

## CHLORIDE-INDUCED CORROSION OF RC STRUCTURES

J. Sobhani\* and A.A. Ramezaniapour

Department of Civil and Environmental Engineering, Amir Kabir University of Technology,  
Tehran, Iran

### ABSTRACT

This paper describes the service life of the reinforced concrete (RC) structures in chloride laden environments. Presence of chloride ions is the most important causes of reinforcing steel corrosion and the subsequent failure of the whole structure. In this paper, the rate of chloride transport in the concrete is defined using Fick's second law of diffusion. Various stages of corrosion process are defined base on the available models. A stochastic model is introduced for RC structures corrosion initiation period and cover cracking time period. It is concluded that a "Lognormal" distribution might best describe the initiation period of corrosion. Moreover, it is found that the "Lognormal" and "Normal" distributions could define the cracking time of RC structures elements appropriately.

**Keywords:** Corrosion, chloride, concrete, service life, cracking, stochastic modeling

### 1. INTRODUCTION

Service life of Reinforced Concrete (RC) structures as a period of time after placement during which all properties exceed the minimum acceptable values when routinely maintained [1]. In the literature, three types of service life have been defined [1]. According to the ACI, three types of service life definitions are

- Technical Service life,
- Functional service life, and
- Economic service life.

In this paper the first definition has been used. Technical service life is the time in service until a defined unacceptable sate is reached, such as spalling of concrete, safety level below acceptable, or failure of elements. Base on Clifton [2], there are five approaches to predict the service life of construction materials, viz.:

- Estimate based on experience;
- Deductions from the performance of similar materials;
- Accelerated testing;
- Mathematical modeling based on the chemistry and physics of degradation

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\* Email-address of the corresponding author: ja\_sobhani@yahoo.com (J. Sobhani)

processes; and

- The application of probability concepts

Methodologies are being developed that predict the service life of existing concrete structures. To predict the service life of existing concrete structures, information is required on the present condition of concrete, rate of degradation, and definition of the end-of-life [2]. In this paper, the fourth and fifth methods are used. For the case of the present paper, the initiation period of corrosion is determined based on corrosion diffusion model. Moreover, the corrosion induced cracking time of concrete cover is introduced and proposed as unserviceability criteria of RC structures.

## 2. LIFE OF RC STRUCTURES

Chloride-induced steel corrosion is one of the major worldwide deterioration mechanisms for RC structures. There are several ways to predict the service life RC structures in chloride laden environments. Tuutti developed a model for predicting the service life of reinforcing steel [2]. The model is based on the chemical process of corrosion sequences as schematically shown in Figure 1(a). Moreover, Liu and Weyers [3] developed a performance-based service life model that is shown in Figure 1(b). The prime difference between the Tuutti's model, and the model proposed by Liu and Weyers [3] in Figure 1, is that the latter employs performance criteria used by structural engineers, such as the serviceability and strength limit states whereas the former uses degree of corrosion to indicate the service life. In Figure 1, the various stages of service life are indicated by black-filled circles in both Tuutti's and Liu and Weyers models. Although the degree of corrosion is closely related to structural capacity deterioration, a conversion from degree of corrosion to structural deterioration is not straightforward as observed by a number of researchers [4].

The meaning of service life model is that the state of corrosion of steel in concrete may be expected to change as a function of time [5]. Corrosion process has three distinct stages, namely; depassivation, propagation, and final state [5], [1], as shown in Figure 1. Depassivation is the loss of oxide (passive) layer over the rebar, which is initially formed due to the high alkalinity of concrete. The process of depassivation takes an initiation period,  $T_i$ , which is the time from completion of the new built structures to the time of corrosion initiation in the structure (depassivation) [1,5].

The second life cycle is the time period from the initiation of corrosion to corrosion induced unserviceability of the structure, denoted as  $T_s$ , alternatively this period is denoted as propagation period. During the propagation period, the rebar corrosion is usually assumed to be in a steady state, as indicated by a straight line [5] in Figure 1. The unserviceability may be defined in many ways, such as the corrosion induced longitudinal cracking ( $T_{cr}$ ) concrete spalling, or a more design criterion related definition; such as deflection [4]. Different definitions of unserviceability can divide the interval ( $T_i$ ,  $T_s$ ) into several sub-life cycles. The third life cycle is the time period from loss of serviceability to ultimate failure of the structure (loss of safety), denoted as  $T_f$ . Again, failure can occur in many modes, such as loss of flexural strength and shear strength. All these are related to structural performance [4].

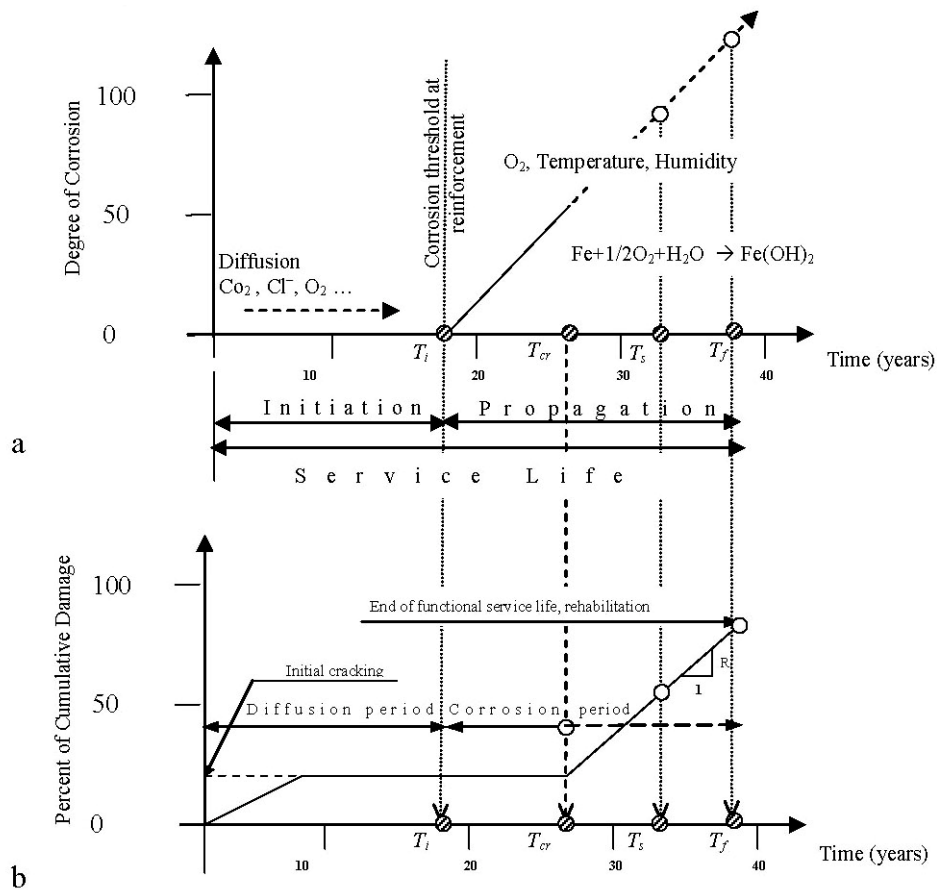


Figure 1. Schematic of conceptual model for corrosion of steel reinforcement in concrete with some improvements; (a) Tutti and (b) Liu-Weyers

### 3. CORROSION INITIATION PERIOD

It is assumed that the time to corrosion initiation, is mainly controlled by chloride ions diffusion, and governed by Fick's second law of diffusion [2]

$$\frac{\partial C(x,t)}{\partial t} = -D_c \frac{\partial^2 C(x,t)}{\partial x^2} \tag{1}$$

Where,  $D_c$  is the diffusion coefficient,  $x$  is distance (depth), and  $t$  is time. In the above equation, the effect of chloride binding is ignored. Clifton (1993) used the concepts of Tuutti's model to predict the effects of chloride ion diffusion coefficient and depth of cover on the length of initiation period [2]. Clifton derived a closed form solution for Eq. (1)

$$\frac{C}{C_s}(x,t) = \sum_{n=0}^{\infty} (-1)^n \left\{ \operatorname{erf} \left[ \frac{(2n+1)-y}{2\sqrt{r}} \right] + \operatorname{erf} \left[ \frac{(2n+1)+y}{2\sqrt{r}} \right] \right\} \quad (2)$$

Where,  $C_s$  is the concentration of chloride ions at the outside surface of concrete, and  $C(x,t)$  is the chloride concentration at depth  $x$  and time  $t$ .  $\operatorname{erf}$  is error function,  $y=(h-x)/h$ ,  $r= D_c t/h^2$ ,  $t$  is the time,  $x$  is depth, and  $h$  is the thickness of concrete element. However, in the present case, only the  $n=0$  term of Eq. (8) need to be considered (the higher order terms have insignificant contribution to summation), so it reduced to [2]:

$$\frac{C(x,t)}{C_s} = 1 - \operatorname{erf} \left( \frac{1-y}{2\sqrt{r}} \right) \quad (3)$$

Substituting values of  $y$ ,  $r$ , in Eq. (3) gives more applicable equation:

$$C(x,t) = C_s \left( 1 - \operatorname{erf} \left[ \frac{x}{2\sqrt{D_c t}} \right] \right) \quad (4)$$

Inverse action on Eq. (4), gives the chloride transport time  $t$  into the concrete element:

$$t = \frac{x^2}{4D_c} \left[ \operatorname{erf}^{-1} \left( \frac{C_s - C(x,t)}{C(x,t)} \right) \right]^2 \quad (5)$$

Where,  $\operatorname{erfc}$  is the complementary error function. Assuming a concrete element (such as Bridge deck) with a concrete cover thickness of  $X_c$  as shown in Figure 2, the initiation period of chloride diffusion determined when  $C(x,t)$  at rebar level reaches a threshold concentration  $C_t$ . Hence if  $x=X_c$ , and  $C(x,t)=C_t$  then initial period derived as follows:

$$T_i = \frac{X_c^2}{4D} \left[ \operatorname{erf}^{-1} \left( \frac{C_s - C_t}{C_s} \right) \right]^2 \quad (6)$$

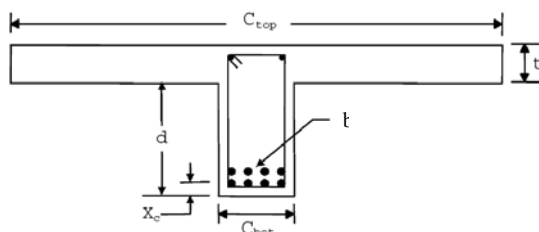


Figure 2. Typical cross section of RC bridges deck

#### 4. CORROSION-INDUCED TIME TO CRACKING

Liu and Weyers (1998) established an analytical model to predict the time to cracking of concrete due to reinforcing bar corrosion [3]. Corrosion of steel embedded in the concrete leads to cracking because of formation of expansive corrosion products. The corrosion products may be expressed as  $m\text{Fe}(\text{OH})_2n\text{Fe}(\text{OH})_3p\text{H}_2\text{O}$ , where the values of  $m$ ,  $n$ , and  $p$  vary considerably, depending on condition such as pH of the solution, the oxygen supply, and moisture content. Obviously, different kinds of corrosion products may have different densities and volume expansions. Figure 3 shows relative volumes of iron and its corrosion reaction products [3].

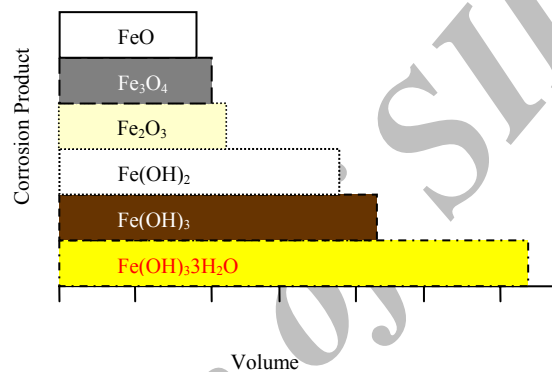


Figure 3. Relative volumes of iron and its corrosion reaction products ( $\text{in}^3=16,387\text{mm}^3$ ) [3].

Table 1 shows ratio of molecular weight of iron to the molecular weight of the corrosion products and ratio of volume of expansive corrosion products to the volume of iron consumed in the corrosion process [6].

Table 1. Correlation between ' $\alpha$ ' and ' $\alpha 1$ ' for various corrosion products [6]

	Name of corrosion products					
	FeO	Fe <sub>3</sub> O <sub>4</sub>	Fe <sub>2</sub> O <sub>3</sub>	Fe(OH) <sub>2</sub>	Fe(OH) <sub>3</sub>	Fe(OH) <sub>3</sub> ·3H <sub>2</sub> O
' $\alpha$ '	0.777	0.724	0.699	0.622	0.523	0.347
' $\alpha 1$ '	1.80	2.00	2.20	3.75	4.20	6.40

##### 4.1 Corrosion Cracking Model

Liu and Weyers [3], Pantazopoulou and Papoulia [7], and Bhargava et al. [6], modeled the cover cracking due to corrosion. To simplicity purposes, modeling restricted to stresses resulting from expansion of corrosion products. It is assumed that uniform corrosion

products formed around the steel surface. Figure 4 presents a schematic diagram of the basic model for the corrosion cracking process. Three stages are considered in the corrosion cracking model; 1-Free expansion, 2-Stress initiation, and 3-Cracking.

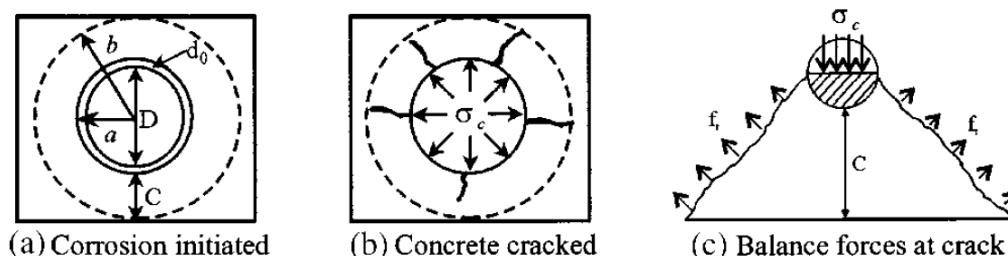


Figure 4. Schematic of the basic model for the corrosion cracking process [4]

Free expansion will take place immediately as passive film is broken by chloride ions. Iron at anode is oxidized to form ferrous ions that can react with hydroxyl ions to produce ferrous hydroxide and then can be further converted to hydrate ferric oxide. These are corrosion products which occupy more volume than iron by itself. It is assumed that there is a porous zone around the steel-concrete interface. This porous zone is caused by the transition from cement paste to steel, entrapped or entrained air voids, and corrosion products diffusing into the capillary voids in cement paste. Actually, the volume of the porous zone is affected by surface area of reinforcement, water to cement ratio, degree of consolidation and hydration of concrete. As corrosion takes place and goes on, the porous zone will gradually fill with corrosion products. When the total amount of corrosion products  $W_T$  is less than the amount of corrosion products required to fill the porous zone around steel-concrete interface,  $W_p$ , the formation of corrosion products in this stage will not create any stress on surrounding concrete. But as  $W_T$  exceeds  $W_p$ , the formation of corrosion products starts to create radial stresses on the surrounding concrete. This stage of corrosion is the stress initiation stage. With continuation of the corrosion process and producing more rust (as corrosion products), the amount of rust exceeds the critical amount of corrosion products  $W_{crit}$  which induces the critical radial stresses on the steel-concrete interface. At this stage (cracking) the radial stresses will exceed the tensile strength of concrete cover and cause the cover to crack. It is obvious that the amount of critical corrosion products depends on the concrete and reinforcing steel quality, and the concrete cover depth. The amount of corrosion depends on their volume by the following famous physical relationship

$$W_p = V_p \cdot \rho_{rust} \quad (7)$$

Where,  $\rho_{rust}$  is the density of corrosion products and  $V_p$  is the total volume of steel-concrete interface porous media. As shown in Figure 4, let denote  $d_0$  as the thickness of porous media, and  $D$  is the reinforcement steel diameter, thus when the amount of corrosion products reaches the  $W_p$ , the increased diameter of reinforcement will be  $D+2d_0$ . Since  $d_0$  is very smaller than reinforcement diameter  $D$ ,  $W_p$  can be estimated from the following equation.

$$W_{P=\pi} \rho_{rust} d_0 D \quad (8)$$

To estimate the critical amount of corrosion products, it is divided into two parts:  $W_P$  as described before and  $W_S$ , the amount of corrosion products that generate the critical tensile stress. Because the thickness of corrosion products needed to generate radial stress,  $d_S$  is very smaller than diameter of reinforcing steel for a unit length of bar,  $W_S$  can be determined from following Eq. [3]:

$$W_S = \rho_{rust} \left( \pi(D + 2d_0)d_S + \frac{W_{st}}{\rho_{st}} \right) \quad (9)$$

Where  $W_{st} = \alpha W_{crit}$ , and  $\rho_{st}$  is the density of steel. (Note that the value of  $\alpha$  is obtained from Table 1). Ignoring the small amount of  $2d_0d_S$ , the above equation will be as follows [3]:

$$W_{crit} = \rho_{rust} \left( \pi(d_S + d_0)D + \frac{W_{st}}{\rho_{st}} \right) \quad (10)$$

From the theory of elasticity, and assuming the thick-wall cylinder with inner and outer radii of  $a = (D + 2d_0) / 2$  and  $b = X_c + (D + 2d_0) / 2$ , as shown in Figure 4 the radial stress,  $\sigma_r$ , can be expressed as [3], [4]:

$$\sigma_r = \frac{2E_{ef}d_s}{(D + 2d_0) \left( \frac{b^2 + a^2}{b^2 - a^2} + \nu_c \right)} \quad (11)$$

Where  $\nu_c$  is the concrete Poisson ratio,  $E_{ef}$  is effective elastic modulus of concrete that is equal to  $E_c / (1 + \varphi_{cr})$  in which  $\varphi_{cr}$  is the concrete creep coefficient. Because the elastic modulus of steel is about seven times greater than that of concrete, it is considered that the radial displacement of the concrete under radial stress  $\sigma_r$ , is the thickness of corrosion products generating the pressure on concrete. It is found that the minimum stress required to cause cracking of cover concrete equals the tensile strength of concrete [3]:

$$\sigma_t = \frac{2X_c f'_t}{D + 2d_0} \quad (12)$$

Where  $f'_t$  is the tensile strength of concrete. Combination of Eqs. (11) and (12), gives

$$d_S = \frac{X_c f'_t}{E_{ef}} \left( \frac{a^2 + b^2}{b^2 - a^2} + \nu_c \right) \quad (13)$$

Therefore the critical amount of corrosion products needed to induce cracking of the cover will be determined from Eqs. (10) and (13), as follows [3]:

$$W_{crit} = \rho_{rust} \left( \pi \left[ \frac{Cf'_t}{E_{ef}} \left( \frac{a^2 + b^2}{b^2 - a^2} + \nu_c \right) + d_0 \right] D + \frac{W_{st}}{\rho_{st}} \right) \quad (14)$$

#### 4.1.1 Growth of expansive corrosion products

The growth of expansive corrosion products is given by following equation [3]:

$$dW_{rust} / dt = k_p / W_{rust} \quad (15)$$

Where  $W_{rust}$  is the amount of rust products (mg/mm),  $t$  is the corrosion process time (year), and  $k_p$  is related to rate of metal loss in (kg<sup>2</sup>/m<sup>2</sup>t) and expressed as follows [6]:

$$k_p = \pi \cdot A_p \cdot D \cdot i_{cor} \quad (16)$$

Where  $D$  is the reinforcing steel diameter,  $i_{cor}$  is the annual mean corrosion rate (mA/cm<sup>2</sup>) and the common value for  $A_p$  is [3]

$$A_p = 0.105(1/\alpha) \quad (17)$$

The amount of rust products can be obtained by integrating the Eq. (15):

$$W_{rust}^2 = 2 \int_0^t k_p dt \quad (18)$$

By knowing the corrosion rate, the amount of rust products for certain period of corrosion can be estimated [3].

#### 4.1.2 Corrosion Induce Cracking

For a constant corrosion rate, the time to cover cracking,  $T_{cr}$ , can be determined when  $W_{rust} = W_{crit}$  as follows [3]:

$$T_{cr} = \frac{W_{crit}^2}{2k_p} \quad (19)$$

In the case that corrosion rate vary with time, the time to cover cracking,  $T_{cr}$ , can be estimated from the following expression [4]:

$$W_{crit} = \left( \int_0^t A_p \pi D i_{cor}(t) dt \right)^{1/2} \quad (20)$$



5. NUMERICAL RESULTS

5.1 Model Validation

Figure 5 shows the effects of cover depth and diffusion coefficient of the corrosion initiation time. Moreover, Figure 6 demonstrates the effect of basic variables on the corrosion-induced cracking of the RC structures.

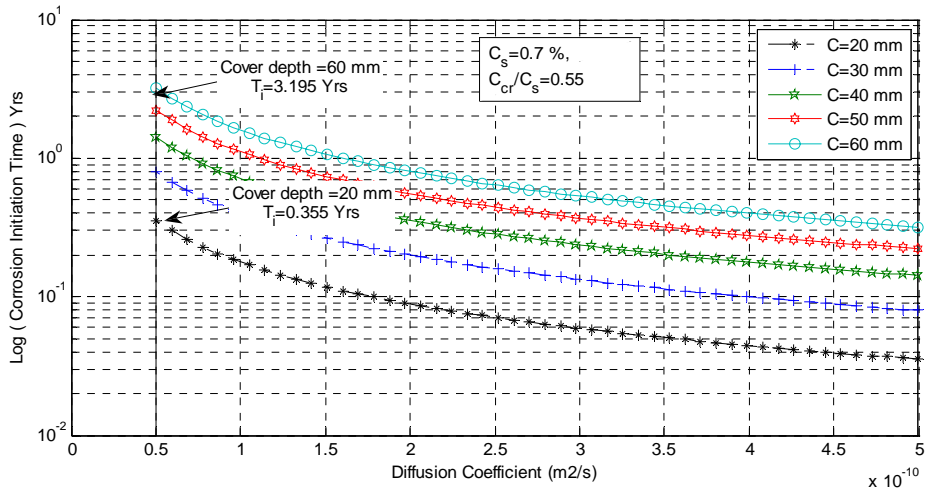


Figure 5. Corrosion initiation time ( $C=X_c$ )

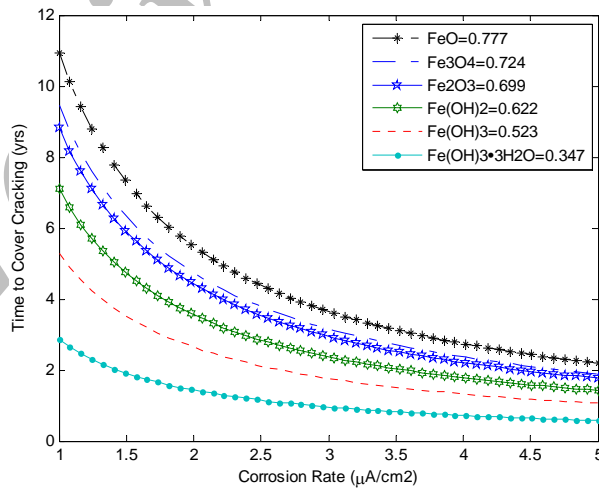


Figure 6. Time to corrosion-induced cracking

To show the validity of presented formulas, a deterministic calculation is carried out on the values of basic variables given in [3]. The time to cover cracking due to rebar corrosion is summarized in the Table 2. The results shows satisfactory approximation of cracking time

as indicated in this table.

Table 2. Model predicted cracking time versus experimental observation

Sample [3]	D (mm)	$X_c$ (mm)	$i_{cor}$ ( $\mu\text{A}/\text{cm}^2$ )	$T_{cr}$			
				Exp. (year)	$\alpha=.622$	$\alpha=.57$	$\alpha=.523$
OA2859.6	16	27	3.75	0.72	0.645	0.591	0.542
OB3859.6	16	48	2.41	1.84	1.8153	1.664	1.526
OE(F)19512.0	16	70	1.79	3.54	3.969	3.638	3.338

### 5.2 Initiation Period

To deal with problems with uncertainty and randomness which is the nature of corrosion process and its effects on structural response, probabilistic approach may be very appropriate. Random nature of measurements such as cover depth, chloride concentration, corrosion rate, bar diameter, and etc., imposes researcher to exploit appropriate modeling techniques such as probabilistic and fuzzy approaches. These methods consider uncertainties arising from the nature of corrosion problem in the modeling procedures [4], and [8].

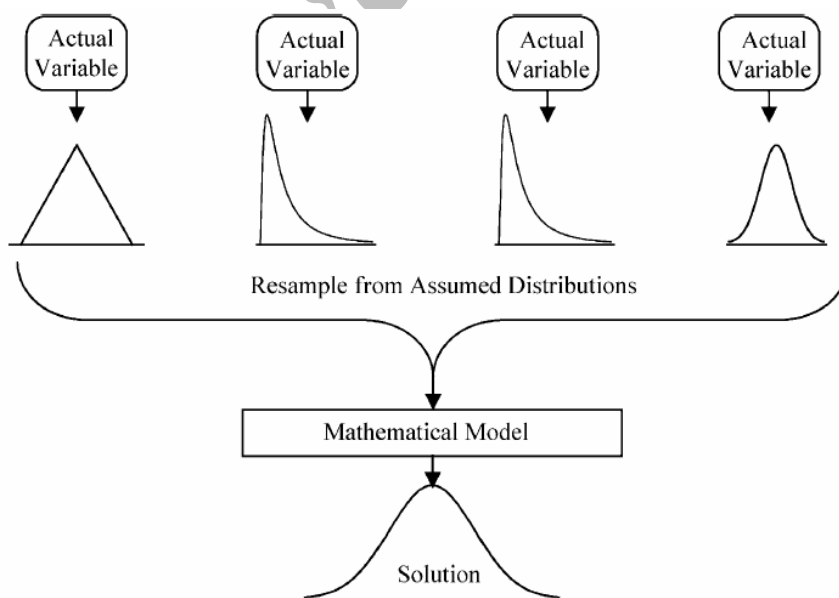


Figure 7. Basis of the MCS calculation process [9]

Monte Carlo Simulation (MCS) is used to calculate the corrosion initiation time period.

Figure 7 shows the basis of the calculation process [9], [10], [11], and [12]. The values of basic stochastic variable are presented in Table 3. The probability distribution functions (pdfs) of these variables are shown in Figure 8. A simple MCS have been performed on Eq. (6). Outcome of the calculation presented in Figure (9).

Table 3. Values of basic stochastic variables

<b>Random Variables:</b>			
Variable	Mean	COV	Unit
$X_c$	45	8	[mm]
$D_c$	33	5	[mm <sup>2</sup> /year]
$C_t$	0.3	0.05	[%]
$C_s$	0.65	0.038	[%]
$D$	16	1.6	[mm]
$i_{cor}$	1.5	2.5	[μA/cm <sup>2</sup> ]
$E_{ef}$	18.82	0.12	[GPa]
<b>Deterministic Variables:</b>			
$f'_t$	3.3	---	[MPa]
$d_0$	12.5	---	[μm]
$\nu_c$	0.18	---	---
$f'_c$	31.5	---	[MPa]
$\alpha$	0.57	---	---
$\rho_{rust}$	3,600	---	[kg/m <sup>3</sup> ]
$\rho_{st}$	7,850	---	[kg/m <sup>3</sup> ]

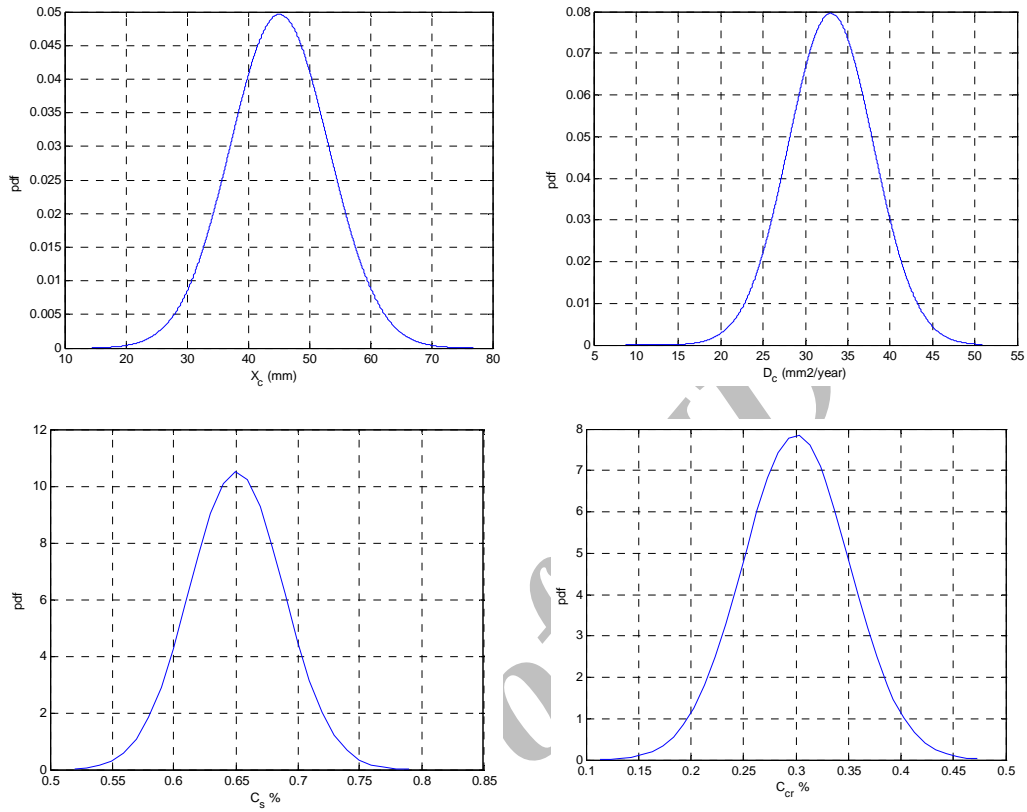


Figure 8. Stochastic variable of cover depth, diffusion coefficient, chloride surface and critical concentration

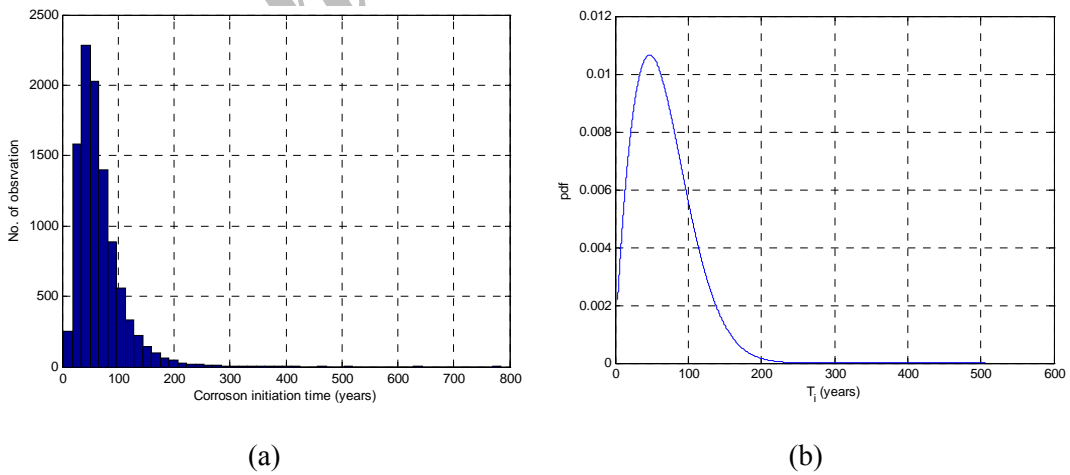


Figure 9. (a) Histogram of  $T_i$  (b) Distribution function of  $T_i$ ,

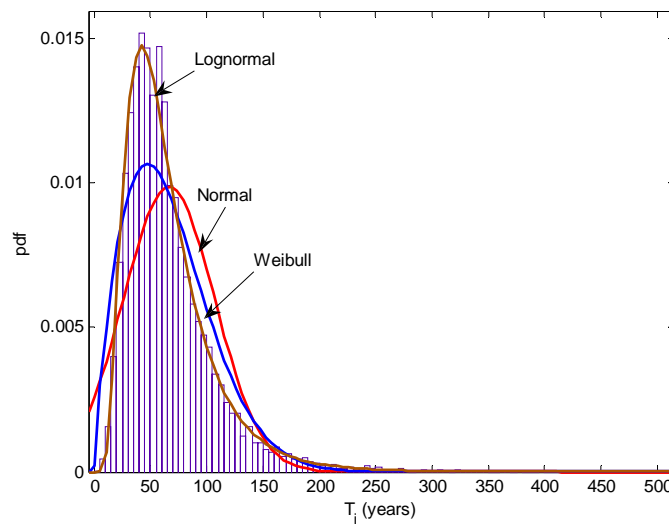


Figure 10. Comparison of lognormal, normal and Weibull distribution fitted on “corrosion initiation time” ( $T_i$ )

Weibull, Normal, and Lognormal distributions are fitted to the histogram (Figure 9) of the corrosion initiation time. Figure 10 illustrates the comparison of the mentioned distributions which are fitted on corrosion initiation time. It is found that (from Table 4) the Lognormal distribution with parameters  $\mu=4.044$  and  $\sigma=0.5535$  appropriately defines the corrosion initiation time, i.e.

$$T_i \approx \frac{1}{1.3875t} e^{\frac{-(\ln t - 4.043)^2}{0.6128}} \tag{21}$$

Table 4. Comparison of Normal and Weibull distributions fitted on “corrosion initiation time”,  $T_i$

Parameter	pdf	Parameter Estimate		Std. Err.
	Normal	$\mu$	66.0486	0.405818
		Sigma	40.5818	0.286978
$T_i$	Lognormal	$\mu$	4.04367	0.00553536
		Sigma	0.553536	0.00391438
	Weibull	a	74.6496	0.44661
		b	1.77283	0.0121588

### 5.3 Time-to-Cover-Cracking

Basic variables of the MC simulation of time-to-cover cracking are presented in Table 2 and Figure 11. Critical amount of corrosion products needed to cause cracking of cover is simulated based on Eq. (14). Moreover, similar calculation is performed on Eq. (19) to determine the time-to-cover-cracking, Figure 12.

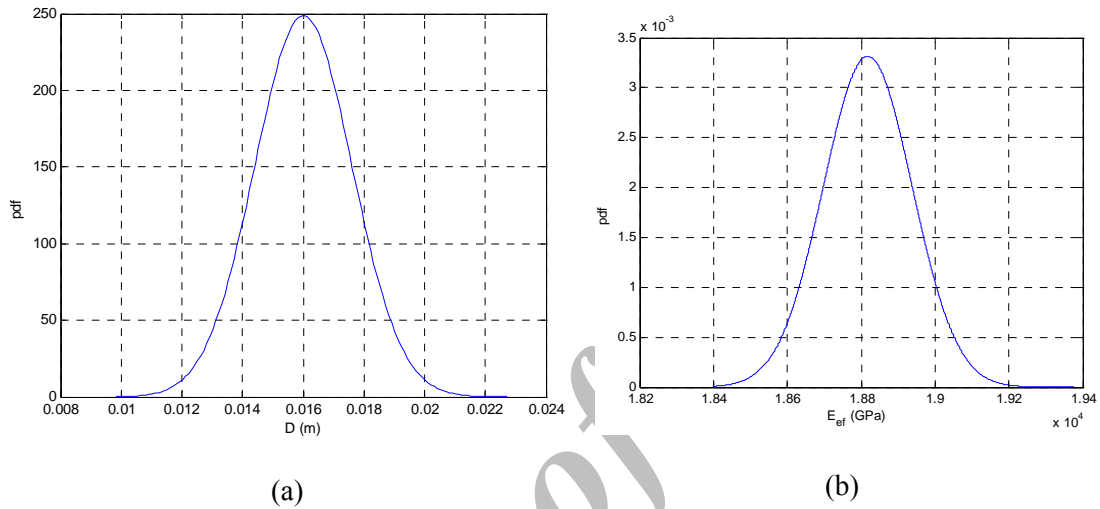


Figure 11. Stochastic variable of (a) bar diameter, (b) and effective modulus of elasticity

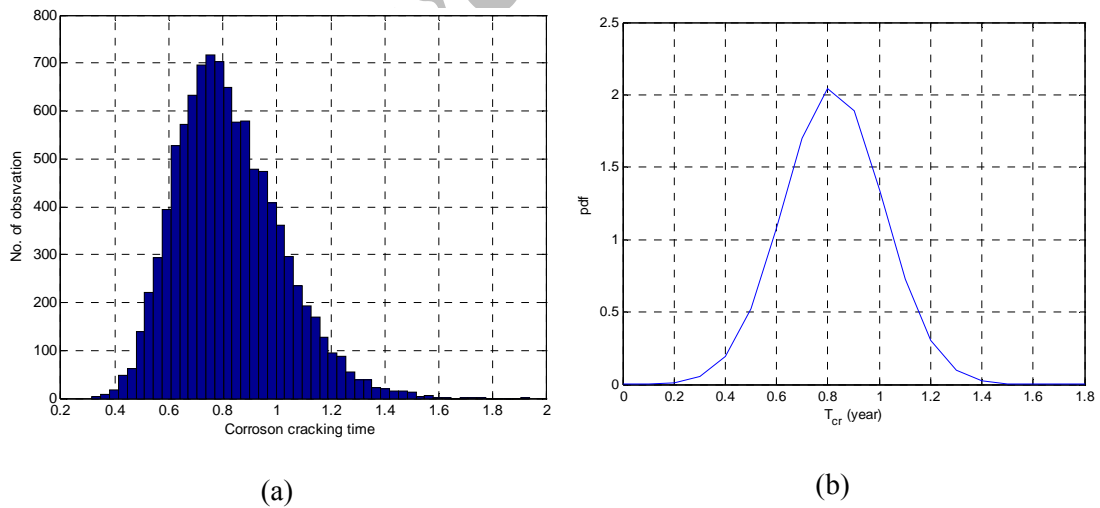


Figure 12. (a) Histogram of  $T_{cr}$  (b) Probability distribution function of  $T_{cr}$

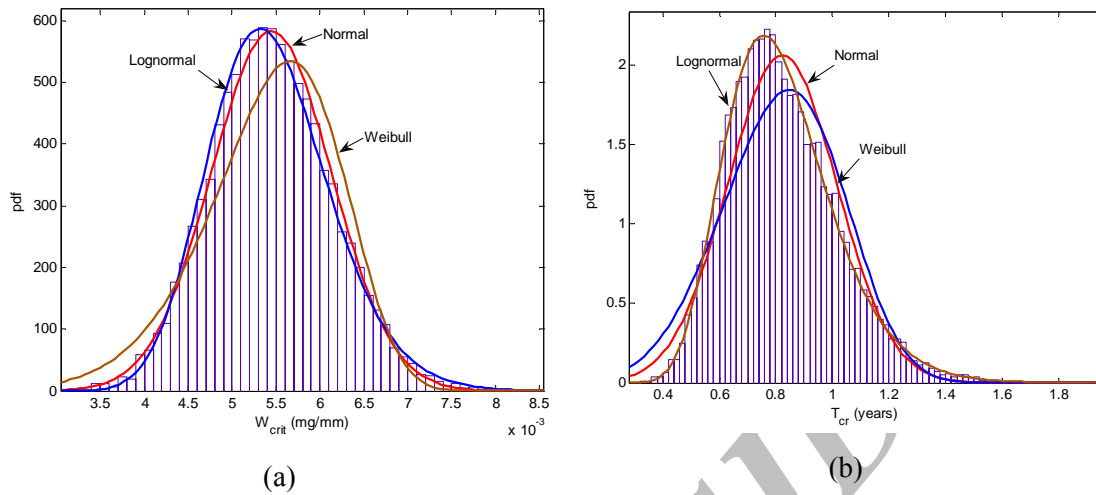


Figure 13. Comparison of lognormal, normal and Weibull distribution fitted on a) “critical amount of corrosion products”,  $W_{crit}$ , “time to cover cracking”,  $T_{cr}$

Table 5. Comparison of normal and Weibull distribution fit on corrosion cracking time

Parameter	pdf	Parameter Estimate	Std. Err.
$W_{crit}$	Normal	mu	0.00543584
		Sigma	6.78802e-006
	Lognormal	mu	0.000678802
		Sigma	4.80022e-006
	Weibull	mu	-5.22262
		Sigma	0.00126118
$T_{cr}$	Weibull	a	0.000891857
		b	0.126118
	Normal	a	0.00573731
		b	0.0601418
	Lognormal	mu	0.822405
		Sigma	0.00193057
Weibull	mu	0.822405	
	Sigma	0.00193057	
	a	0.193057	
	b	0.00136522	
Lognormal	mu	-0.222698	
	Sigma	0.0023383	
	a	0.23383	
	b	0.00165355	
Weibull	a	0.898979	
	b	0.00217344	
Weibull	a	4.38537	
	b	0.0315018	

Table 5 summarized the simulation results. Normal, lognormal and Weibull distribution are fitted on numerical results. Figure 13 illustrate the simulation results. According to the Table 5 and Figure 13, it can be concluded that two lognormal distributions with parameters  $\mu=-0.222698$ ,  $\sigma=0.23383$ , and  $\mu=-5.22262$ ,  $\sigma=0.126118$  give satisfactory results for  $T_{cr}$  and  $W_{crit}$  respectively, i.e.:

for  $W_{crit}$ :

$$W_{crit}(Norm) \approx \frac{1}{0.0017} e^{-\frac{(t-0.00544)^2}{9.22e-7}} \quad (22)$$

$$W_{crit}(LogN) \approx \frac{1}{0.3161t} e^{-\frac{(\ln t+5.223)^2}{0.0318}} \quad (23)$$

for  $T_{cr}$ :

$$T_{cr} \approx \frac{1}{0.5861t} e^{-\frac{(\ln t+0.2227)^2}{0.1094}} \quad (24)$$

## 6. CONCLUSIONS

In this paper, service life of RC structures was defined in chloride laden environment. Chloride-induced corrosion imitation period time was described based on the Fick's second law of diffusion. The corrosion induced cracking model was presented based on well-known Liu and Weyers model. A stochastic procedure was introduced to determine the corrosion initiation period and the time-to-cover cracking period of RC members. It was concluded that a lognormal distribution (Logn[4.044, 0.5536]) might best fit to the initiation period. Also, it is found that a normal distribution (Norm[0.005436, 0.000679]) and a lognormal distribution (Logn[-0.2227, 0.2339]) could describe the critical amount of rust formation during the corrosion process, and the cover cracking time of RC structures elements, respectively.

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