Influence of the exposure scenario and spatial correlation on the probabilistic life-cycle seismic performance of deteriorating RC frames

Andrea Titi, Silvia Bianchi, Fabio Biondini, and Dan M. Frangopol

ABSTRACT

The probabilistic life-cycle seismic performance of reinforced concrete (RC) frames under chloride-induced corrosion is investigated considering the influence of the environmental aggressiveness and exposure scenario and the role of spatial correlation of the random variables. Chloride ingress and corrosion damage are described at cross-sectional level by two-dimensional concentration maps and damage indices. At the structural level, the seismic performance is evaluated in terms of lateral load response of the deteriorating structural system by means of time-variant non-linear analysis over the structural lifetime. The uncertainties involved in the problem are taken into account in probabilistic terms by Monte Carlo simulation. The procedure is applied to life-cycle assessment of a three-storey RC frame under different exposure scenarios, defined by varying both the concentration level and the spatial distribution of chlorides on the external surface of the columns, as well as different correlation levels of the random variables involved in the probabilistic analysis.

Introduction

Life-cycle concepts and methods are necessary for a rational approach to seismic design of structural systems considering the detrimental effects of ageing and deterioration of materials and components under uncertainty (Biondini & Frangopol, 2016). For reinforced concrete (RC) structures exposed to corrosion, the check of durability requirements is usually limited to the control of the quality of materials and to the compliance of technical prescriptions such as the minimum cover depth (CEB, 1992; CEN-EN, 1992-1, 2004; fib, 2006).

However, design for durability should also consider in a quantitative way the effects of the local damage of materials and components on the overall structural performance, particularly when continuous deterioration due to corrosion interacts with seismic hazard (Akiyama, Frangopol, & Matsuzaki, 2011; Akiyama, Frangopol, & Suzuki, 2012; Biondini, Camnasio, & Palermo, 2014; Biondini, Palermo, & Toniolo, 2011). In addition, the life-cycle seismic performance of corroding RC structures may significantly be affected by the environmental aggressiveness and exposure scenario. Nevertheless, these issues are not explicitly addressed in seismic design codes, guidelines, specifications and standards (e.g., CEN-EN, 1998-1, 2004).

To overcome this drawback, the assessment of the life-cycle seismic performance of deteriorating RC structures should be based on general methodologies able to reproduce the diffusion process of aggressive agents, such as chlorides, and the effects of the mechanical damage induced by diffusion on the overall system performance under uncertainty (Biondini, Bontempi, Frangopol, & Malerba, 2004, 2006; Biondini & Frangopol, 2008; Titi & Biondini, 2014a, 2016). A probabilistic approach is presented herein to investigate the influence of the environmental aggressiveness and exposure scenario on the life-cycle seismic performance of deteriorating RC frames under chloride-induced corrosion. Moreover, the effects of the deterioration process on the evolution over time of the role of uncertainties are investigated by taking into account the spatial correlation of the random variables.

It is worth noting that the level of environmental aggressiveness and the exposure scenario do not only affect the scale of the deterioration process, but they might significantly modify over time the damage propagation mechanisms and the role of uncertainties depending on the spatial correlation of the random variables. Chloride ingress is modelled at cross-sectional level based on the Fick’s laws and is described by two-dimensional concentration maps. The effects of corrosion, including the mass loss of the reinforcing steel bars, the reduction of steel ductility, and the deterioration of concrete due to splitting cracks and cover spalling, are described through damage indices. The time-variant seismic capacity of the deteriorating structure is evaluated over the structural lifetime by means of time-variant non-linear static (pushover) analyses under seismic lateral load distribution. The uncertainties involved in the problem are taken into account in probabilistic terms by Monte Carlo simulation based on Latin Hypercube Sampling (LHS).
The proposed approach is applied to the life-cycle seismic assessment of a three-storey RC frame under different exposure scenarios. A parametric analysis is performed by varying the concentration level, the spatial distribution of chlorides on the external surface of the columns, and the level of spatial correlation over the building levels to reproduce the uncertainty effects associated with the building construction process. The results show the significant role played by environmental aggressiveness, exposure severity, and correlation of random variables on the probabilistic life-cycle seismic performance of corroding RC structures.

Modelling of corrosion damage under uncertainty

A lifetime seismic assessment of RC structures exposed to aggressive environment involves both the diffusion process of chemical agents, such as chlorides, and the subsequent mechanical damage induced by diffusion, including corrosion of reinforcing steel bars and deterioration of concrete (Bertolini, Elsener, Pedeferrri, & Polder, 2004). Several uncertain factors may affect the time to corrosion initiation as well as propagation of corrosion and its consequences on the serviceability and performance of RC structures (Andrade & Alonso, 1994; Bertolini, 2008; Melchers & Li, 2009). Therefore, a probabilistic approach is clearly necessary to cover the relevant aleatory and epistemic uncertainties involved in the deterioration modelling (Frangopol, Kallen, & Noortwijk, 2004).

Chloride diffusion

Multi-mechanistic-coupled transport models of heat, moisture and various chemical substances in concrete can be found in literature (Xi & Bažant, 1999), but they usually involve complex modelling and significant computational cost. Macro-models can also be efficiently used to predict concrete deterioration over time (Baasher, Chidiac, & Long, 1996) and most observations indicate that transport of chlorides in concrete is mainly diffusion controlled with a relatively small convection zone (Hunkeler, 2005; Papakonstantinou & Shinouzuka, 2013). Therefore, the Fick's laws of diffusion generally provide a convenient tool for predicting the onset of corrosion in practical applications. The Fick's model is described by the following partial differential linear equation (Glicksman, 2000):

\[ D \nabla^2 C = \frac{\partial C}{\partial t} \]

where \( D \) is the diffusivity coefficient, \( C = C(\mathbf{x}, t) \) is the chloride concentration at point \( \mathbf{x} \) and time \( t \), \( \nabla C = \nabla \cdot C(\mathbf{x}, t) \) and \( \nabla^2 = \nabla \cdot \nabla \). The numerical solution of the diffusion equation is achieved by means of cellular automata (Biondini et al., 2004; Titi & Biondini, 2016).

Effects of reinforcing steel corrosion

Damage due to corrosion starts to develop locally in the reinforcing steel bars and propagates affecting both the corroded steel bars and the surrounding volume of concrete. The mass loss of corroded steel bars is described through a dimensionless damage index \( \delta_s(t) \) which provides a measure of damage in the range \([0;1] \). The area \( A_s(t) \) of a corroded bar can be represented as a function of the damage index as follows:

\[ A_s(t) = [1 - \delta_s(t)]A_{s0} \]

where \( A_{s0} \) is the area of the undamaged steel bar. The relationship between damage index and corrosion penetration depends on the type of corrosion mechanism, i.e. uniform or pitting corrosion (Biondini & Vergani, 2015).

The corrosion process causes also a reduction of steel ductility (Apostolopoulos & Papadakis, 2008). Based on fitting of available experimental data, the steel ultimate \( \varepsilon_{su} \) of a corroded bar is related to the damage index \( \delta_s \) as follows (Biondini & Vergani, 2015):

\[ \varepsilon_{su}(t) = \left\{ \begin{array}{ll}
\varepsilon_{su0}, & 0 \leq \delta_s \leq 0.016 \\
0.1521 \cdot \delta_s^{0.4583} \varepsilon_{su0}, & 0.016 < \delta_s \leq 1
\end{array} \right. 
\]

where \( \varepsilon_{su0} \) is the steel ultimate strain of the undamaged bar.

Moreover, the formation of oxidation products may lead to propagation of longitudinal splitting cracks and concrete cover spalling, particularly in case of uniform corrosion with low penetration rate (Vidal, Castel, & François, 2004). The consequences of these splitting cracks on the capability of concrete to sustain compressive stresses are generally represented by reducing the effective resistant area of the concrete matrix (Biondini et al., 2004), or the concrete compression strength (Coronelli & Gambarova, 2004). In this paper, the compression strength \( f_c \) of deteriorated concrete is evaluated as follows:

\[ f_c = \frac{f_{c0}}{1 + \kappa \left( \varepsilon_s / \varepsilon_{c0} \right)} \]

where \( f_{c0} \) is the compression strength of the undamaged concrete, \( \kappa \) is a coefficient related to bar diameter and roughness (\( \kappa = 0.1 \) for medium-diameter ribbed bars), \( \varepsilon_{c0} \) is the strain at peak stress in compression, and \( \varepsilon_s \) is the transversal strain depending on the crack width \( w = w(\delta) \) which, in turn, can be related to the damage index \( \delta_s \) (see Biondini & Vergani, 2015).

Corrosion initiates once the concentration reaches a critical threshold \( C(t)=C_{cr} \) and evolves in time with a corrosion rate depending on the chloride concentration as follows (Biondini et al., 2004):

\[ \frac{\partial \delta_s(t)}{\partial t} = q_s \cdot C(t) \]

where \( q_s \) is a damage rate coefficient depending on the type of corrosion mechanism. Corrosion rate in the range 0–200 mm/year and chloride content in the range 0–3% could be reasonable for structures exposed to severe environmental conditions (Bertolini et al., 2004; Liu & Weyers, 1998; Thoft-Christensen, 1998).

Probabilistic model

The diffusion process and the corrosion damage induced by diffusion are affected by uncertainty and have to be investigated in probabilistic terms. The probabilistic model considers the following quantities as random variables: concrete compression strength \( f_c \); steel yielding strength \( f_{sy} \); concrete diffusivity \( D \); steel
damage rate coefficient \( q_s \); surface chloride concentration \( C_0 \); critical concentration \( C_{cr} \). The probability density functions listed in Table 1 are assumed (Biondini et al., 2006; Dolšek, 2009; fib, 2006).

The probabilistic analysis is carried out based on Monte Carlo simulation. To reduce the computational cost, the simulation is performed through LHS (Iman & Conover, 1982) with correlation control (Vořechovský & Novák, 2009). The realisations of random variables are based on the midpoint rule and the correlation matrix is fulfilled as the result of an optimisation problem solved based on a Simulated Annealing procedure (Vořechovský & Novák, 2003, 2009). Further details on the implementation of this procedure can be found in Titi (2012).

### Seismic assessment of RC frames

#### Case study

The three-storey RC frame shown in Figure 1, with beam span of 5.50 m and column height of 3.50 m, is considered (adapted from: Ghannoum, Moehle, & Bozorgnia, 2008; Titi & Biondini, 2014b). Figure 2 displays the cross-sections and reinforcement layout of beams (Figure 2(a)) and columns (Figure 2(b)). The behaviour of the materials is characterised by the following nominal values of the material properties: concrete compression strength \( f_c = 38 \) MPa; steel yielding strength \( f_{sy} = 450 \) MPa; concrete ultimate strain in compression \( \varepsilon_{cu} = 0.35\% \); steel ultimate strain \( \varepsilon_{su} = 6.5\% \). The seismic capacity of the RC frame is investigated through non-linear static (pushover) analysis under a seismic lateral load distribution and effective seismic weight \( p = 55 \) kN/m, including the contribution from self-weight, dead loads and live loads, applied at each storey.

#### Structural modelling and limit states

The structural model has been developed in OpenSees (Mazzoni, McKenna, Scott, Fenves, 2006) and is based on beam elements with material non-linearity concentrated at the ends, where plastic hinges are expected to occur (Biondini et al., 2014). The moment-curvature diagrams are computed based on a fibre modelling of the critical cross-sections. The model proposed by Mander, Priestley, and Park (1988a) is adopted for concrete. According to this model, the effects of confinement of the columns are also considered based on the stirrups shown in Figure 2 and the concrete ultimate strain at cover spalling \( \varepsilon_{sp} = 0.64\% \) is assumed (Mander et al., 1998b). In this paper the corrosion of the longitudinal steel bars only is investigated. However, it is noted that the confinement effects can be reduced by the corrosion of the stirrups. A bilinear elastic-plastic model is assumed for reinforcing steel. The hysteretic behaviour is based on the model proposed by Lowes et al. (2004), with a backbone curve defined by a four-points stepwise linearisation of the bending moment vs. curvature diagram. The length of the plastic hinges is evaluated according to Paulay and Priestly (1992). It is assumed that shear failures are avoided over the structural lifetime based on a proper capacity design of the transversal reinforcement (Titi & Biondini, 2014a).

The pushover analyses are performed assuming a linear distribution of lateral forces over the height of the building. Two limit states are investigated: Damage Limitation (DL), that is attained when all columns at any storey of the frame reach the first yielding, and Near Collapse (NC), associated with the achievement of the ultimate curvature in one of the columns (Dolšek, 2012).

#### Probabilistic pushover analysis

A probabilistic pushover analysis is performed based on the random variables with probability distribution and parameters listed in Tables 1 and 2, respectively. The effective seismic weight is assumed as deterministic to investigate the role of randomness associated with both the structural properties and deterioration

![Figure 1. Three-storey RC frame.](image)

![Figure 2. Geometry of the cross-sections and reinforcement layout: (a) beams; (b) columns.](image)

### Table 1. Probability density functions.

<table>
<thead>
<tr>
<th>Random variable ((t = 0))</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete strength, ( f_c )</td>
<td>Lognormal</td>
</tr>
<tr>
<td>Steel strength, ( f_{sy} )</td>
<td>Lognormal</td>
</tr>
<tr>
<td>Diffusivity, ( D )</td>
<td>Normal*</td>
</tr>
<tr>
<td>Damage rate coefficient, ( q_s )</td>
<td>Normal*</td>
</tr>
<tr>
<td>Surface concentration, ( C_0 )</td>
<td>Normal*</td>
</tr>
<tr>
<td>Critical concentration, ( C_{cr} )</td>
<td>Beta</td>
</tr>
</tbody>
</table>

*Truncated distributions with non-negative outcomes.

### Table 2. Mean values, standard deviations, and coefficients of variation.

<table>
<thead>
<tr>
<th>Random Variable ((t = 0))</th>
<th>Mean</th>
<th>St. Dev.</th>
<th>C.o.V.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete strength, ( f_c )</td>
<td>38 MPa</td>
<td>5 MPa</td>
<td>–</td>
</tr>
<tr>
<td>Steel strength, ( f_{sy} )</td>
<td>450 MPa</td>
<td>30 MPa</td>
<td>–</td>
</tr>
<tr>
<td>Diffusivity, ( D )</td>
<td>15.8 ( \times 10^{-12} ) m²/sec</td>
<td>–</td>
<td>0.20</td>
</tr>
<tr>
<td>Damage rate, ( q_s )</td>
<td>((0.02\text{ year}^{-1})/C_0)</td>
<td>–</td>
<td>0.30</td>
</tr>
<tr>
<td>Surface concentration, ( C_0 )</td>
<td>(1.0 - 3.0\text{ wt.%}/c)</td>
<td>–</td>
<td>0.30</td>
</tr>
<tr>
<td>Critical concentration, ( C_{cr} )</td>
<td>(0.6\text{ wt.%}/c)</td>
<td>–</td>
<td>0.25</td>
</tr>
</tbody>
</table>

*Lower bound \( C_{cr,\text{min}} = 0.2\text{ wt.\%}/c\); Upper bound \( C_{cr,\text{max}} = 2.0\text{ wt.\%}/c\).
In this paper, the following average value is assumed:

\[ \rho_{I,II} = \rho_{I,III} = \rho_{II,III} = 0.0, 0.2, 0.4, 0.5, 0.6, 0.8, \text{ and } 1.0. \]

In order to highlight the effect of the correlation level, Figure 3 shows samples of the concrete compression strength based on three different values of correlation, i.e., \( \rho = 0.0, 0.5, 1.0. \)

Monte Carlo simulation based on LHS with a sample size \( N = 200 \) usually provides good accuracy in terms of convergence of the statistical parameters of base shear capacities of RC frames (Dolšek, 2009). In this application, the comparison among exact statistics and numerical estimates of mean value and coefficient

\[
\rho_{I,II}^+ = \rho_{I,II}^+ \rho_{I,III} + \sqrt{(1 - \rho_{I,II}^2)(1 - \rho_{I,III}^2)} \quad (8)
\]

A parametric analysis is hence carried out with the following positive values of the spatial correlation coefficients: \( \rho = \rho_{I,II} = \rho_{I,III} = 0.0, 0.2, 0.4, 0.5, 0.6, 0.8, \text{ and } 1.0. \)

In order to highlight the effect of the correlation level, Figure 3 shows samples of the concrete compression strength based on three different values of correlation, i.e., \( \rho = 0.0, 0.5, 1.0. \)

Monte Carlo simulation based on LHS with a sample size \( N = 200 \) usually provides good accuracy in terms of convergence of the statistical parameters of base shear capacities of RC frames (Dolšek, 2009). In this application, the comparison among exact statistics and numerical estimates of mean value and coefficient

\[
\rho_{I,III} = \bar{\rho}_{I,III} = \rho_{I,II}^+ + \rho_{I,III}^+ = \rho_{I,II}^+ \rho_{I,III} \quad (9)
\]
of variation of the random variables indicates very good accuracy with negligible error over the entire 50-year lifetime for all the exposure scenarios and correlation levels investigated.

Figure 4 depicts the set of 200 capacity curves with indication of the DL and NC limit states for $\rho = 0$ (Figure 4(a)) and $\rho = 1$ (Figure 4(b)). It is noted that for the undamaged structure, i.e. at time $t = 0$, the influence of the spatial correlation on the lateral load response is quite limited. This is because of the relatively low random variability of the material strengths (coefficients of variations: 5/38 = 0.13 for concrete and 30/430 = 0.07 for steel) compared to the variability of other random variables associated with the chloride diffusion and corrosion process.

**Life-cycle seismic assessment under chloride-induced corrosion**

**Exposure scenario**

The influence of the exposure scenario on the seismic capacity of the RC frame shown in Figure 1 is investigated by assuming a diffusive attack from chlorides on the external surfaces of the columns. The exposure scenario is shown in Figure 5, with concentration $C_0$ on the outermost side of the two lateral columns and $\alpha C_0$ on all the other column sides. A parametric analysis is carried out by varying the exposure level $\alpha$ in the range $0\div1$ and the surface chloride concentration $C_0$ in the range 1%÷3% [wt.%/c].

Chloride diffusion is simulated by assuming a nominal diffusivity coefficient $D = 15.8 \times 10^{-12}$ m$^2$/sec. Figure 6 presents the contour maps of chloride concentration $C(x,t)/C_0$ of the cross-section of the lateral columns for two exposure levels, $\alpha = 0$ and $\alpha = 1$, after 10, 30, and 50 years from the initial time of diffusion penetration. The corrosion damage induced by chloride ingress is evaluated by assuming a nominal damage rate $q_s C_0 = 0.02$ year$^{-1}$, with corrosion initiation associated with a nominal critical threshold of concentration $C_{cr} = 0.6\%$ [wt.%/c].

**Time-variant corrosion damage and structural capacity**

Figures 7 and 8 illustrate the nominal 50-year damage index $\delta_s$ of the steel bars #1 and #2 (see Figure 2(b)) for external columns (Figure 7) and internal columns (Figure 8) vs. surface concentration $C_0$ for different exposure levels ($\alpha = 0, 0.25, 0.50, 0.75, \text{and} 1.00$). As expected, corrosion damage increases with both the chloride content $C_0$ and exposure level $\alpha$. This trend is
the effects of corrosion are relevant also for moderate exposure levels with $\alpha > 0.25$. However, as already mentioned, for severe exposures, i.e. $\alpha = 1.00$, the deterioration over time of the structural performance is almost independent on $C_0$.

The results of the deterministic analyses of the nominal systems are similar to the average values obtained from the probabilistic analyses. The most important information obtained from the probabilistic investigation is the increasing dispersion of the results over time. Moreover, the dispersion effects are exacerbated by the severity of the exposure scenario. This is illustrated in Figures 12 and 13, which show the sample of 200 exacerbations for the steel bar#2 located on the outermost side of the external columns, that is exposed to the maximum chloride content in all the investigated scenarios. However, the exposure scenario represents a key factor only for low to moderate exposure levels, since for severe exposures ($\alpha = 0.75$ and 1.00) the concrete matrix is saturated by chlorides and the damage index is almost independent on the surface concentration $C_0$.

It is worth noting that this type of damage scenarios is not infrequent for RC buildings exposed for decades with no maintenance to very aggressive environments (Biondini, Tattoni, & Titi, 2016). A similar trend is found at the system level as shown in Figure 9 for the 50-year nominal maximum base shear $F_{max} = \max F(d)$ of the RC frame vs. surface concentration $C_0$ for different exposure levels ($\alpha = 0, 0.25, 0.50, 0.75,$ and 1.00).

**Probabilistic life-cycle assessment**

The probabilistic life-cycle analysis is carried out based on the random variables with probability distribution and parameters listed in Tables 1 and 2, respectively. Figures 10 and 11 show the results over a 50-year lifetime in terms of capacity curves associated with the mean value of the base shear for different exposure levels ($\alpha = 0, 0.25, 0.50$, and 1.00) and chloride content with mean values $C_0 = 1\%$ (Figure 10) and $C_0 = 3\%$ (Figure 11) considering $\rho = 1$. These results confirm the trend found for the nominal system. In fact, for $C_0 = 1\%$ the deterioration of the seismic performance is not particularly relevant for low to moderate exposure levels with $\alpha < 0.50$. Contrary, for $C_0 = 3\%$ the effects of corrosion are relevant also for moderate exposure levels with $\alpha > 0.25$. However, as already mentioned, for severe exposures, i.e. $\alpha = 1.00$, the deterioration over time of the structural performance is almost independent on $C_0$.

The results of the deterministic analyses of the nominal systems are similar to the average values obtained from the probabilistic analyses. The most important information obtained from the probabilistic investigation is the increasing dispersion of the results over time. Moreover, the dispersion effects are exacerbated by the severity of the exposure scenario. This is illustrated in Figures 12 and 13, which show the sample of 200
functions associated with the corresponding base shear capacities (Figure 13) for $C_0 = 1\%$ and different exposure levels ($\alpha = 0$, $\alpha = 0.25$, $\alpha = 0.50$, $\alpha = 1.00$).
α > 0.25. Moreover, under severe exposure (α = 1.00) the probability distribution of the base shear capacities tends over time to change from uni-modal to bi-modal.

0.25, 0.50, and 1.00) considering ρ = 1. It can be noted that the dispersion of the capacity curves after a 50-year lifetime is extremely relevant even for moderate exposure levels with α > 0.25. Moreover, under severe exposure (α = 1.00) the probability distribution of the base shear capacities tends over time to change from uni-modal to bi-modal.
The role of the spatial correlation of the random variables on the probabilistic performance of the RC frame over a 50-year lifetime is shown in Figures 14 and 15 with reference to a chloride content $C_0 = 1\%$ and different exposure levels ($\alpha = 0, 0.25, 0.50, 0.75$, and $1.00$) for correlation levels $\rho = 0, 0.5, 1.0$. Figure 14 shows the mean value of the base shear capacity factor $F_{NC}(t)/F_{NC}(0)$ associated with the NC limit state. A similar trend is found for the DL limit state. Figure 15 shows the mean value of the displacement ductility factor $\mu_d(t)/\mu_d(0)$, where $\mu(t)=d_{NC}(t)/d_{DL}(t)$ with $d_{DL}$ and $d_{NC}$ displacements associated with the DL and NC limit states, respectively.

These results indicate that, on average, the influence of spatial correlation is limited for low to moderate exposures. However, it is beneficial to mitigate the detrimental effects of severe corrosion processes on the deterioration of the overall seismic performance in terms of both base shear capacity and displacement ductility.

Similar conclusions are found for higher chloride contents (i.e. $C_0 = 3\%$). This is because high levels of correlation among the model parameters tend to increase the dispersion in the structural capacity, and vice versa (Kramar, Isaković, & Fischinger, 2010). Actually, as shown in Figure 3 for the concrete strength, high levels of correlation cause the structural models to have uniform characteristics, whereas low levels of correlation lead to structural models with mixed characteristics.

The variability of structural capacity for systems with uniform characteristics tends to be larger with respect to systems with mixed characteristics. Therefore, on the average, the impact of structural deterioration over time is expected to be lower for highly correlated structural models with larger variability of structural capacity. This is illustrated in Figure 16 with reference to the probability mass functions of the base shear capacity associated with the DL and NC limit states at the initial time.

![Figure 14](image1.png)  
**Figure 14.** Evolution over a 50-year lifetime of the mean base shear capacity factor $F_{NC}(t)/F_{NC}(0)$ associated with the NC limit state for a surface chloride concentration with mean value $C_0 = 1\%$ and different exposure levels ($\alpha = 0, 0.25, 0.50, 0.75$, and $1.00$): (a) $\rho = 0$; (b) $\rho = 0.5$; (c) $\rho = 1$.

![Figure 15](image2.png)  
**Figure 15.** Evolution over a 50-year lifetime of the mean displacement ductility factor $\mu_d(t)/\mu_d(0)$ for a surface chloride concentration with mean value $C_0 = 1\%$ and different exposure levels ($\alpha = 0, 0.25, 0.50, 0.75$, and $1.00$): (a) $\rho = 0$; (b) $\rho = 0.5$; (c) $\rho = 1$. 
The investigation should be extended to consider the actual dynamic structural response under ground motion. However, the results presented in this paper clearly indicate that durability requirements cannot be limited to quality of materials and compliance of technical prescriptions such as the minimum cover depth. A life-cycle-oriented seismic design of durable structures should consider in a quantitative way the effects of the local damage of materials and components on the overall structural performance of the system by taking the environmental aggressiveness and exposure severity into account. An effort is needed to incorporate these concepts in design seismic codes and standards (Biondini & Frangopol, 2016).

Disclosure statement
No potential conflict of interest was reported by the authors.

ORCID
Fabio Biondini http://orcid.org/0000-0003-1142-6261

References

Figure 16. Probability mass functions of the base shear capacity associated with the DL and NC limit states at the initial time and after a 50-year lifetime for a surface chloride concentration with mean value $C_0 = 1\%$, exposure level $\alpha = 1.00$, and different correlation levels: (a) $\rho = 0$; (b) $\rho = 1.00$. 

and after a 50-year lifetime for a surface chloride concentration with mean value $C_0 = 1\%$, exposure level $\alpha = 1.00$, and different correlation levels.

Conclusions
The influence of environmental aggressiveness and exposure scenario on the life-cycle seismic performance of RC structures has been investigated for a three-storey frame building under chloride-induced corrosion. A parametric pushover analysis under a seismic lateral load distribution has been performed for given exposure scenarios by varying both the concentration level and the spatial distribution of chlorides on the external surface of the structural members, as well as the level of spatial correlation of the random variables over the building levels.

It has been found that, as expected, corrosion damage increases with both the chloride content and exposure level of the structural members. In particular, an increase in the severity of the exposure scenario, in terms of both surface chloride concentration and exposure levels, leads to increased deterioration rate, particularly for low to moderate exposures. In fact, the exposure scenario represents a key factor only for low to moderate exposure levels, since for severe exposures the concrete matrix is saturated by chlorides and the damage process is not significantly changing with the surface chloride concentration.

Conversely, the role of spatial correlation of the random variables is emphasised under severe exposures. In fact, the influence of spatial correlation is limited for low to moderate exposures, but tends to be beneficial under severe corrosion processes to mitigate the deterioration of the overall seismic performance.

The investigation should be extended to consider the actual dynamic structural response under ground motion. However, the results presented in this paper clearly indicate that durability requirements cannot be limited to quality of materials and compliance of technical prescriptions such as the minimum cover depth. A life-cycle-oriented seismic design of durable structures should consider in a quantitative way the effects of the local damage of materials and components on the overall structural performance of the system by taking the environmental aggressiveness and exposure severity into account. An effort is needed to incorporate these concepts in design seismic codes and standards (Biondini & Frangopol, 2016).


