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Corrosion initiation time models in RC coastal structures based on reliability approach

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Abstract. The present work proposes new engineering models for determining corrosion initiation time in concrete reinforcing steels in marine environment. The models are based on Fick's second law that is commonly used for chloride diffusion. The latter is based on deterministic analyses involving the most influencing parameters such as distance of the concrete structure from the seaside, depth of steel concrete cover, ambient temperature, relative humidity and the water-cement ratio. However, a realistic corrosion initiation time cannot be estimated because of the uncertainties associated to the different parameters of the models. Therefore a reliability approach using FORM/SORM method has been applied to develop the proposed engineering models integrating a limit state function and a reliability index β. As a result, the corrosion initiation time is expressed by new exponential engineering models where the uncertainties are associated to the model parameters. The main emerging result is a realistic decision tool for corrosion planning inspection.

Keywords: corrosion initiation time; RC beam; chloride diffusion; reliability index; uncertainties

1. Introduction

Prestressed or reinforced concrete structures are usually designed for long lifetime. However when they are submitted to aggressive environment as in the presence of ions of chloride near the lifetime decreases because of corrosion in the reinforcing concrete steel (Vedalakshmi *et al*. 2011, Yang *et al*. 2017). The former corrosion process is well described by the Portland Cement Association (PCA 2002) suggesting that when steel corrodes, the resulting rust occupies a volume that expands up to creating tensile stresses in the concrete, which can eventually cause cracking, delamination, and spalling. Meanwhile the corrosion process as reported by Tuutti (1982), occurs in two distinct time stages characterising the phenomenon; a corrosion initiation stage followed by a corrosion propagation stage. As far as corrosion initiation has not been observed then the reinforced concrete structure remains reliable over the whole period of lifetime for which it was first designed. But when the chloride concentration at the reinforcing steel exceeds a threshold concentration then corrosion initiation starts limiting therefore the initiation stage from the propagation stage. Therefore, recently much more investigated in comprehensive analyses of the corrosion process in concrete structures.

Wang *et al*. (2019) have investigated strand corrosion-induced concrete cracking under various prestress experimentally and analytically. They have reported that the critical time of cover cracking decreases 22% and the crack propagation rate increases 9%.

Dai *et al*. (2019) have proposed an analytical model incorporating the effects of strand cross-section reduction, material deterioration, concrete cracking, and bond degradation in order to predict the flexural capacity of corroded prestressed concrete beams. They have pointed out that the flexural capacity deterioration of prestressed concrete beams depends on corrosion degree and brought significant information since strand corrosion less than 5.5% can lead to a slight decrement of flexural capacity.

Moreover, the knowledge of time of corrosion initiation is very important in controlling the lifetime of the reinforced concrete structure. Therefore investigations on corrosion inspection continue to fall from over the world. Djeddi *et al*. (2013) have proposed a contribution on using acoustic emission technique in order to inspect and detect corrosion and stress corrosion cracking on prestressing steel strands. Liu *et al*. (2017) have developed on-stream inspection system for pitting corrosion defect inspection in order to assess internal integrity of pressure vessels.

Eventually there are several factors contributing in corrosion initiation on steel in concrete such as, the concrete quality, the thickness of the concrete cover and environmental parameters. For instance reinforced concrete structures build in offshore or in coastal areas are highly sensitive to corrosion because of seawater which is, like de-icing, most effective source of chloride ions migrating through porous concrete cover to reinforcing steel. So a large number of papers continue to fall from all other the world treating the lifetime of reinforced concrete subjected

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to corrosion. Meanwhile, Kioumarsi *et al*. (2017) have studied the effect of variation of pit distance on structural reliability of reinforced concrete (RC) beam and revealed that it has a significant influence on the probability of failure. Wang *et al*. (2017) have investigated the effects of corrosion-induced crack on the bond between strand and concrete showing that bond performance is reduced and the presence of stirrups contributed in delaying the de bond deterioration. Wu *et al*. (2017) have field investigated the effect of exposure conditions on chloride ingress into concrete and time-dependent chloride diffusivity of concrete showing that the splash zone affects the durability of concrete structures more harshly than tidal and atmospheric zones. Prachasaree *et al*. (2017) have studied the causes of deterioration of highway bridges exposed to the tropical marine environment along the southern coastline of Thailand; Exposure to tropical marine environment may cause very early initiation of reinforcement corrosion at 6 years of service. Shetty *et al*. (2015) have observed the detrimental effect of different levels of corrosion on bond behaviour in steel reinforced concrete.

In the mid-nineties, Neville (1995) has reported an interesting overview on chloride attack of reinforced concrete and explained the mechanism of corrosion of steel in concrete. He has established the profile of the propagation of salts towards the reinforcing steel under alternating wetting and drying. The profile is characterised by a plot of chloride content versus distance from surface of the concrete steel cover to the rebar.

In the beginning of the twenty first century, Chen and Mahadevan (Chen and Mahadevan 2008) have developed an integrated a finite element methodology to assess the chloride-induced degradation of reinforced concrete structures. They have reported a good overview on various empirical and numerical models; Tuutti (1982), Cady and Weyers (1983), Bazant (1979), Morinaga (1988), Liu and Weyers (1998) to closely track the three stages of the corrosion process. As the first stage concerns corrosion initiation because of chloride penetration a modified form of Fick's law (Fick 1855) is applied. In the second and third stage, a reinforcement corrosion and rust expansion model based Faraday's law have been proposed. However, they have pointed out that because of uncertainties associated the structure, the materials, environment and the degradation process probabilistic approach should be used for realistic results. Nowadays, it is admitted that huge uncertainty exists in the corrosion process. This is supported by a recent work reported by Ma *et al*. (2019) that have proposed a critical region method to predict the fatigue life of notched steel wires used in bridges. Their method can be performed to perform and simulate the effects of corrosion pit morphologies on the performance of steel wires which depends on the natural environment conditions particularly the corrosion process that can be influenced by many factors such as corrosion locations and the number of corrosion pits, exist in natural corrosion process. Therefore they have suggested that a probabilistic inference method may be a rational way to represent these uncertainties.

Over the last decade, reliability methods have been widely used in assessing the lifetime of corroded steel in buried or covered structures. In a recent paper, Zhang (2018) has presented a durability reliability analysis of reinforced concrete structures subject to the action of marine chloride. He has pointed out that most of the reliability investigations have been focused on new structures (Sarveswaran *et al*. 1998, Choi and Seo 2009, Zhang *et al*. 2010, Shetty 2015) using imprecise probability theory and little have applied the purely probabilistic method in which the uncertainties are modelled as random variables. Baji *et al*. (2016) pointed out the lack of research conducted regarding the probabilistic aspects of inelastic RC deformation and ductility and proposed a reliability approach based on a limit state function where the probability of failure is measured using a reliability index that integrated many sources of uncertainties. Nogueira *et al*. (2012) have proposed a simplified probabilistic method by coupling a Fick's diffusion law based on mechanical behaviour and reliability algorithms using FORM and Monte Carlo simulation to quantify the probability of corrosion start in reinforced concrete structures subjected to chloride ingress in order to obtain optimal values of concrete cover and time intervals for periodic inspection procedures.

The aim of the present work is to provide a realistic method to estimate the corrosion initiation time in reinforcing steel concrete in marine environment. The method is based on first, developing mechanical reliability models from the commonly used deterministic Fick's second law characterising the chloride diffusion in reinforced concrete, secondly, uncertainties associated to the parameters in the mechanical models are integrated trough probabilistic models and finally, a limit state function is proposed according to an expected service life of the structure. Then a reliability index β is calculated in order to sort out a relationship between the separating distances of the reinforced structure from the sea. The reliability index β will be considered as a risk based decision parameter to estimate corrosion initiation time as a function of the concrete quality, the thickness of the concrete steel cover, temperature and relative humidity. The new correlating models can be employed as a decision tool to start corrosion inspection in reinforced concrete structures.

2. Reinforced concrete reliability models

The reliability methodology for assessing lifetime of concrete reinforcing steel under chloride environment is based on first applying an engineering model that defines the behaviour of chloride ions diffusion in reinforced concrete, second associating the uncertainties to the parameters involved in the engineering model that are expressed by their probabilistic distributions, third defining a limit state function that will be used as a supporting mechanical engineering model for reliability analyses and then finally exploring the reliability results in order to provide a maintenance tool making decision.

2.1 Mechanical engineering model

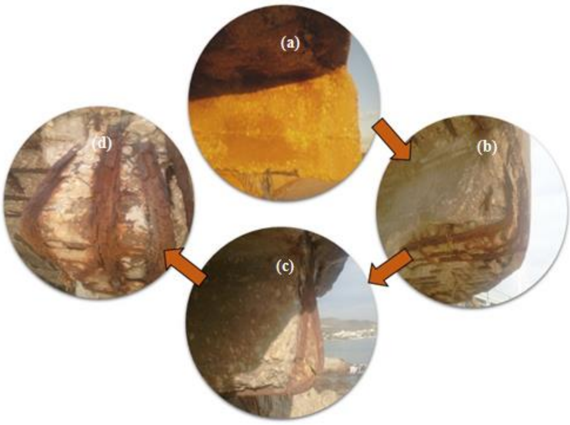


Fig. 1 Corrosion process in 15 year old reinforced concrete beam in coastal area: (a) Initial beam; (b) Concrete cover steel damage (6 year old); (c) Localised steel fracture (9 year old); (d) Area of metal loss

The mechanical engineering model is developed from the commonly used Fick's second law for determining chlorides ions ingression in reinforced concrete. In near sea water, when concrete is water saturated then rapid corrosion occurs because the transport of chloride ions is governed by pure process diffusion rather than diffusion and convection (Val and Trapper 2008).

Fig. 1 illustrates the corrosion process generated by chloride ions diffusion in 15 year old reinforced concrete structures located close to seaside.

According to Vu and stewart (2000), the chloride ions Cl^- concentration in the reinforced concrete cover can be calculated by solving Fick's second law, in pure diffusion process expressed by Eq. (1)

$$\frac{dc}{dt} = D_c \cdot \frac{\partial^2 c}{\partial x^2} \tag{1}$$

The solution demonstrated by Vu and stewart (Vu and Stewart 2000) is given in Eq. (2)

$$C(x,t) = C_s + (C_0 - C_s).erf\left(\frac{x}{2\sqrt{D_c.t}}\right) \tag{2}$$

Where,

$C(x,t)$: is the concentration of Cl^- ions at t-time t and at a x-distance from the surface of the structure.

C_s : is the concentration of chloride Cl^- ions at the surface of the concrete structure.

C_0 : is the initial concentration of chloride Cl^- ions in the concrete structure, usually equals to Zero.

D_c : is the diffusion coefficient of chloride Cl^- ions in the concrete structure.

In literature, several models have been proposed to evaluating D_c with respect to an influencing factor**.** In near sea zones, the main effective factors that have been considered are humidity, temperature and the ratio of water-cement ratio. Therefore, in the present work, the determination of D_c is oriented to the models including the three main factors as summarised in Table 1.

A deterministic application on a reinforced concrete structure like a beam or a slab would permit to obtain a diffusion profile of chlorides Cl^- ions within the reinforcing steel cover. Fig. 2, shows a geometrical model making in evidence the chloride ions diffusion process in the reinforcing steel concrete cover of a given thickness, b. Once chloride ions diffusion starts, the chloride concentration within the cover increases until a threshold concentration value C_{th}, according to (Prachasaree 2017) and (Li 2017), where the pH drops from 12 to 8 making then the steel corrosion process effective. A simple way of observing the time dependant diffusion process is to compute Eq. (2) by varying the intended time of corrosion process.

In a healthy concrete, the alkalinity of the interstitial solution (pH of about 13) contained in the pores of the concrete causes the formation of a very thin film of oxides (Fe_2O_3 and Fe_3O_4) on the surface of the rebars (Koleva *et al*. 2006). In the absence of chloride ions, the steel rebar is in the passive state with negligible corrosion rate. As chloride ions enter the porous network of concrete, they diffuse into the interstitial solution of concrete and reach the steel rebar.

When their concentration reaches a critical threshold (C_{th}) (Alonso *et al*. 2000), the morphology of the passive film that protects the armature is modified by the production of $FeCl^{-3}$ ions, then a decrease in pH saturation

Table 1 Models for diffusion coefficient of Cl^- in concrete structures

Model	Engineering expression and parameters		Effective Factor
Saetta *et al*. (1993)	$D_c = \dfrac{D_{100\%}}{1+(\frac{1-RH}{1-RH_c})^4}$ RH : is Relative Humidity $D_{100\%}$: is the diffusion factor of chloride at 100% humidity RH_c : is the critical value of relative humidity when; $D_c = \frac{1}{2} D_{100\%}$	(7)	Relative Humidity
Samson and Marchand (2007)	$D_c = D_{c,ref}.\exp[0.028(T - T_{ref})]$ $D_{c,ref}$: is the diffusion coefficient at critical reference temperature. T_{ref}: is reference temperature = 23°C. T : is Temperature	(8)	Temperature
Hobbs and Matthews (1998)	$D_c = 0.04(1166^{W_c})10^{-12}$	(9)	Water/cement ratio W_c

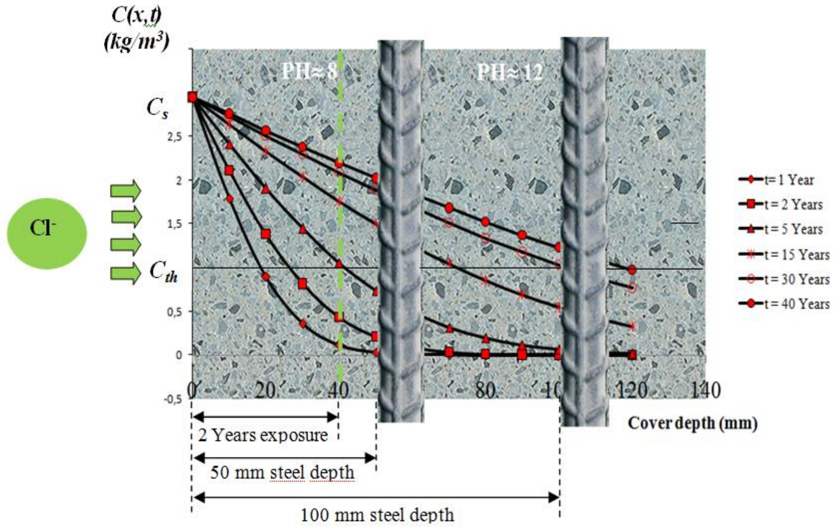


Fig. 2 Profile of chloride ions diffusion process in a reinforcing steel concrete cover as a function of exposure time for a structure located at 100m from the seaside

occurs (Koleva *et al*. 2006). These reactions lead to the destruction of the protective film generating pitting becoming small anodes and then forming electrochemical cells of active corrosion with a low pH (Prachasaree 2017). The anodic reaction is expressed by Eq. (3)

$$Fe \rightarrow Fe^{2+} + 2e^{-} \tag{3}$$

In the presence of oxygen then the chatodic reaction is expressed by Eq. (4)

$$2H_2O + O_2 + 4e^{-} \rightarrow 4OH^{-} \tag{4}$$

The ferrous ions combine with the OH^- ions to form ferrous hydroxide (ferrous hydroxide) expressed by Eq. (5)

$$Fe^{2+} + 2OH^{-} \rightarrow Fe(OH)_2 \tag{5}$$

As ferrous hydroxide $Fe(OH)_2$ is unstable in an oxygenated solution then it oxidizes into the ferric form $Fe(OH)_3$, Eq. (6)

$$4Fe(OH)_2 + 2H_2O + O_2 \rightarrow 4Fe(OH)_3 \tag{6}$$

Volume growth of corrosion products in concrete-bar interface increases the compressive force exerted on the concrete, which may causes cracking of the latter.

As a result chloride content $C(x,t)$ at a distance x from the concrete surface at time t can be plotted in order to illustrate the diffusion process as a function of intended years of corrosion initiation (see Fig. 2).

For instance, for 2 years exposure, in 100 mm depth of reinforcing steel cover, the chloride ions concentration is 40 mm deep. (C_{th}=1 kg/m^3), at the surface, $C(x,t)=C_s=2.95$ kg/m^3.

Placing a rebar at 50 mm, there is no corrosion process to starts immediately, but when increasing exposure time, then the first apparent corrosion attack would appear after 10 years as the threshold chloride concentration is reached. When placing steel rebar, then it seems that there will never be a corrosion attack suggesting that the reinforced concrete structure is safe over a period of 30 years. But in reality the behaviour is more complex that what is being expected. As a consequence, as long as chloride ions diffusion has not reached the steel bar, then corrosion will not occur. Therefore, the time of corrosion initiation is dependent of chloride diffusion and this can be expressed as time for chloride ions to cross all the concrete cover until they reach the steel rebar.

As a result, this time can be considered as the starter time for corrosion inspection of steel reinforced concrete.

Therefore, using reliability method for assessing the lifetime of reinforced concrete under aggressive chloride ions environment will bring explicit information required in making a decision for renovation or replacement of the structure.

So if the coefficient of diffusion is constant then time to corrosion initiation, T_{ini}, can be considered as the mechanical model for reliability analyses of the steel reinforced concrete lifetime. T_{ini} can be determined by solving Eq. (2) and can be expressed by Eq. (10)

$$T_{ini} = \frac{b^2}{4D_c}\left[erf^{-1}\left(1-\frac{C_{th}}{C_s}\right)\right]^{-2} \tag{10}$$

Where, C_{th} is the chloride ions concentration threshold near the steel reinforcement (kg/m^3), C_s is the chloride concentration at the surface (kg/m^3) and b is the depth or thickness of the steel concrete cover (mm), D_c is the diffusion coefficient for chloride in concrete (mm^2/year), erf^{-1} is the inverse standard error function.

Chloride concentration on the surface of reinforced concrete constructions C_s is greater when the construction is close to the sea. Eq. (10) shows that the higher C_s, the lower the corrosion initiation time T_{ini} priming time, the faster the corrosion is initiated on the reinforcing concrete steel.

2.2 Probabilistic models

In this section, the probabilistic models to be used when assessing the lifetime of reinforced concreted under

Table 2 Factors and probabilistic distribution for chloride ions diffusion models

N	Factor	Designation	Unit	Distance of the structure from the seaside	Distribution Law	Mean Value	C.V/ Standard deviation
1	Diffusion coefficient at reference conditions (Val and Trapper 2008)	$D_{c,ref}$	m^2/s		LN	6.10^{-12}	0.2
2	Diffusion coefficient at 100% of humidity (De Vera *et al*. 2007)	$D_{100\%}$	m^2/s		N	379.10^{-14}	23.10^{-14}
3	Critical Relative Humidity (De Vera *et al*. 2007)	RH_c	%		N	83,1	0,23
4	Chloride concentration at the surface (McGee 1999)	Cs	kg/m^3	b <10 m	LN	7.35	0.7
				b <100 m		2.95	0.5
				100 m<b<2840 m		1.15	0.5
5	Threshold surface chloride concentration (Enright and Frangopol 1998)	C_{th}	kg/m^3		LN	1	0.1
6	Steel concrete cover (DuraCrete 2000)	b	M		LN	0.05	0.3
7	Temperature (DuraCrete 2000)	T	°C		N	T_{mean}	0.1
8	Relative humidity (DuraCrete 2000)	RH	%		N	RH_{mean}	0.1
9	Water to Concrete ratio	Wc	%		N	0.5	$0.1Wc$

aggressive environment are presented. Uncertainties are associated to the parameters involved in the mechanical engineering model through random variables described by their probability distribution type, usually, mean and standard deviation.

Table 2 summarises the probabilistic models of the factors involved in the present investigation. Uncertainties have been associated to factors through their probabilistic distribution and their coefficient of variation. Basically where it is possible these are collected from the literature otherwise, for factors such as distance of the structure from the seaside, thickness of steel concrete cover, temperature and water cement ratio, normal probabilistic distribution been adapted with a coefficient of variation of 10% of the respective value.

2.3 Limit state function

This study aims at investigating the corrosion initiation time in reinforced concrete structures. Previous studies (Olawale *et al*. 2019, Vagelis 2013) are based on the Fick law solution given by Eq. (1) so that the concentration evolution of ion chlorides in concrete can be determined. The time taken by these ions to reach a critical concentration close to the reinforcements is the corrosion initiation time given by Eq. (10). Results of these studies have been demonstrated and validated by the authors. Nevertheless, the corrosion initiation time depends on several parameters; each parameter is subject to uncertainties. Each parameter was studied to determine its probabilistic model, see Table 2.

The probabilistic method takes into account the uncertainties related to these parameters and determines the effect of these uncertainties on the corrosion initiation time, which offers more realistic models than those provided by the deterministic methods.

The reliability method estimates the probability of reaching a limit state (In our case the limit state is the initiation of corrosion on reinforcing steel).

Consequently a limit state function $G(x)$ corresponding to a boundary between desired and undesired performance of a structure, is developed from the margin between the calculated initiation time T_{ini} from Eq. (10) and the expected time, T_{exp} extrapolated from Fig. 2.

The limit state function $G(x)$ is expressed by Eq. (11).

$$G(X) = T_{ini} - T_{\exp} \tag{11}$$

When associating uncertainties to the parameters involved in the limit state function, then specific algorithms are applied for searching the most probable failure configuration. In the present work, the software PHIMECA which can be found in (PHIMECA 2002) has been used to perform the reliability analyses. This software offers several methods for reliability calculation such as Monte Carlo simulations and First/Second Order Reliability Methods, FORM/SORM as presented by Lemaire (2013).

The margin is defined such as $G(x)>0$ indicates safety and $G(x)\leq 0$ corresponds to conventional failure. For the failure scenario, the reliability index β is defined as the minimum distance between the origin and the failure domain in the equivalent Gaussian space. The failure probability is evaluated by Eq. (12):

$$P_f = P_r[G(\leq 0)] = \Phi(-\beta) \tag{12}$$

Where, P_r is the probability operator and Φ is the cumulative Gaussian probability function.

3. Strategy of reinforced concrete reliability assessment

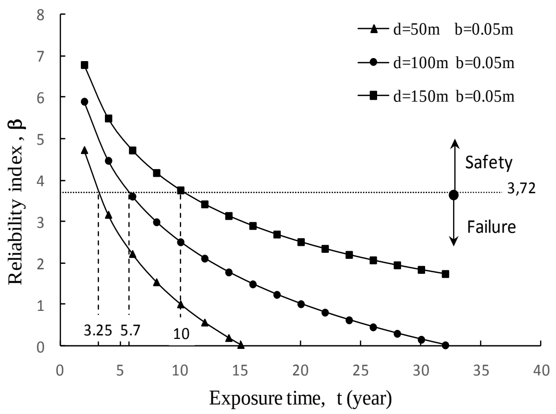


Fig. 3 Effect of time exposure to Cl^- diffusion on the reliability index β of reinforced concrete: with regards to the thickness steel concrete cover, b and the distance between the structure and sea, d

The reliability assessment is focused on the exposure time of reinforced concrete to chloride ions diffusion in concrete structures build on the seaside. The objective is to determine the initiation time, T_{ini} of corrosion in the concrete covered reinforcing steel.

The corrosion initiation time corresponds to the time to the threshold time when chloride ions concentration is reached, Fig. 2, usually C_{th}=1 kg/m^3. Then corrosion in steel rebar will start. So this is very detrimental in assessing the reinforced concrete lifetime.

Deterministic approach revealed that for a steel reinforcing cover thickness or depth of 0.1m, the time for corrosion initiation T_{ini} is 30 years.

As a consequence, the strategy adapted within the present work is to compare the reliability results expressed by the reliability index β to a reliability level of β=3.7192 corresponding to a failure probability level of 10^{-4} admitted in general engineering structures. This suggests that when $\beta \geq 3.7192$ then the structure is safe and when $\beta < 3.7192$ then failure occurs. Failure in the present case is attributed to the opportunity for corrosion to take place in steel. The reinforced concrete structure continues to be effective but it is not reliable as failure is unpredictable and depends on how much corrosion has progressed in steel rebar. Hence preventing steel rebar from corrosion means increasing lifetime of the reinforced concrete structure.

The first stage of the lifetime is dependent on the time of chloride concentration to reach its threshold value corresponding to the initiation time of corrosion, T_{ini}.

Five main factors affecting of the corrosion initiation time have been considered in the present work: i) depth or thickness of the steel concrete cover, b; ii) the distance of the concrete structure to the seaside, d; iii) temperature, T;

iv) the relative humidity, RH and v) water-cement ratio, Wc.

When these factors meet together, the aggressiveness of the environment is maximal.

3.1 Steel concrete cover, location and time exposure

Regarding the location of the structure towards the

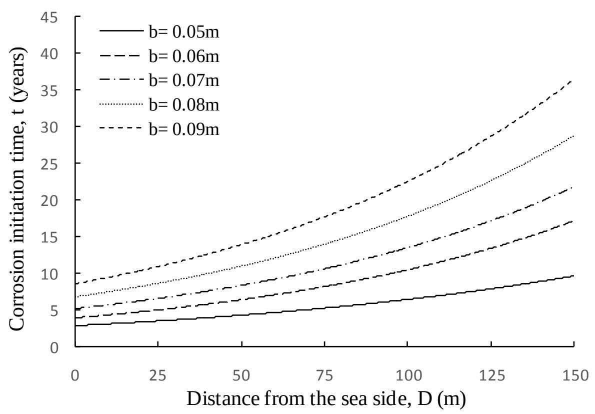


Fig 4 Corrosion initiation time as a function of structure distance from the seaside for different steel concrete cover

seaside, the reliability of the structure is dependent on the exposure time of the reinforced concrete to chloride ions diffusion and this is expressed through the evolution of reliability index β as a function of the exposure time, Fig. 3. The reliability index β curve decreases as the exposure time increases passing from a safe domain to failure domain when β reaches the allowable level of 3.7192. The latter is dependent on the location of the structure from the seaside. Far is the structure from the seaside higher is time to exposure. For a structure with a steel cover thickness of 0.05m, the time to exposure increases from 3.25 to 5.7 and 10 years when the distance from the seaside of the structure is relatively, 9, 99 and 150 m. The exposure time corresponding to the allowable level of reliability index β is a precious indictor for corrosion initiation time in the reinforced concrete structure. Therefore corrosion initiation time as a function of the structure distance from the seaside can be plotted as illustrated in Fig. 4.

As expected when the steel cover is small corrosion initiation time is small. For a steel cover of 0.05 m, when the concrete structure is adjacent to the seaside, then inspection can start very soon in the next few 2 to 3 years. As the steel cover thickness increases then corrosion initiation time increases up to 9 years for a steel cover thickness of 0.09. The fitting curves following an exponential engineering model, Eq. (13) show that corrosion initiation time remains almost the same when the structure is built far to 40m from the seaside.

$$T_{ini}(b) = A_b.e^{n_1.d} \tag{13}$$

Where,

$T_{ini(b)}$ is the corrosion initiation time depending on the steel cover depth, b.

A_b and n_1 are exponential equation parameters.

Beyond 40m, the corrosion initiation time increases and is related to the exponential parameters of Eq. (10) that are dependent on the distance of the structure from the seaside and the steel cover thickness.

Theses parameters as function of steel cover thickness are expressed as

$$A_b = 798b^{1.8883}, n_1 = 0.0093 \tag{14}$$

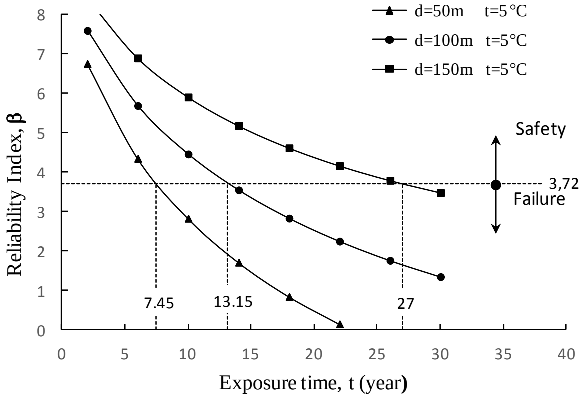


Fig. 5 Effect of time exposure to Cl- diffusion on the reliability index β of reinforced concrete: with regards to temperature, T and the distance between the structure and sea, d

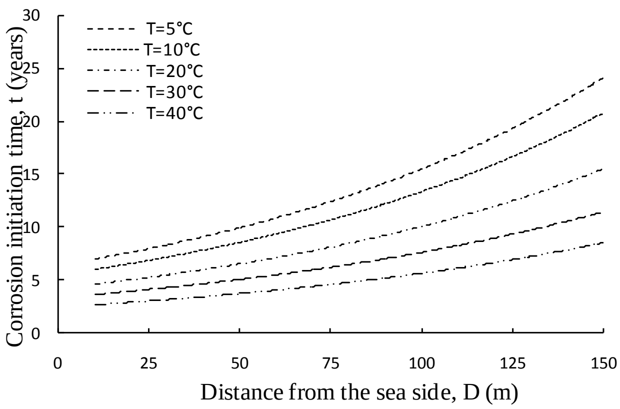


Fig. 6 Corrosion inspection time as a function of structure distance from the seaside for different ambient temperatures

3.2 Temperature, location and time exposure

Ambient temperature always fluctuates within a specific range according to the seasons and the region. For instance in south Mediterranean sea temperature ranges from 0° to 42°C as in cold season, night temperatures are around 5°C during almost 3 months and in hot seasons, day ambient temperatures are around 35°C during 3 months. Fluctuation in temperature is very significant in the diffusion of chloride ions in concrete steel cover leading to corrosion initiation reinforcing steel. Therefore reliability analyses are carried out to find out the effect of ambient temperature on the chloride ions diffusion process in reinforced concrete steel. Fig. 5 illustrates the effect of exposure time to chloride ions diffusion in concrete structure at constant temperature and at different distances of the structure from the seaside. In the latter case where the steel cover thickness b is 0.1 m and ambient temperature is 5°C, structures at 50m distance from the seaside, revealed that the reliability index β decreases drastically showing that the admitted reliability index value of 3.7192 is reached within 7.45 years. Increasing the distance of location of the structure to 99 m and 150 m from the seaside resulted in higher exposure time respectively 13.5 and 27 years. Increasing ambient temperature by from 5°C to 40°C resulted in higher exposure time for corrosion initiation in reinforcing steel to occur. So the time at which the admitted reliability index is obtained, can be considered as the corrosion initiation time. Fig. 6 shows the relative plot of corrosion initiation time as a function of distance of structure from the sea. An exponential engineering law characterises the behaviour of the corresponding curve, and the corresponding corrosion initiation time depending on the temperature, $T_{ini(T)}$ is expressed as

$$T_{ini}(T) = A_T.e^{n_2.d} \quad (15)$$

Where,

A_T and n_2 are exponential equation parameters.
The corresponding parameters are

$$A_T = 7.307e^{-0.026T}, n_2 = 0.0085 \quad (16)$$

3.3 Relative humidity, location and time exposure

Fig. 6 is an important feature in estimating chloride ions diffusion particularly in equatorial regions where ambient temperature ranges from 26 to 28°C and rainfall is high most of the year. For structures built at 150 m, even when the steel cover is 0.1m, exposure time to corrosion initiation falls to 17 years suggesting that the inspection time of the structure should start earlier than that expected with deterministic data. Moreover the relative humidity has great effect on the inspection time of reinforced concrete structure.

Fig. 7 shows the effect of time exposure to Cl- diffusion on the reliability index β of reinforced concrete with respect to relative humidity, R_H and the distance between the structure and seaside, d. There should be great consideration of the location of the structure towards the relative humidity. Far from the seaside is located the structure less is the chloride ions diffusion if the concrete structure. For instance when the relative humidity RH is 0.55%, a structure built at 150 m away from the seaside shows long time of chloride ions diffusion. At short distance the reliability index decreases rapidly. The respective values of the admissible reliability index are reached at 23, 43 and 100 years for a structure located at 9, 99 and 150 m.

The corrosion initiation time as a function of relative humidity and structure location can be derived from the fitting curve of the plots given in Fig. 8 and written as given in Eq. (17)

$$T_{ini}(RH) = A_{RH}.e^{n_3.d} \quad (17)$$

Where,

$T_{ini}(RH)$ is the corrosion initiation time depending on relative humidity.
A_{RH} and n_3 are exponential equation parameters expressed as

$$A_{RH} = 10^7.RH^{-3.287}, n_3 = 0.011 \quad (18)$$

3.4 Water-cement ratio, location and time exposure

The chloride ions diffusion in reinforced concrete

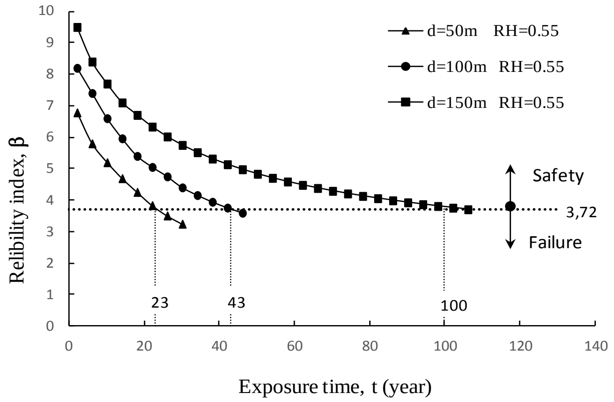


Fig. 7 Effect of time exposure to Cl^- diffusion on the reliability index β of reinforced concrete with relative humidity, *RH* and the distance between the structure and sea, *d*

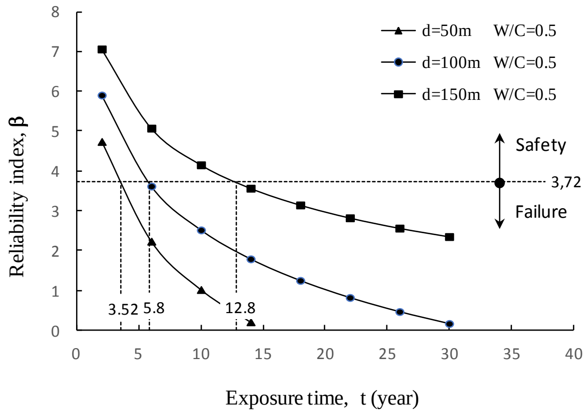


Fig. 9 Effect of time exposure to Cl^- diffusion on the reliability index β of reinforced concrete: with regards to the water-cement ratio, W_c and the distance between the structure and sea, *d*

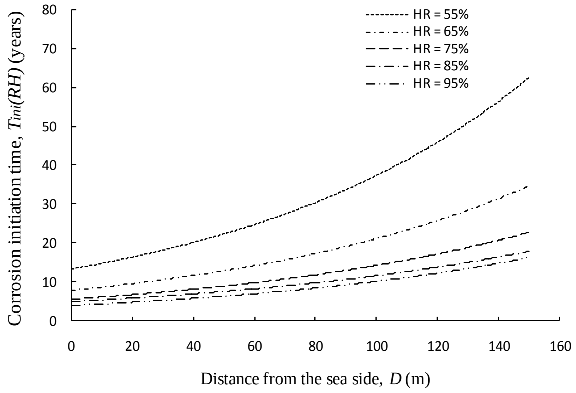


Fig. 8 Corrosion initiation time as a function of structure distance from the seaside for different values of relative humidity

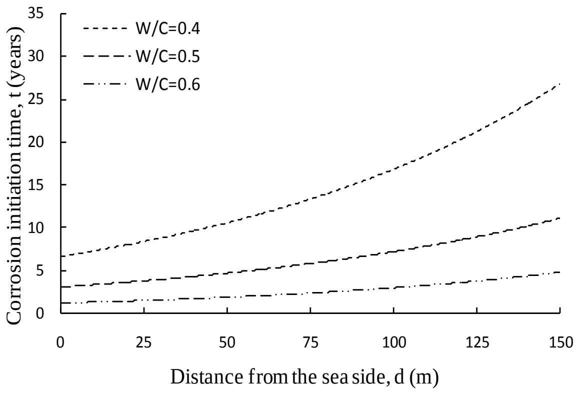


Fig. 10 Corrosion initiation time as a function of structure distance from the seaside for different water cement ratio

structure is very dependent on the water-cement ratio, W_c. Fig. 9 illustrates the effect of time exposure to Cl- diffusion on the reliability index β of reinforced concrete. Plots are given with respect to water-cement ratio, W_c and to the distance between the structure and seaside, *d*. In fact, the reliability index β falls drastically when the structure is built neighbouring the seaside.

For a W_c concentration of 0.5, the admissible reliability index is soon reached in at a distance of 9 m in 3.52 years as the distance gets longer, the exposure time increases to 5.8 and 12.8 years respectively up to 99 and 150 m.

When varying the water-cement ratio, a plot of the corrosion initiation as a function of the location of the structure towards the seaside, permits to deduce from the fitting curves (see Fig. 10) an exponential engineering model that can be expressed by Eq. (19)

$$T_{ini}(Wc) = A_{wc}.e^{n_4.d} \tag{19}$$

Where,

$T_{ini}(Wc)$ is the corrosion initiation time depending on water-cement ratio.

A_{WC} and n_4 are exponential equation parameters.

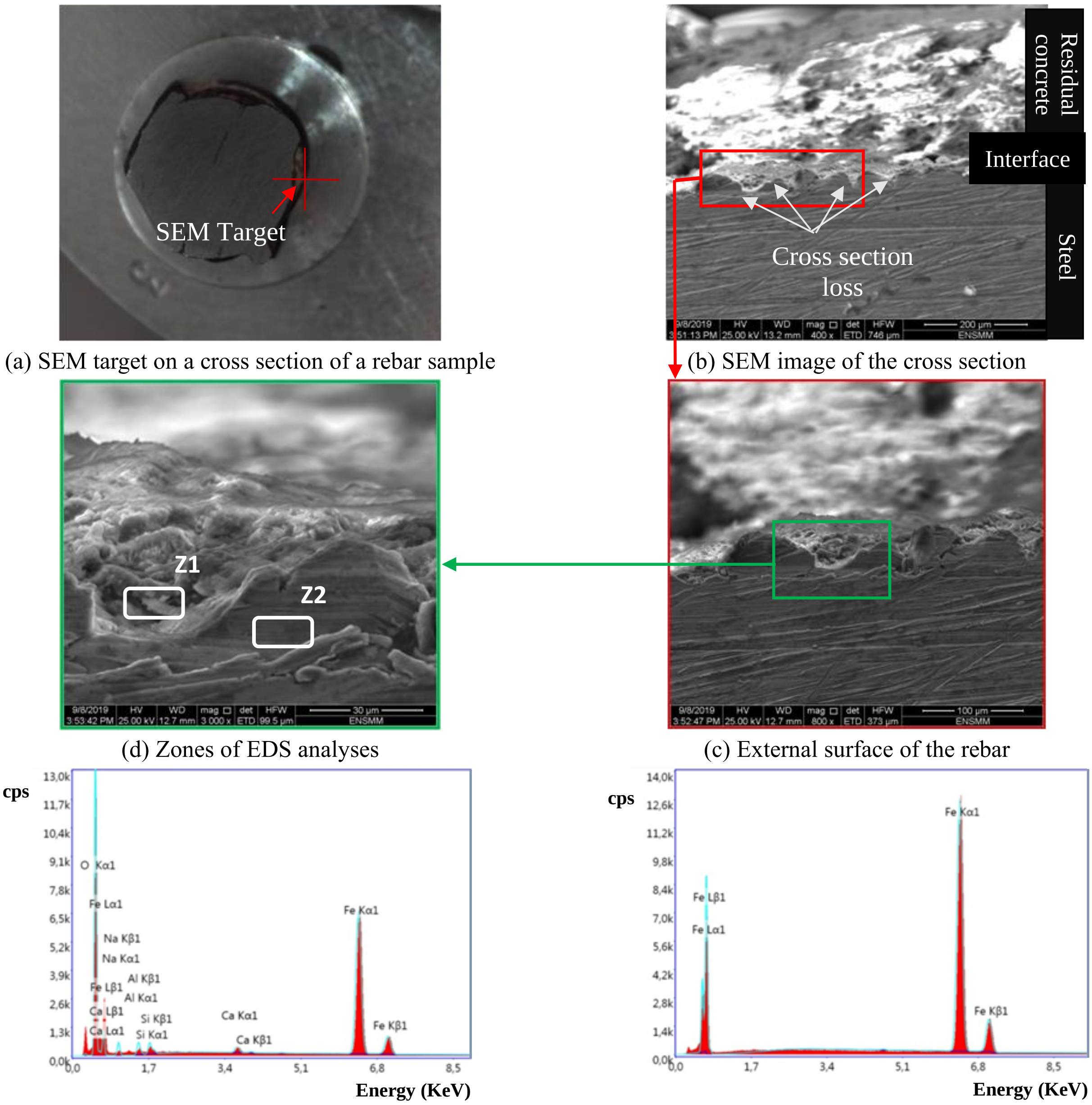
$$A_{Wc} = 0.1266.W_c^{-4.374}, n_4 = 0.0093 \tag{20}$$

The best performance is observed for a structure located at 150 m from the seaside when water-cement ratio W_c is 0.4 and an ambient temperature of 20°C (see Fig. 10).

4. SEM and EDS observations

One of the main features of the present investigation is to show that reliability approach is more realistic than the deterministic approach in estimating corrosion time initiation. In fact according to Fick's low for a case of a reinforcing concrete beam with a steel cover of 50mm and located at 50 meters from a seaside, corrosion initiation time would be 10 years. Comparing to the reliability results, the corrosion initiation time is almost 2 times lower than that expected by the determinist approach. In fact the corrosion initiation time is depending on the chloride diffusion process that is difficult to follow with regards the controlling parameters and huge uncertainties in the breakdown of the oxide film.

In order to have a comprehensive understanding of the corrosion estimating time, SEM and EDS (energy-dispersive *x*-ray spectrometers) observations on a 6 years old reinforcing concrete steel have been carried out. A portion of a 12 mm diameter rebar with a 50 mm concrete



(a) SEM target on a cross section of a rebar sample (b) SEM image of the cross section

(d) Zones of EDS analyses (c) External surface of the rebar

(f) EDS spectra of corroded zone (Z1) (e) EDS spectra of clean zone (Z2)

Fig. 11 SEM and EDS analyses of steel bar

Table 3 Chemical composition of analyzed zones

Zone	Element	Weight%	Atomic%
Corrosion Zone (S1)	O K	59.32	78.43
	Na K	7.63	7.02
	Al K	2.97	2.33
	Si K	1.9	1.43
	Ca K	0.78	0.41
	Fe K	27.4	10.38
	Totals %	100	100
Steel* (S2)	Fe K	100	100

*The composition consists of 99% of iron and 0.22 to 0.32 %C and small percentage of alloying elements (Si, Mn, S and P)

cover and located at 50 meters from the sea side has been extracted. Then a sample has been prepared to investigate the outer surface on the cross section as shown in Fig. 11(a).

The steel concrete interface is presented in Fig. 11(b) that illustrates the corroded surface around the external surface of the rebar. The corroded surface is characterized by cross section lost with different areas as it can be seen in Fig. 11(c). EDS analyses have been conducted in damage zone Z1 and in the steel zone Z2 to determine the chemical composition. Figs. 11(e)-(f) shows the respective chemical composition characterized by the presence of some chemical elements such as O, Na, Al, Si, Ca, in addition to steel. Table 3 presents the various chemical elements in weight % and in atomic % in the analyzed zones. Relatively, the clean zone is mainly composed of Fe (metallic substrate).

The present observations are interesting since they show that corrosion is not uniform around a rebar, local loss of cross-section indicates that the steel undergoes pitting corrosion according to Zhu and François (2013). Therefore the deterministic approach of Fick's law gives global estimation of the corrosion initiation time. Meanwhile the reliability approach is more realistic. For instance when considering the effect of the distance from the sea side, a structure located at 50 meters, with a steel cover of 50mm, the initiation time is 4.8 years (see Fig. 4) rather than 10 years given by Fick's low.

5. Conclusions

A contribution in developing models for determining corrosion initiation time in steel reinforced concrete structures located close to the seaside has been proposed through a reliability approach. The corrosion initiation time in steel reinforced concrete corresponded to the time when the chloride ions diffusion process within the steel concrete cover reaches the chloride concentration value. Reliability analyses have been achieved using FORM/SORM method that suggests a limit state function corresponding to a boundary between desired and undesired performance of a structure developed from the margin between the calculated initiation time T_{ini} and the exposure time for corrosion to occur, $T_{exp.}$ The uncertainties within the mechanical models for reliability analyses have been associated to their parameters through probabilistic laws. Fick's second law has permitted to develop engineering models to estimate the starting time of corrosion inspection in steel reinforced concrete structure as a function of influencing factors such as distance of the structure from the seaside, thickness of steel concrete cover, ambient temperature, relative humidity and water-cement ratio. Four models have been proposed in the form of exponential equation expressing corrosion initiation time (T_{ini}) as a function of the distance between the concrete structure and seaside. The parameters of the exponential laws are expressed relatively with respect to the influencing factors.

The main emerging results show that as expected, far is located the structure from the seaside longer is time for corrosion to occur. Reliability analyses are more realistic in estimating the corrosion initiation time that is well below of that given by deterministic approach. Moreover, when combining the four proposed models there should be a better appreciation in deciding when to start corrosion inspection in steel reinforcing concrete which is planned as a complementary future work. SEM observations have revealed that the corrosion damage dimensions are not uniform around the steel rebar suggesting that the corrosion pits are random. EDS analyses have shown that chemical composition on the outer surface of the steel bar after corrosion, the presence of an oxide film with 78.43% of O and 10.38% of Fe. Therefore deeper investigation involving the corrosion damage parameters is required in future work.

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