosion and Corrosion Protection of Steel in Concrete, R.N. Swamy, Sheffield Academic Press, pg. 591-602

[16] Lee, H. S., Tomosawa, F. and Noguchi, T. (1996), Effect of Rebar Corrosion on the Structual Perfomance of Singly Reinforced Beams, Durability of Building Materials and Components, Vol. 7, C. Sjostrom, E&FN Spon, London, pg. 571-580

[17] Cairns, J., Plizzari, G., Du,Y. Law, D.W. and Franzoni C., (2005), Mechanical Properties of Corrosion-Damaged Reinforcement, ACI Materials Journal, Vol. 102 n°4, pg. 256-264

[19] Wang, X. and Liu, X (2008), Modeling the Flexural Carrying Capacity of Corroded RC Beams, J. Shangai Jiaotong Univ. (Sci.), 13(2): 129-135

[20] Imperatore, S., Rinaldi, Z. and Drago C. (2017), Degradation Relationships for the Mechanical Properties of Corroded Steel Rebars, Construction and Building Materials, Vol. 148, pg. 219-230

[21] Kobayashi, K. (2006). The seismic behavior of RC members suffering from chloride-induced corrosion. Proceedings of the 2nd International fib Congress.

[22] Biondini, F., & Vergani, M. (2011). Modellazione del degrado di strutture in calcestruzzo armato soggette a corrosione (in Italian). Giornate AICAP 2011, Padua, May 19–21

[23] Apostolopoulos, C.A., & Papadakis, V.G. (2008). Consequences of steel corrosion on the ductility properties of reinforcement bar. Construction and Building Materials, 22, 2316–2324

[24] Camansio, E. (2013), Lifetime performance and seismic resilience of concrete structures exposed to corrosion, PhD Thesis, University of Milane, IT

[25] Kashani, M.M., Crewe, A.J. and Alexander N.A. (2012), Stress-Strain Response of Corroded Reinforcing Bars under Monotonic and Cyclic Loading, 15 WCEE Conference, Lisboa

[26] Razvi, S. and Saatcioglu, M. (1999), Confinement Model for High-Strength Concrete, ASCE, Journal of Structural Engineering, Vol. 125 N°3, pg. 281-289

[27] SeismoStruct, FEM Software, SeismoSoft, Earthquake Engineering Software Solutions, Piazza Castello 19, 27100 Pavia – Italy, info@seismosoft.com

[28] J. B. Mander, M. J. N. Priestley, and R. Park, (1988), Theoretical Stress-Strain Model for Confined Concrete, ASCE, Journal of Structural Engineering, Vol. 114 N° 8, pg. 1804-1826

[29] J.G. Cabrera, Deterioration of concrete due to reinforcement steel corrosion, Cem. Concr. Compos. 18 (1) (1996) 47–59.

[30] K. Bhargava, A.K. Ghosh, Y. Mori, S. Ramanujam, Suggested empirical models for corrosion-induced bond degradation in reinforced concrete, J. Struct. Eng. 134 (2) (2008) 221–230

[31] Y.X. Zhao, H.W. Lin, K. Wu, W.L. Jin, Bond behaviour of normal/recycled concrete and corroded steel bars, Constr. Build. Mater. 48 (2013) 348–359.

[32] Cheng Jiang, Yu-Fei Wu, Ming-Jiang Dai, (2018), Degradation of steel-to-concrete bond due to corrosion¸ Durability of Innovative Construction Materials and Structures, Vol. 158 pg. 1073-1080

[33] Tapan, M. and Aboutaha, R. S. (2008),Strength Evaluation of Deteriorated RC Bridge Columns, ASCE, Journal of Structural Engineering, Vol. 13 pg. 226-236

[34] Aboutaha R.S. (2004). Guide for Maintenance, and Rehabilitation of Concrete Bridge Components with FRP Composites-Research into Practice, TIRC & NYSDOT, NY, USA.