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Corrosion effects of RC bridges considering the climate change impact

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ABSTRACT: Climate change is associated with significant variations of temperature, atmospheric humidity, and carbon dioxide concentration levels. These changes potentially produce a double negative effect on the safety and the life cycle of civil engineering structures: increased climatic actions and rate of material degradation. In fact, changes in these variables affect the service life of reinforced concrete and steel structures by acting on the rate of carbonation and corrosion. Corrosion has a detrimental effect especially on the seismic vulnerability influencing strength, ductility and affecting the dynamic response and consequently the failure of reinforced concrete structures. Particularly bridges, as structures directly exposed to the weather effects, are more susceptible to these phenomena. In this paper, a framework to quantitatively account for the effects of climate change on carbonation-induced corrosion is proposed, focusing on the loss of concrete passivity, and thus widespread corrosion. Different scenarios for the expected variations in CO_2 concentrations and temperature are analyzed and seismic risk indexes are evaluated through a real case study of bridge located in the province of Massa-Carrara (Italy).

1 INTRODUCTION

Corrosion has a detrimental impact on life cycle and on the seismic performance particularly of reinforced concrete structures. The effects of corrosion are more significant on strength than on ductility (Berto et al., 2012). Typically, reinforced concrete bridges, in which all the structural elements are exposed to the environmental conditions, are more prone to corrosion than steel bridges, where the possibility of inspection and maintenance are more effective, and buildings, where the structure is fully protected (Biondini et al. 2014).

Existing reinforced concrete bridges can be interested by damaging or collapse due to aging, design errors and usually the deterioration can be exacerbated by lack of maintenance and climate change impacts. The main failures are due to steel corrosion producing loss of prestress and a wide of brittle failure, especially diffused in the Gerber type bridges (Sassu et al. 2023).

Climate changes strickles existing structures and infrastructures with several effects. Rainstorms or tropical cyclones threaten the stability of bridges, particularly the one of reduced spans, producing erosion or additional actions (Sassu et al. 2017) (Puppio et al. 2021). Maintenance and visual inspections, joined with modern strategy of vulnerability assessment and refurbishment, are key action in the prevention of bridge failures (Mistretta et al. 2015) (Stochino et al 2018)(Pucci et al 2021)(Coni et al. 2021) (Hasa et al 2022).

The effects of climate change on civil engineering structures are now recognized and investigated into international context, considering different models and scenarios (Stewart et al., 2011) (Bastidas-Arteaga et al., 2013) (Croce et al., 2019). The Joint Research Center of the European Commission produced new international guidelines on the expected implications of climate changes on the corrosion of structures (Sousa et al., 2020). The report highlighted the impact of the increase of CO_2 levels and temperature levels on corrosion processes of r.c. structures thus calling for adaptation strategies guaranteeing that the corrosion damage probability will be not compromised from future climate.

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The topic is of strategic concerns in Italy particularly considering the huge diffusion of r.c. bridges, the seismic exposure of the environments and the current state of maintenance. The paper proposes a method of investigation to consider the effects increase of temperature on seismic vulnerability of r.c. bridge and considering a real case of study in the province of Massa Carrara.

2 EFFECTS OF GLOBAL WARMING ON CORROSION RATE

The durability of reinforced concrete structures is affected by climate change mainly entailing the variations of three environmental parameters: temperature, relative humidity, and carbon dioxide (CO2) concentration levels. In this work, the attention is focused on the impact of temperature increase on corrosion rate i_{corr}.

Future climate is predicted based on assumptions about future trends in socio-economic dynamics, future concentrations of greenhouse gasses, variations in land use and land cover. These assumptions lead to an increase in radiative forcing, i.e. the change in energy flux, in the year 2100 equal to 2.6, 4.5, 6.0 and 8.5 W/m^2 compared to the preindustrial era and define the so-called Representative Concentration Pathways (RCPs) (van Vuueren et al., 2011). The scenarios which are mostly considered in climate risk studies are RCP4.5 and RCP8.5, for which most climate projections are available. They correspond to medium and maximum pathways, and they have been adopted in the present study as well. Expected changes in climate parameters are thus estimated by the analysis of climate projections provided by high-resolution Regional Climate Models according to RCPs scenarios (Jacob et al., 2014). The limited number of climate projections can be then increased to provide a probabilistic description of temperature variations by means of the use of weather generation techniques such as that presented in (Croce et al., 2021). In Figure 1, the variations of yearly average temperature are shown for the location of the bridge, which will be investigated in the following sections, Massa in Italy (lon=10.141; lat=44.025).

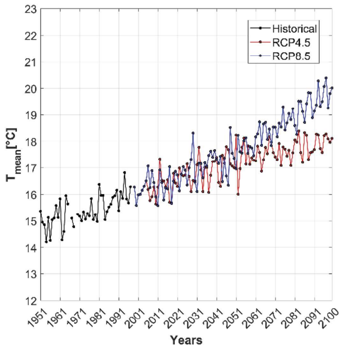

Figure 1. Historical and future variation of yearly average temperature at Massa (Italy).

Temperature raises are associated with an increase of corrosion rate, which is generally described by the model developed by (DuraCrete, 2000):

$$i_{corr}(t) = i_{corr,20}[1 + K(T(t) - 20)] \tag{1}$$

where $i_{corr,20}$ is the corrosion rate at 20°C, which depends on the environmental exposure, and K is a factor can be assumed $K = 0.025\ °\mathrm{C}^{-1}$ if $T(t) < 20\ °\mathrm{C}$ and $K = 0.073\ °\mathrm{C}^{-1}$ if $T(t) > 20\ °\mathrm{C}$. Assuming $i_{corr,20} =$ 0.345,0.172, and 0.431 μA/cm^2, average values given in (Stewart et al., 2011) for exposure class C2 - Wet-rarely dry (unsheltered), C3 - Moderate humidity (sheltered), and C4 -Cyclic wet-dry (unsheltered), variation of corrosion rate i_{corr} with time are evaluated. Different outcomes, are obtained starting from the reference values $i_{corr,20}$ given in (DuraCrete, 2000) for slight, moderate, and high exposure: 0.1,1, and 5 μA/cm^2. Another model which is commonly used to describe temperature effects on corrosion rate is the one based on the Arrhenius Law (Pour-Ghaz et al., 2009):

$$i_{corr}(t) = i_{corr,20}\exp\left(\frac{E}{R}\left(\frac{1}{293} - \frac{1}{273 + T(t)}\right)\right) \quad (2)$$

where E is the activation energy of the diffusion process (40 kJ/mol) and R is the gas constant (8.314 × 10−3 kJ/mol K). In this case, the percentage of variations will be higher than the previous one, leading to increases up to 30% at the end of the century. Variation of corrosion rate i_{corr} with time are again evaluated considering the same reference values of $i_{corr,20}$ given in (Stewart et al., 2011) and (DuraCrete, 2000).

3 STUCTURAL MODELLING AND ANALYSIS METHOD

To evaluate the corrosion effects due to carbonation on the seismic performance of existing RC bridges, the approach proposed by (Crespi et al., 2022) has been considered, based on the implementation of simplified 3D Finite Element Models (FEMs) using MIDAS Civil commercial software. The piers, the pier caps and the deck have been modelled with beam elements, while the elastomeric bearings have been schematized through elastic links having rotational and translational stiffnesses calculated according to EN 1337-3:2005. To guarantee the connection between the beam elements and the elastic links, a series of rigid links have been applied (Crespi et al., 2022). The abutments have been considered as perfect restrains and the non-structural elements have been implemented in the FEM as uniform distributed beam loads (Zucca et al., 2023).

To obtain the correct dynamic behavior of the bridge, the reduction of the bending stiffness of the piers due to the concrete cracking has been introduced through specific scale factors applied to the concrete gross-section elastic stiffness of each pier, calculated starting from the moment-curvature (M-χ) diagrams of the gross-section of the piers according to EN 1998-3:2005. On the contrary, the stiffness of the deck is not scaled (Chen & Duan, 2000) and the traffic load has been neglected according to as reported in (Decreto Ministeriale, 2018).

Two different failure mechanisms are taken into consideration for each pier: the ductile and the brittle collapse mechanism. In particular, the ductile collapse mechanism is related to the moment-curvature diagram of the cross-section of the pier, and it is characterized by an initial elastic branch followed by a large strain hardening plastic trend while the brittle failure mechanism presents a linear load-displacement trend until reaching the ultimate shear resistance. The ductile collapse mechanism is regulated by the rotational capacity of the plastic hinge while the brittle collapse mechanism depends on the shear strength of the monitored structural element.

The non-linear behavior of the concrete and of the of the steel reinforcement bars has been considered using, respectively, Kent and Park model (Kent & Park, 1971) and Park Strain Hardening constitutive law (Park & Paulay, 1975). The two different verification criteria considered in this work are the following: for the ductile mechanism the achievement of ¾ of the ultimate rotation θ_u while for the brittle failure mechanism the achievement of the shear resistance of the monitored structural element, calculated considering the cyclic shear resistance reported in EN 1998-2, 2005. The corrosion effects due to carbonation have been considered in the FEM through a simplified analytical model related to the progressive reduction of the steel reinforcements diameter and where the penetration law in a generic concrete volume follows a parabolic trend:

$$s = k \cdot t^{\frac{1}{n}} \quad (3)$$

where s = thickness of the carbonated layer of concrete; k = penetration rate coefficient; and t = time. For existing RC bridges built around 1970's, it is possible to assume the parameter n equal to 2 because they were realized using normal compacted concrete (Saetta & Vitaliani, 2004).

As mentioned before, the existing RC bridges considered in this work were built around the 1970's and they have been designed without considering the seismic action. For this reason, the proposed approach directly considers the influence of the steel reinforcements area reduction on the seismic capacity of the bridges, according to Equations 4 and 5

$$d(t) = d_0 - 2P(t) = d_0 - 2i_{corrk(t-t_i)} \quad (4)$$

$$A_{s(t)} = \frac{\pi\left[d_0 - 2i_{corrk(t-t_i)}\right]^2}{4} \tag{5}$$

Equation 4 considers the variation of the diameter of the steel reinforcement d as a function of the corroded thickness P(t) while Equation 5 is related to the variation of cross-section area $A_{s(t)}$.

As mentioned in previous Sections, three different corrosion scenarios have been considered: slight, moderate and high. For these scenarios two different assumptions were made for the evaluation of i_{corr} value. In the first assumption, the value of i_{corr} has been obtained considering the average values given in (Stewart et al., 2011) which indicates values of i_{corr} equal to 0.172, 0.345, and 0.431 µA/cm^2, respectively for slight, moderate and high corrosion level. In the second case, the values of i_{corr} have been calculated according to as reported in (DuraCrete, 2020) that is 0.1, 1 and 5 µA/cm^2 respectively for slight, moderate and high corrosion scenario.

The reduction of the steel reinforcements diameter has been evaluated considering the difference between the initial steel reinforcements diameter d_0 and the actual one $d(t)$. The following values of the other parameters are taken into consideration: water/cement ratio (w/c) = 0.6, the compressive strength of the concrete f_{ck} = 28 MPa, the penetration rate coefficient k = 0.0116 and the steel rebar ultimate deformation $\varepsilon_{u,0}$ = 9 % are considered as constant for the different corrosion levels analysed. The initiation time t_i is assumed constant and equal to 13.5 years as in (Berto et al., 2009), disregarding the effect of climate change, especially the increase of CO_2 levels and temperatures, on the diffusion process. In this work, the corrosion effects are evaluated at different times (construction time and after 13.5, 50, 75 and 100 years of bridge service life) to obtain the variation of the seismic performance of the bridge over time. To evaluate the seismic behaviour of the bridges, multi-modal pushover approach has been chosen considering the Capacity Spectrum Method (CSM) for the determination of the performance point (ATC-40, 1996). Several capacity curves have been obtained and for each of them, corresponding to a vibration mode shape with a participating mass greater than 1% and a modal loading profile, the performance point is calculated considering the relevant seismic demand spectrum. For each vibration mode, the internal actions acting on the monitored structural element have been determined in correspondence to the performance point obtained by the intersection of the capacity curve and the demand spectrum in ADRS plane. The internal actions obtained for each capacity curve are combined through the complete quadratic combination (CQC) rule, for the safety verification purposes. Further detail about modelling can be found in (Zucca et al., 2023).

4 CASE STUDY

The procedure described in previous Section has been applied to a one existing RC bridge located in the province of Massa-Carrara and built around the 1970's. The main seismic parameters which characterize the site are the following: soil type C and PGA equal to 0.156 g. The analyzed bridge is characterized by the presence of two adjacent and independent carriageways, consisting in a sequence of four simply supported 40.40 m spans. The planimetric and altimetric layout is rectilinear. The overall width of the roadway is equal to 9.86 m and each span is realized by a precast concrete girder of three longitudinal prestressed I beams and five transverse beams. The bridge deck consists in a 20 cm concrete slab. Each span is supported by 2 x 3 elastomeric bearings located into the hammer cap. The deck is supported by three hexagonal hollow RC piers characterized by a height ranging between 5.06 m and 15.51 m (Figure 2). Table 1 reports the main characteristics of the piers. The first three fundamental periods which characterize the dynamic behaviour are T_1 = 2.73 s, T_2 = 2.56 s and T_3 = 2.41 s.

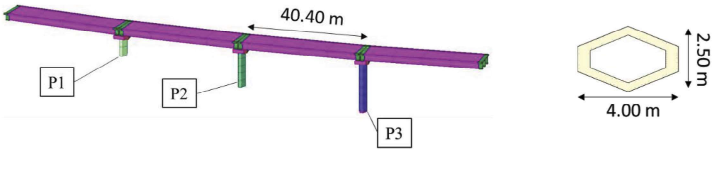

Figure 2. The analyzed bridge.

Table 1. Piers main characteristics.

Piers [n°]	Cross-section dimensions [m]	Height [m]	Longitudinal steel reinforcement [-]	Transverse steel reinforcement [-]	Piers thickness [m]
1	4.0 x 2.5	5.06	148Ø14	Ø10/20	0.35
2	4.0 x 2.5	10.84	148Ø14	Ø10/20	0.35
3	4.0 x 2.5	15.51	148Ø14	Ø10/20	0.35

Tables 2 and 3 summarizes the results of the corrosion effects on the steel reinforcements expressed in terms of diameter and area reductions as a function of the age of the bridge considering, respectively, the reference values of i_{corr} suggested by (Stewart et al., 2011) and (DuraCrete, 2020). It is important to highlight that the reduction of the steel rebar ultimate deformation $\varepsilon_{u,0}$ has been calculated according to (Lee & Choo, 2009). On the contrary, considering the i_{corr} values suggested by (DuraCrete, 2020) significant steel reinforcements area reductions can be observed as early as 50 years after the construction of the structure for the high corrosion scenario characterized by i_{corr} = 5 $\mu A/cm^2$. Considering the high corrosion level, it is possible to notice that, after 100 years from the construction of the bridge the transverse steel reinforcements appear completely corroded. As a result a slight increase of the natural periods of the bridge can be observed especially for the first vibration modes.

Table 2. Corrosion effects on steel reinforcements (Stewart et al., 2011).

	Slight Corrosion i_{corr} = 0.172 [$\mu A/cm^2$]				Moderate Corrosion i_{corr} = 0.345 [$\mu A/cm^2$]				High Corrosion i_{corr} = 0.431 [$\mu A/cm^2$]			
t [years]	d_0 [mm]	d [mm]	ΔA_s [%]	ε_u [%]	d_0 [mm]	d [mm]	ΔA_s [%]	ε_u [%]	d_0 [mm]	d [mm]	ΔA_s [%]	ε_u [%]
0-13.5	10.00	10.00	0.00	9.00	10.00	10.00	0.00	9.00	10.00	10.00	0.00	9.00
	14.00	14.00	0.00	9.00	14.00	14.00	0.00	9.00	14.00	14.00	0.00	9.00
50	10.00	9.85	1.46	8.79	10.00	9.71	2.92	8.59	10.00	9.64	3.65	8.36
	14.00	13.85	1.04	8.85	14.00	13.71	2.09	8.70	14.00	13.64	2.61	8.54
75	10.00	9.75	2.45	8.57	10.00	9.51	4.92	8.14	10.00	9.39	6.15	7.92
	14.00	13.75	1.75	8.69	14.00	13.51	3.52	8.38	14.00	13.39	4.39	8.23
100	10.00	9.65	3.45	8.39	10.00	9.31	6.92	7.78	10.00	9.14	8.65	7.48
	14.00	13.65	2.47	8.57	14.00	13.31	4.95	8.13	14.00	13.14	6.18	7.92

Table 3. Corrosion effects on steel reinforcements (DuraCrete, 2020).

	Slight Corrosion i_{corr} = 0.1 [$\mu A/cm^2$]				Moderate Corrosion i_{corr} = 1 [$\mu A/cm^2$]				High Corrosion i_{corr} = 5 [$\mu A/cm^2$]			
t [years]	d_0 [mm]	d [mm]	ΔA_s [%]	ε_u [%]	d_0 [mm]	d [mm]	ΔA_s [%]	ε_u [%]	d_0 [mm]	d [mm]	ΔA_s [%]	ε_u [%]
0-13.5	10.00	10.00	0.00	9.00	10.00	10.00	0.00	9.00	10.00	10.00	0.00	9.00
	14.00	14.00	0.00	9.00	14.00	14.00	0.00	9.00	14.00	14.00	0.00	9.00
50	10.00	9.92	0.85	8.88	10.00	9.15	8.47	7.80	10.00	5.77	42.34	1.57
	14.00	13.92	0.60	8.91	14.00	13.15	6.05	8.15	14.00	9.77	30.24	3.69
75	10.00	9.86	1.43	8.75	10.00	8.57	14.27	6.50	10.00	2.87	71.34	1.17
	14.00	13.86	1.02	8.82	14.00	12.57	10.19	7.21	14.00	6.87	50.96	2.33
100	10.00	9.80	2.01	8.65	10.00	7.99	20.07	5.48	10.00	0.00	100.00	0.00
	14.00	13.80	1.43	8.75	14.00	11.99	14.33	6.48	14.00	3.97	71.67	1.01

To complete the evaluation of the seismic behaviour of the analysed bridge, multi-modal pushover analyses have been carried out considering an iterative process. Once the determination of the peak ground acceleration which leads to the collapse of the first structural elements (PGA_C) it is possible to calculate the risk indices which characterize the bridge for the different corrosion scenarios analysed through Equation 6, where PGA_D = design peak ground acceleration:

$$RI_{PGA} = \frac{PGA_C}{PGA_D} \tag{6}$$

Values of risk indices close or greater than one concern cases of safe bridges, whereas values smaller than one indicate structures with a high risk of seismic failure. Tables 4 and 5 summarize the values of the risk indices obtained for the investigated corrosion scenarios, i_{corr} determined as reported in (Stewart et al., 2011) and in (DuraCrete, 2020), and where X indicates the direction along the longitudinal axis of the bridge and Y the transverse direction.

The reduction of the risk indices is more evident considering the moderate and high corrosion scenarios characterized by i_{corr} values suggested by (DuraCrete, 2020). It is possible to notice that after 100 years from the construction of the bridge, taking into consideration a value of i_{corr} = 5 μA/cm^2, the reduction of the risk indices reaches 80% for the ductile collapse mechanism and exceeds 90% for the brittle collapse mechanism while for i_{corr} = 1 μA/cm^2 there is a significant reduction of the brittle failure mechanism risk index in Y direction which slightly exceeds 75%. Important reduction of the risk indices is also highlightable after 75 years of the construction of the structure.

Table 4. Risk indices values considering i_{corr} given in (Stewart et al., 2011).

		Ductile mechanism					
		50 years		75 years		100 years	
	Corrosion scenario	X	Y	X	Y	X	Y
RI_{PGA}	Slight	5.342 (0.00%)	3.936 (0.00%)	5.342 (0.00%)	3.936 (0.00%)	5.231 (-2.08%)	3.851 (-2.16%)
	Moderate	5.262 (-1.50%)	3.888 (-1.22%)	5.201 (-2.64%)	3.866 (-1.79%)	5.171 (-3.20%)	3.815 (-3.07%)
	High	5.231 (-2.08%)	3.851 (-2.16%)	5.171 (-3.20%)	3.815 (-3.07%)	5.100 (-4.20%)	3.799 (-4.14%)
		Brittle mechanism					
RI_{PGA}	Slight	1.379 (0.00%)	0.959 (0.00%)	1.379 (0.00%)	0.959 (0.00%)	1.257 (-8.46%)	0.889 (-7.30%)
	Moderate	1.313 (-4.79%)	0.913 (-4.80%)	1.297 (-5.94%)	0.901 (-6.04%)	1.221 (-11.45%)	0.836 (-12.82%)
	High	1.257 (-8.46%)	0.889 (-7.30%)	1.221 (-11.45%)	0.836 (-12.82%)	1.144 (-17.04%)	0.632 (-34.09%)

Table 5. Risk indices values considering i_{corr} given in (DuraCrete, 2020).

		Ductile mechanism					
		50 years		75 years		100 years	
	Corrosion scenario	X	Y	X	Y	X	Y
RI_{PGA}	Slight	5.342 (0.00%)	3.936 (0.00%)	5.342 (0.00%)	3.936 (0.00%)	5.342 (0.00%)	3.936 (0.00%)
	Moderate	5.100 (-4.20%)	3.799 (-4.14%)	5.083 (-4.84%)	3.801 (-3.43%)	4.537 (-15.01%)	3.004 (-23.68%)
	High	4.968 (-7.00%)	3.782 (-4.56%)	3.194 (-40.21%)	2.348 (-40.35%)	1.114 (-79.15%)	0.876 (-77.74%)
		Brittle mechanism					
RI_{PGA}	Slight	1.379 (0.00%)	0.959 (0.00%)	1.379 (0.00%)	0.959 (0.00%)	1.379 (0.00%)	0.959 (0.00%)
	Moderate	1.144 (-17.04%)	0.632 (-34.09%)	1.003 (-27.26%)	0.413 (-56.93%)	0.829 (-39.88%)	0.222 (-76.85%)
	High	0.937 (-32.05%)	0.299 (-68.82%)	0.442 (-67.95%)	0.241 (-74.87%)	0.123 (-91.08%)	0.054 (-94.37%)

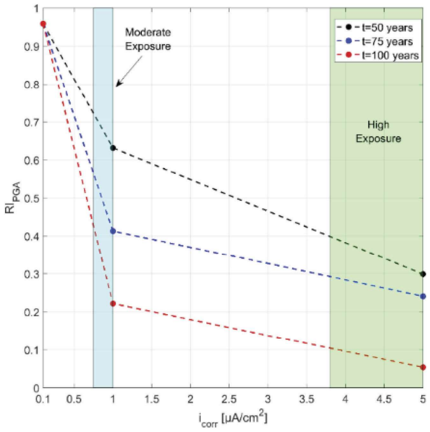

Figure 3. Variation of seismic risk index with i_{corr}.

The results for moderate and high exposure in Y direction are summarized in Figure 3. The results presented above are obtained considering constant reference values of i_{corr}, and can be used to assess the impact of global warming on seismic risk when different i_{corr} values are expected as illustrated in Section 2. Looking at RI_{PGA} for brittle mechanism in Y direction, the range of values of i_{corr} for the location of the bridge predicted in section 2 for moderate and high exposure lead to the variation of seismic risk indexes highlighted by the shaded colored areas in Figure 3.

5 CONCLUSIONS

In this work a framework to considers the effects of the increase of temperature on the corrosion of steel reinforcement in r.c. structures are presented and applied to a case of study in the province of Massa Carrara (Italy). The analyses considered both extreme as well as verisimilar scenarios; the results are definitely affected by the limited availability of data for corrosion rate i_{corr}. In any case, the situation at 100 years of age appears deserving of attentions, even considering numerous uncertainties and the fact that the method should be subject to successive refinements.

In any case, it should be considered that as at today the investigate viaduct has already 50 years of service life and that projections to 100 years are to be referred to 2070. Since most of the national heritage is built in the 50-70s an improvement of the framework could be to consider the current state of corrosion for numerical analyses. This, coupled with experimental i_{corr} knowledge and specific to that area, allow an improvement in the reliability of the numerical analysis.Considering the corrosion scenarios characterized by i_{corr} values suggested by (Stewart et al., 2011), a significant reduction of the risk indices values occurs only in the case of high corrosion level (i_{corr}= 0.431 μA/cm^2) for the brittle collapse mechanism. The slight corrosion scenario does not lead to significant reductions of risk indices values for the considered collapse mechanisms due to the small reduction of the steel reinforcements area that characterizes such a corrosion level. Different conclusions can be drawn from the i_{corr} values suggested by (DuraCrete, 2000), where more significant reduction of the risk indices is obtained with reduction up to 80% for the ductile collapse mechanism and exceeds 90% for the brittle collapse mechanism.Further refinement of the method and the introduction of other kind of degradation due to the environmental actions are expected as subsequent development of the works.

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REFERENCES

ATC-40:1996. Seismic Evaluation and Retrofitting of Concrete Buildings. Applied technology council, 8.1–8.66, Redwood City, CA.

Bastidas-Arteaga, E., Schoefs, F., Stewart, M.G., Wang, X. 2013. Influence of global warming on durability of corroding RC structures: A probabilistic approach. *Engineering Structures* 51: 259–266.

Berto, L., Vitaliani, R., Saetta, A.V. & Simioni, P. 2009. Seismic assessment of existing RC structures affected by degradation phenomena. *Structural Safety* 31(4): 284–297.

Berto, L., Saetta, A., Simioni, P. 2012. Structural risk assessment of corroding RC structures under seismic excitation. *Construction and Building Materials* 30: 803–813.

Biondini, F., Camnasio, E., Palermo, A. 2014. Lifetime seismic performance of concrete bridges exposed to corrosion. *Structure and Infrastructure Engineering*, Vol. 10, No 7, 880–900.

Chen, W.F. & Duan, L. 2000. *Bridge engineering – seismic design*. CRC press, Boca Raton, FL.

Coni, M., Mistretta, F., Stochino, F., Rombi, J., Sassu, M., Puppio, M. L. 2021. Fast falling weight deflectometer method for condition assessment of rc bridges. *Applied Sciences*, 11(4),1–19.

Crespi, C., Zucca, M., Valente, M., Longarini, N. 2022. Influence of corrosion effects on the seismic capacity of existing RC bridges. *Engineering Failure Analysis* 140: 106546.

Croce, P., Formichi, P., Landi, F. 2019. Climate change: Impacts on climatic actions and structural reliability. *Applied Sciences* 9:5416.

Croce, P., Formichi, P., Landi, F. 2021. Enhancing the output of climate models: A weather generator for climate change impact studies. *Atmosphere* 12, 1074.

Decreto Ministeriale 17/01/2018, Ministero delle Infrastrutture e dei Trasporti, G.U. Serie Generale n.42 del 20/02/2018– S.O.8.

DuraCrete. 2000. *Statistical quantification of the variables in the limit state functions. Dura-Crete-Probabilistic performance-based durability design of concrete structures*. EU-brite EuRam III. Contract BRPR-CT95-0132. Project BE95-1347/R9. January 2000. p. 130.

Hasa, L., Corsini, G., Diani, M., Battagliere, M.L., Sassu, M., Puppio, M.L. Territorial scale monitoring of civil infrastructures through remote sensing. *Proceedings of the International Conference on Natural Hazards and Infrastructure2022 3rd International Conference on Natural Hazards and Infrastructure, ICONHIC 2022 Athens*, 5-7 July 2022 Code 282299.

Jacob D., et al. 2014. EURO-CORDEX: New high-resolution climate change projections for European impact research. *Reg. Environ. Chang*. 14, 563–578.

Kent, D.C. & Park, R. 1971. Flexural members with confined concrete. *Journal of the Structural Division* 97: 1969–1990.

Lee, H.S. & Cho, Y.S. 2009. Evaluation of the mechanical properties of steel reinforcement embedded in concrete specimen as a function of the degree of reinforcement corrosion. *International Journal of Fracture* 157(1): 81–88.

Mistretta, F., Piras, M. V., Fadda, M. L. 2015. A reliable visual inspection method for the assessment of r.c. structures through fuzzy logic analysis. Paper presented at the Life-Cycle of Structural Systems: Design, Assessment, Maintenance and Management - Proceedings of the 4th International Symposium on Life-Cycle Civil Engineering, IALCCE 2014, 1154–1160.

Park, R. & Paulay, T. 1975. *Reinforced Concrete Structures*. John Wiley and Sons, New York.

Pour-Ghaz, M., Burkan Isgor, O., Ghods P. 2009. The effect of temperature on the corrosion of steel in concrete. Part 1: Simulated polarization resistance tests and model development. *Corrosion Science*, 51, 415–425.

Pucci, A., Puppio, M. L., Sousa, H. S., Giresini, L., Matos, J. C., Sassu, M. 2021. Detour-impact index method and traffic gathering algorithm for assessing alternative paths of disrupted roads. *Transportation Research Record*, 2675(12), 717–729

Puppio, M. L., Novelli, S., Sassu, M. 2018. Failure evidences of reduced span bridges in case of extreme rainfalls the case of Livorno. *Frattura Ed Integrità Strutturale*, 12(46), 190–202.

Saetta, A.V. & Vitaliani, R. 2004. Experimental investigation and numerical modelling of carbonation process in reinforced concrete structures: Part I: Theoretical formulation. *Cement and Concrete Research* 34(4): 571–579.

Sassu M., Doveri F., Ferrini M., Mistretta, F., Puppio M. L. Time and cost-effective intervention strategy for r.c. bridges with Gerber beams: methodology and a real case study, Sustainable and Resilient Infrastructure, preprint version.

Sassu, M., Giresini, L., Puppio, M. L. 2017. Failure scenarios of small bridges in case of extreme rainstorms. Sustainable and Resilient Infrastructure, 2(3), 108–116.

Sousa, M.L., et al. 2020. *Expected implications of climate change on the corrosion of structures*. EUR 30303 EN, Publications Office of the European Union, Luxembourg.

Stochino, F., Fadda, M. L., Mistretta, F. 2018. Assessment of RC bridges integrity by means of low-cost investigations. *Frattura Ed Integrita Strutturale*, 12(46), 216–225.

Stewart M. G., Wang X., Nguyen M. N. 2011. Climate change impact and risks of concrete infrastructure deterioration. Engineering Structures, 33, 2011, 1326–1337.

van Vuuren, D.P., et al. 2011. The representative concentration pathways: An overview. *Climatic Change* 109, 5–31.

Zucca, M., Crespi, P., Stochino, F., Puppio, M.L. Coni, M. 2023. Maintenance interventions period of existing RC motorway viaducts located in moderate/high seismicity zones. *Structures* 47: 976–990.