Assessment of corrosion effects on reinforced concrete (RC) buildings through a probabilistic framework

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Abstract: This paper describes the assessment of the effects of ageing on reinforced concrete (RC) buildings through a probabilistic framework. Ageing in RC structures can lead to corrosion when certain environmental and material circumstances are met and impact the structure's performance through the passing of time. The probabilistic framework considers the different possible scenarios that can trigger corrosion through sampling different values for environmental conditions and, thus, obtaining corrosion initiation times. Three-dimensional (3D) models of building structures, designed according to old and modern standards, were assessed through nonlinear static analyses, by altering the properties of some of their structural members, with the aim of representing corrosion according to the building's age and exposure. The structures' models are bare frames and infilled frames and include the modelling of both the flexural and shear behaviour of the structural elements. The main outcome of this study is that the effects of ageing clearly depend on the structure´s design level and impact differently on each of the building types. Older structures are more susceptive to corrosion effects than newer structures. Nevertheless, these effects are less impactful on infilled frame structures given that, for these structures, the behaviour is controlled by the infill walls.

Keywords: corrosion effects, reinforced concrete buildings, probabilistic assessment, building classes

1. Introduction

Reinforced concrete buildings located on seismic areas may be negatively impacted by the effects of ageing due to corrosion, since these effects can degrade the structure's performance over its service life. The structures exposed to this phenomenon exhibit reduction on its load carrying capacity, redistribution of forces and loss of structural redundancy, especially if their members are subjected to increasing levels of corrosion over time.

The loss of capacity of the corroded reinforced concrete elements happens due to corrosion of materials forming on the perimeter of the reinforcement bars, which reduces the effective steel area, and decreases the element strength and ductility (Coronelli and Gambarova, 2004). This also causes a volumetric expansion around the bars, which leads

to cracking on the concrete and cover spalling, reduction of the steel and concrete bond and reduction on moment, shear and anchorage capacities of the exposed members.
The negative impact on the seismic performance of structures that are exposed for large periods of time to these environmental conditions has been explored by several authors. Pitilakis et al (2014) noticed an increase of the seismic fragility of corroded buildings by including the effect of ageing in the modelling of concrete and steel members of concrete frames. Yu et al (2017) concluded that older structures, with severe corrosion, are more vulnerable to progressive collapse than newly constructed ones.
Regarding the overall impact of corrosion effects and its relationship with the level of seismic design of a given structure, relevance is given to the work of Berto et al (2020), who showed that the reduction in the capacity and ductility due to corrosion is heavily influenced by the type of design. Additionally, Di Sarno et al (2020), who analysed modern designed buildings using models with different levels of exposure, concluded that corrosion effects may shift the structural behaviour from ductile to brittle.
In this study, the practical consequences of corrosion are assessed with a fully probabilistic approach, considering several corrosion scenarios which represent a diverse range of environmental conditions, combined with different building ages or exposure times, to provide a complete and practical depiction of their performance over time. The work is carried out using three-dimensional (3D) models, which consider the effects of corrosion on the elements located at the structure's perimeter with detailed representations of the shear and bending behaviours, for different types of seismic structural design.

2. Corrosion effects on reinforced concrete elements

One of the main aspects to consider when assessing the effects of corrosion on exposed concrete members is time (Fig. 1). The time at which the effects start to influence the member's behaviour is defined as corrosion initiation time (Ti). The time after that, designated as propagation time, dictates how much the steel and concrete properties will be modified, depending on the degree of corrosion.

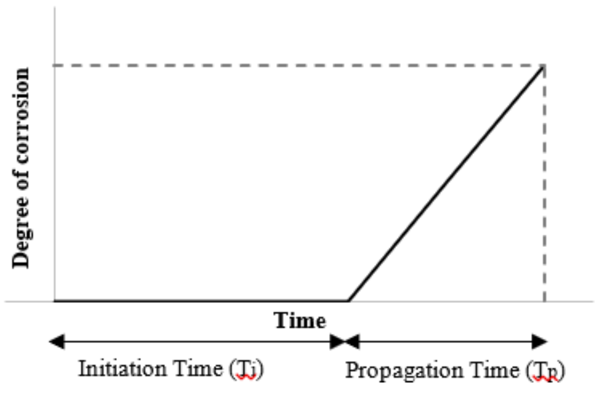


Fig. 1 – Temporal corrosion process

The initiation time was obtained through Siemes and Edvardsen (1999) probabilistic model, which considers the environmental conditions such as humidity, the actual concrete member properties and both physical and curing methods. This model accounts for the uncertainty associated to each of the mentioned variables, including the RC element properties. Table 1 shows the variables' distributions and conditions selected for this study.

$$Ti = X_I\left[\frac{d_c^2}{4k_e k_t k_c D_0(t_0)^n}\left[\text{erf}^{-1}\left(1-\frac{C_{cr}}{C_s}\right)\right]^{-2}\right]^{1/(1-n)} \tag{1}$$

Once the propagation phase begins, the properties of the steel and concrete begin to degrade progressively with the advancement of time. The main parameters affected by this phenomenon are the rebar diameter, the yield and ultimate steel stresses, the steel ultimate strain and the concrete strength. For the purposes of this study, the effects of corrosion on bond-slip behaviour will not be considered, since its impact is not significant, as it has been shown by Lin et al (2019).

Table 1. Parameters for initiation time

Compounds	Conditions	Distribution	Mean	Std. Dev.
XI: Uncertainty coefficient	-	Lognormal	1	0.05
dc: Cover depth of concrete column	From FIM	None	30 (mm)	-
ke: Environmental correction factor	Atmospheric	Gamma	0.676	0.114
D0: Reference diffusion coefficient at t_0 = 28 days	*w/c* = 0.5	Beta	473 (mm^2/yr)	43.2 10^{-6} (mm^2/s)
kt: Correction factor for tests	All	Normal	0.832	0.024
kc: Curing time correction factor	28 days	Normal	0.8	0.1
n: Aging factor	All	Beta	0.362	0.245
Ccr: Critical chloride content (mass-% of binder)	Humid/dry cycles	Normal	0.9	0.15
Cs: Chloride surface concentration (mass-% of binder)	Atmospheric			$C_{29}H_{33}N_3O_3$

The computation of the reduced steel rebar diameter, as a function of time and corrosion level, was done through the model proposed by Choe *et al* (2008). This model considers the diminishing effects on the corrosion rate over time, as the corrosion products around the rebar prevent the chemical process to continue at the same scale. Therefore, the reduced steel rebar diameter is function of the present time, initiation time, the rebar's initial diameter, the water cement relationship and the cover depth.
The reduction of the yield and ultimate steel strengths, as the reduction of the steel strains, which are both function of time, were computed using the Carins *et al* (2005) model. The percentage of average section loss was evaluated based on the expressions proposed by Du *et al* (2005), while the concrete loss of strength (f_c*) due to corrosion was estimated according to Cornelli and Gambaroba (2004).

3. Probabilistic framework

In this section, a probabilistic framework is proposed to evaluate the buildings' performance evolution over time, for different external conditions, as shown in Fig. 2, where BIM, ABIM and AFIM mean, respectively, Building Information Model, Aged Building Information Model and Aged Fragility Information Model Different building classes are considered with several design conditions, to encompass the various seismic design outcomes that could be expected from structures designed either recently or many years ago. Then, *j* samples of ageing or environmental parameters are introduced on the models using the different distributions listed in Table 1. The initiation times for each element per *j* sample are computed by combining the ageing parameter with the properties of each exposed member for a given building design.
After getting the initiation times for each element, the aged properties for concrete and steel are computed for a given set of building ages from T=0 to T=50 years, in 10-year intervals. This information allows the beams and columns to be modelled according to

these new computed properties, obtaining a set of aged finite element models for each *j* sample and time *i*. These models are then subjected to modal and nonlinear static (pushover) analyses in both directions, to characterize the local and global behaviour of the structures. The global response parameters, such as displacement and base reactions, together with the elements' local responses, allow to assess the loss of capacity and possible changes on the structure's failure mechanism over time.

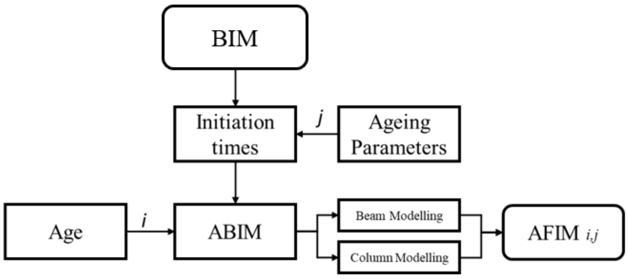


Fig. 2 – Probabilistic framework flowchart

The number of samples of environmental parameters is defined through estimating the initiation time using a Latin Hypercube Sampling (LHS) on all the distributions of the variables identified in Table1. To obtain a reasonable range of all initiation times within a normal building's lifecycle (0 to 50 years), different sample sizes were initially considered, from 25 to 10000. The minimum value that provides a complete array of observations, without being computationally time consuming, is 50 samples.

4. Studied Cases

4.1. Buildings' description and classification

The proposed framework was applied to a set of buildings with different seismic design levels, with four and five storeys height and the plan configuration shown in Fig.3. It consists of five bays in the X direction and three bays in the Y direction, with a typical frame spacing of 4.5m in both directions. An exception is made for the middle bay in the X direction, where the stairs are located, that only has 3m length. The buildings' story height is 2.8m for all storeys.

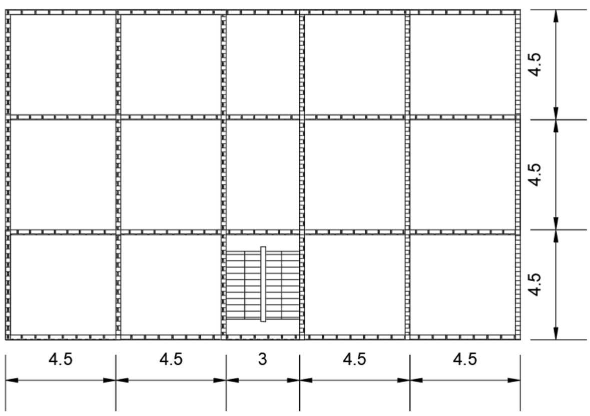


Fig. 3 – Building's plan configuration

The buildings were grouped into classes according to their design level. The buildings labelled as Design Class High (DCH) are RC structures that consider modern seismic design practices, such as capacity design and local ductility measures recommended in modern design codes. These buildings have a high global ductility achieved through a controlled mechanism, with high levels of shear reinforcement, preventing shear failure. The buildings designated as Design Class Medium (DCM) are structures that have been designed according to older seismic codes, in which lateral loads are included in the design process through scaling factors, with overall low ductility and less control of the failure mechanism. This class of buildings accounts for two different levels of seismic action, by adopting a seismic coefficient, *β*, equal to 0 and 0.15. An additional class was considered for DCM, named DCMR, with a slight increase on shear capacity to prevent sudden failures that could cause difficulties observing the effects of corrosion.

Table 2. Building classes classification

Design class	Seismic Design β	N. Storeys	Designation
Design Class High	0.15	4	DCH- 4- $\beta_{0.15}$
Design Class Medium	0.00	4	DCM- 4- β_0
Design Class Medium	0.15	4	DCM- 4- $\beta_{0.15}$
Design Class Medium - Shear Reinforced	0.15	4	DCMR- 4- $\beta_{0.15}$
Design Class High	0.15	5	DCH- 5- $\beta_{0.15}$
Design Class Medium	0.00	5	DCM- 5- β_0
Design Class Medium	0.15	5	DCM- 5- $\beta_{0.15}$
Design Class Medium - Shear Reinforced	0.15	5	DCMR- 5- $\beta_{0.15}$

4.2. Modelling assumptions

4.2.1. General modelling assumptions

The 3D structure models were built using the nonlinear analysis software OpenSees (McKenna, 2000), applying a lumped plasticity approach. It consists of a combination of elastic elements (beams and columns) with non-linear springs that simulate the flexural and shear behaviour of the elements.

The flexural behaviour of the beams and columns was modelled according to the Ibarra-Medina-Krawinkler (IMK) model (Lignos and Krawinkler, 2011). The different parameters that define the moment-rotation relationship were computed as proposed by Haselton *et al* (2016), with the exception of the yield rotation which was calculated according to Grammatikou *et al*. (2017).

The shear behaviour was modelled through a three-point limit state curve, based on the work by Sezen and Moehle (2006). This model captures the shear failure and accounts for the shear degradation due to cyclic loading.

For the cases of buildings with infill walls, the structures' design was kept the same as the bare frames, but the infill walls were included in the numerical models. The masonry infills of these buildings consisted of two leaves of horizontal hollowed brick units with an internal cavity between them, covered externally with a layer of plaster. These walls were introduced in the numerical models through a simplified approach, developed within the SERA framework (Romão et al., 2019), that accounts for the strength and stiffness contributions of the walls.

4.2.2. Modelling of corrosion

To assess the degradation due to ageing, the elements exposed to corrosion, located at the perimeter of the building, had their original properties modified once their initiation time was exceeded. The corrosion effects on the columns' flexural springs were modelled following the empirical model proposed by Dai *et al.* (2020), which uses modification

factors, called corrosion-induced deterioration coefficients (CIDC), evaluated for the different points of the backbone curve of the IMK spring, and multiplied by their corresponding parameters, effectively reducing the strength and ductility of the springs.
For both flexural and shear springs, the corroded properties of the columns and beams were computed following the same equations that define the uncorroded model. The inclusion of ageing comes from applying the values of the aged properties to the steel and reducing the concrete strength, as a function of the corroded area, following the Di Sarno and Pugliese (2019) model.

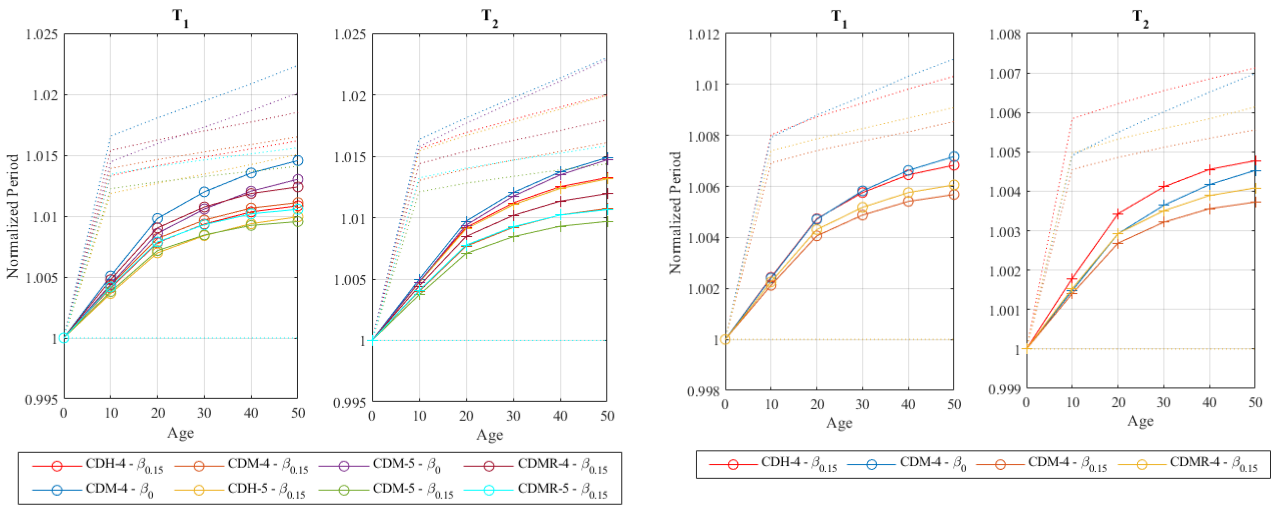
5. Performance Assessment

5.1. Damage state definition

The damage states were defined to have an objective measure of the structure's performance both at the global and local levels. These limit states were firstly defined locally, using the material properties, and then associated to global damage states. The local limits are based on the chord rotations defined for each of the elements, where DS1 and DS2 correspond to the yield and capping curvatures, respectively. Additionally, DS2 may also be considered whenever the element reaches its shear strength capacity. The global limit states DS1 and DS2 are then met by the first occurrence of local damage states in the beams or columns.

5.2. Effect of corrosion on dynamic properties

The mean results of the modal analysis are shown in Fig.4, which illustrates the first two periods (fundamental periods in each orthogonal direction) of the structures. These remain almost unchanged for all design types, throughout all the considered years of study and across all samples. This happens because the effects of corrosion do not seem to have much influence on the elastic properties of the buildings and only take place once the plastic deformations are reached. Therefore, no significant changes on the dynamic properties of the structure are observed. These results are of importance whenever the selection of a response spectrum, or any task associated to the dynamic characterization of the structure, is needed.



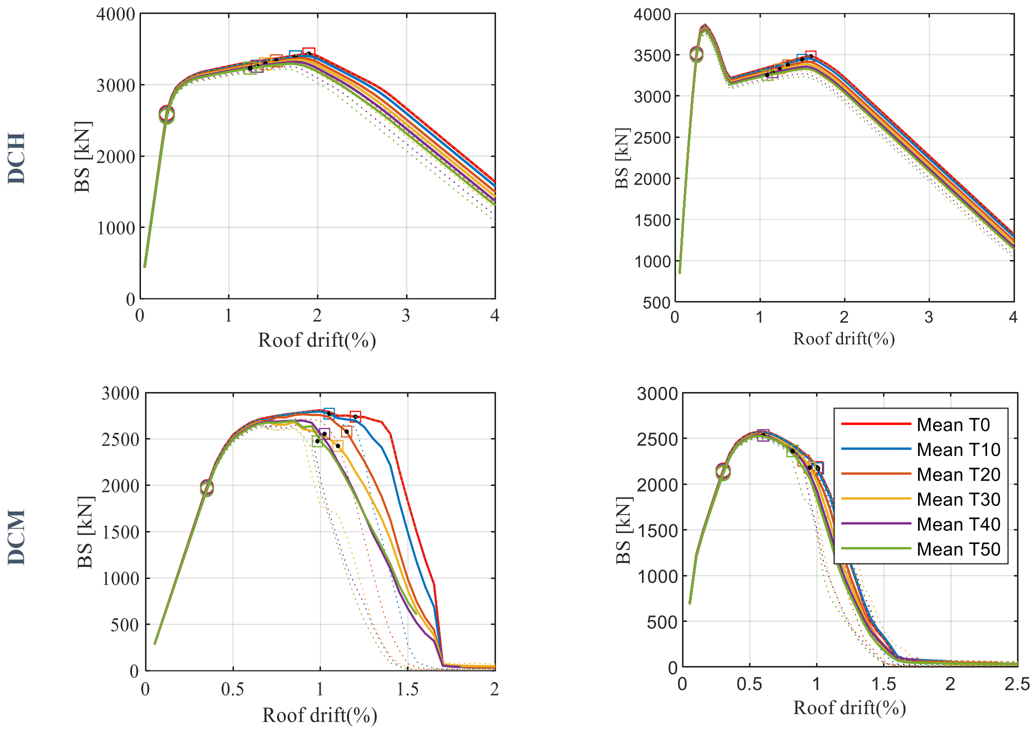
(a) **(b)**

Fig. 4 – Fundamental periods of vibration of the studied classes for: (a) Bare frame structures and (b) Infilled frame structures

5.3. Effects of corrosion on the buildings' response

The mean pushover curve from all samples, computed throughout the roof drift levels, for the DCH and DCM$_{\beta 0.15}$ buildings, is shown in Fig. 5. It is noticeable that there is a slight decrease in the base shear, as well as in the global ductility with the passing of time from T=0 to T=50 years, for both building classes. This observation becomes more evident in the nonlinear range, as the response up to yielding remains almost unchanged for all the analysed structures. The effects of corrosion on the overall form of the pushover curve are more unfavourable for the classes with an inferior seismic design level, as it can be seen comparing DCM and DCH bare frame building classes, where it appears to be no plastic hardening, as well as an earlier start of its strength degradation. Fig. 5 also shows that these effects are less impactful on the infilled frame structures, given that for those structures the behaviour is controlled by the infill walls and the degradation on the perimeter frame elements becomes less relevant through all the design classes with this configuration.

The elements' local response is also depicted in Fig. 5 through the attainment of the damage states DS1 (circles) and DS2 (squares). A trend observed across all cases is the reduction of the roof drift at which DS2 is achieved. For the DCH buildings, this decrease is caused by the perimeter elements that reach their peak response earlier and without causing significant modifications to the shape of the pushover curve. Conversely, for the DCM buildings, the achievement of DS2 limit is related to shear failure, which happens at similar levels of drift for both building classes, even with the influence of ageing. As mentioned earlier, the lack of change in the linear range of the structure response causes the structure to reach DS1 at the same drift value across all analyses.



(a) **(b)**

Fig. 5 – Mean pushover curves for the DCH and DCM$_{\beta 0.15}$ considering: (a) Bare frame structures and (b) Infilled frame structures

The several values of initiation times and the degrees of corrosion introduced into the models resulted in an increase of variability, over the time. For new buildings, the global behaviour is always more stable, as little to no corrosion occurs, and the elements have their intact properties, as it can be seen in Fig. 6. The first row of Fig. 6 graphs shows that, at T0, all the samples and their mean are overlapped, for all design types. Conversely, for older structures (T20 and T50 plots), the variability of the behaviour increases due to age, with structures behaving closely to the pristine condition (with an upper limit that tends to T0) and structures that exhibit noticeable drops on both strength and deformation capacities.

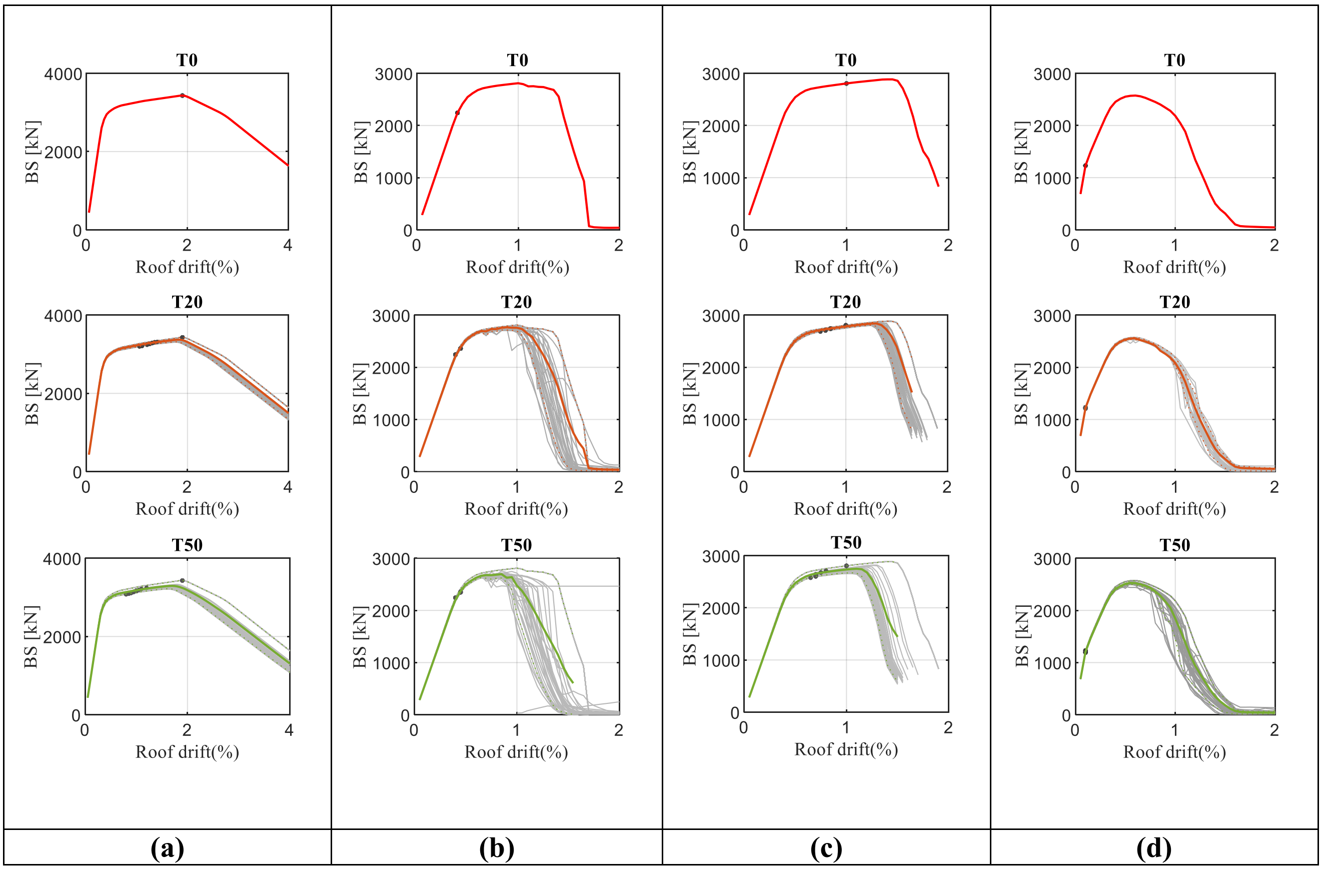


Fig. 6 – Changes on pushover response over time for (a) DCH, (b) DCM, (c) DCMR (d) DCM Infilled

Fig. 6 also shows that the variability is also dependent on the type of seismic design. Accordingly, for T=50 years, the dispersion observed in the pushover curves obtained for the DCH structures is low, having only slight variations with respect to its mean values. This outcome illustrates the importance that the type of design has on the control of the global failure mechanism, as it remains almost constant across time. The structural elements start developing damage locally at low drift levels, shown in the figures as grey dots, but the overall structural behaviour is not significantly affected over time.

The larger variability on the DCM and DCMR bare frame buildings (Fig.6-b and Fig.6-b), pushover curves is caused by the presence of shear failures combined with changes on the hinge locations and accumulation of damage in some elements caused by corrosion. These frames show the opposite results of the ones designed according to modern seismic design principles, as the global failure mechanism changes significantly with no substantial changes in the element's local response. This observation is clearer when making a comparison between all figures (Fig.6-a to Fig.6-d) where it can be observed that the

structures with fewer shear failures (DCH and DCMR) exhibit higher variability in the location of this DS than the structures more prone to shear failures (DCM and Infilled DCM).
The small variability on the pushover shape of the infilled frame structures (Fig6-d) is justified by the presence of the infill walls, which have a large influence on the structural behaviour, as already observed.

5. Conclusions

This study focused on the probabilistic assessment of corrosion effects on the seismic behaviour of RC buildings. The framework adopted considers the different possible scenarios that can trigger corrosion through sampling different values for environmental conditions and, thus, obtaining different corrosion initiation times. Several buildings with the same floor configuration and different number of storeys (4 and 5 storeys) are designed according to old and modern standards. The behaviour assessment of bare and infilled frames is performed through nonlinear static analyses. The properties of some of structural members are modified with the aim of representing corrosion according to the building's age and exposure.
The results indicate that corrosion effects do not have a relevant influence on the elastic properties of the buildings and only influence the behaviour once plastic deformations develop in the members. Therefore, no significant changes on the dynamic properties of the structure are observed.
Regarding the overall behaviour of the structures analysed, it is observed for both the bare and infilled frame structures, that the effect of corrosion causes a slight decrease of the base shear and displacement capacities with the passing of time. Moreover, the effects of corrosion on the overall behaviour are more unfavourable for the classes with an inferior seismic design level. Nevertheless, these effects are less impactful on the infilled frame structures, given that for those structures the behaviour is controlled by the infill walls. The analyses of the results also show that for newer structures the global behaviour is stable, and a limited influence of corrosion effects is observed. Finally, it is concluded that ageing effects increase the variability of the global behaviour of older structures over time. The main outcome of this study is that ageing effects clearly depend on the structure´s design level and impact differently on each of the building types.

Acknowledgements
The authors would like to acknowledge the financial support of Fundação para a Ciência e a Tecnologia (FCT, Ministério da Educação e Ciência, Portugal) through the FCT Research Program: MitRisk - Framework for seismic risk reduction resorting to cost-effective retrofitting solutions, POCI-01-01456-Feder-031865.

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