WARSAW UNIVERSITY OF TECHNOLOGY Index 351733
FACULTY OF CIVIL ENGINEERING
COMMITTEE FOR CIVIL AND WATER ENGINEERING
POLISH ACADEMY OF SCIENCES ISSN 1230-2945

DOI: 10.24425/ace.2022.140659

ARCHIVES OF CIVIL ENGINEERING

Vol. LXVIII ISSUE 2 2022

pp. 563 –576

Research paper

Research corrosion propagation time of reinforced concrete structures considering load influence

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Abstract: Prediction of propagation time of corrosion is a key element in evaluating the service life of corroded reinforced concrete (RC) structures. Corroded steel products often expand in volume and thus generate tensile stress in the concrete cover. When this tensile stress exceeds the tensile strength of the concrete, cracking occurs. The tensile stresses in concrete due to corrosion are usually perpendicular to the longitudinal axis of the reinforcement. In the reinforced concrete beams, tensile stresses in concrete due to bending is perpendicular to the longitudinal direction of stirrups. In the reinforced concrete slabs, the tensile stresses in concrete due to bending is also perpendicular to the axis of longitudinal reinforcement subjected to bending in the other direction. In such cases, the tensile stresses in concrete due to corrosion of reinforcement has the same direction as the tensile stress caused by bending. When the load-induced stress in the concrete has the same direction as that of the corrosion-induced stress, cracks will likely appear more quickly and vice versa. The main objective of this paper is to build a predictive model of corrosion propagation time taking into account: (1) the effect of stresses due to load; (2) the change of corrosion current density. The model was implemented on Matlab software. The results show the influence of the load, and other parameters on the corrosion propagation stage, when considering the end of this corrosion propagation stage is cracking of concrete cover.

Keywords: cracked, corrosion, load, reinforced concrete, propagation, stirrups

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1. Introduction

The reinforced concrete structures working in the marine environment are affected by chloride ions ingress, which causes corrosion of steel, leading to a reduction in performance as well as safety of RC structures.

Tuutti (1980) [1] gave the notion of service life of concrete structures exposed chloride. The service life includes two periods, as Eq. (1.1).

$$t = t_1 + t_{\mathrm{cr}} \tag{1.1}$$

where: t_1 – initiation time of corrosion, t_{cr} – propagation time of corrosion.

The first period: initiation time of corrosion is the necessary time to chloride ions diffusion into concrete and concentrate on steel surface to reach "concentration threshold causing corrosion". There were many models for predicting initiation time of corrosion have been developed as: DuraCrete (2000) [2] LIFECON DELIVERABLE D3.2 Service Life Models (2003) [3]; Life 365TM Service Life Prediction ModelTM (1999–2000) [4].

The second period: Propagation time of corrosion is time period from initiation corrosion to induced corrosion cracking of concrete cover.

The propagation period of corrosion is the basis to decide the maintenance and repair time of RC. Therefore, a reliable prediction of the time from the onset of reinforcing corrosion to the crack of concrete protection is important. The length of this period is influenced by many factors including [5–8]: (1) corrosion current density; (2) structural parameters such as concrete protective layer thickness, steel diameter; (3) material parameters such as tensile strength, modulus of elastic, creep coefficient, poisson coefficient of concrete; (4) environmental parameters: temperature, humidity. Besides the above mentioned factors, load also has an impact on the corrosion propagation time [9–11]. The timelines after corrosion of reinforced concrete are depicted in Table 1. The paper proposes a model of the effect of stress due to frequent loads on propagation time from onset corrosion to full cracking of concrete layer protecting steel. The objective of this study is to establish a theoretical model that helps to understand all the factors affecting corrosion propagation time (Fig. 1).

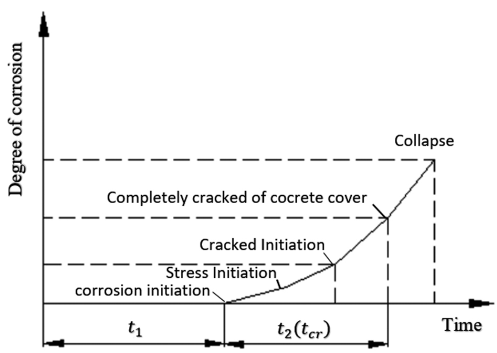

Fig. 1. Time interval from initiation of steel corrosion to complete cracking of concrete cover and to collapse

Table 1. Notation

c	thickness of concrete cover (mm)	φ_{cr}	the creep coeficient of concrete
C_t	is the total chloride content (kg/m^3 of concrete)	v	the Poisson coefficient of concrete
d	the diameter of steel bars (mm)	ρ_{rust}	the density of rust
E_c	elastic modulus of concrete (MPa)	ρ_{st}	the density of steel
E_{eff}	effective elastic modulus of concrete (MPa)	δ_0	the thickness of porous area around the steel-concrete interface
f_{ct}	the tensile concrete strength (MPa)	a	$a = 0.5(d + 2\delta_0)$
i_{cor}	corrosion rate	b	$b = c + 0.5(d + 2\delta_0)$
M	the atomic weight of Fe	$\sigma_{\mathrm{load}-x}$	load-induced stress
M_{loss}	the loss weight of consumed steel	r_0	$r_0 = 0.5d + \delta_0$

2. Existing corrosion propagation models

2.1. Morinaga's empirical model

Morinaga (1988) [12] proposed a model for time period prediction from onset corrosion to cracking, this model based on data obtained in the field and laboratory as follows:

$$t_{\mathrm{cr}} = \frac{Q_{\mathrm{cr}}}{i_{\mathrm{cor}}} \tag{2.1}$$

where: t_{cr} is the time to cracking (days); Q_{cr} is the critical mass of corrosion products (10^{-4} g/cm^4); i_{cor} is the corrosion rate (g/day).

Q_{cr} is caculated as follows:

$$Q_{\mathrm{cr}} = 0.602d \left(1 - \frac{2c}{d}\right)^{0.85} \tag{2.2}$$

This model does not to account to change in the time of corroson rate and tensile strength of concrete.

2.2. Bazant's corrosion propagation time model

Bazant (1979) gave the time period from onset corrosion to complete cracking of concrete layer protecting steel, t_{cr}, follows [5]:

$$t_{\mathrm{cr}} = \rho_{\mathrm{cor}} \frac{d\Delta d}{s j_r} \tag{2.3}$$

$$\Delta d = 2 f_{\mathrm{ct}} \frac{c}{d} \delta_{pp} \tag{2.4}$$

where: s is the bar spacing; Δd – change in diameter of the steel bar; j_r – the rust production rate; ρ_{cor} – a function represensing the relationship between the mass densities of steel and rust; δ_{pp} – the bar hole flexibility.

$$\rho_{\text{cor}} = \frac{\pi}{2\left(\frac{1}{\rho_r} - \frac{0.523}{\rho_s}\right)} \tag{2.5}$$

The model assumed that: $\rho_r = 0.25\rho_s$, where ρ_r – the density of rust; ρ_s – the density of steel.

$$\delta_{pp} = \left(\frac{d\,(1+\varphi_{\text{cr}})}{E_c}\right)\left[(1+\nu) + d^2\left(\frac{2}{s^2} + \frac{1}{4c\,(c+d)}\right)\right] \tag{2.6}$$

Bazant's model did not take into account the change over time of the corrosion rate.

2.3. Youping Liu's models

In 1996, Youping Liu [8] proposed a method to determine the time period from the onset of corrosion to the crack of concrete cover due to corrosion, Fig. 2. There are three periods as follows:

1. Free expansion period: As corrosion occurs on surface of the steel, porous area around the steel – concrete interface will be fill with corrosion products. When $W_T \le W_p$ there are not stressed in the protective concrete layer (W_T is the total quantity of corrosive products; W_p is the necessery amount of corrosion products to fill in the porous area around the steel-concrete interface).
2. Stress Initiation: As $W_T > W_p$, the stresses in concrete cover will form.
3. Concrete cracking: As $W_T = W_{\text{crit}}$ the corrosion-induced cracking appear and propogate to face of concrete outside (W_{crit} is the critical amount of necessery corrosion products to induced cracking).

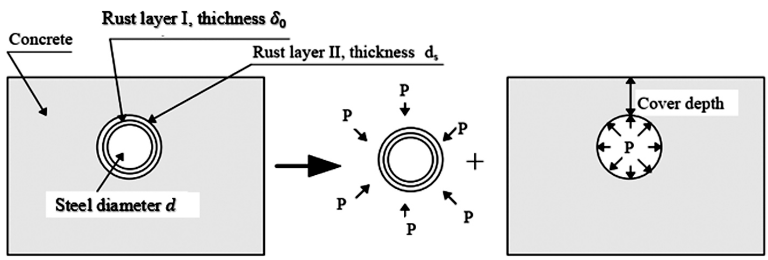

Fig. 2. Liu's model about stress generation due to corrosion

The critical amount of necessery corrosion products to induced cracking is calculated from Eq. (2.7):

$$W_{\text{crit}} = \rho_{\text{rust}}\left\{\pi\left[\frac{c f_{\text{ct}}}{E_{ef}}\left(\frac{a^2+b^2}{b^2-a^2} + \upsilon_c\right) + d_0\right] d + \frac{W_{\text{st}}}{\rho_{\text{st}}}\right\} \tag{2.7}$$

when the corrosion rate is constant, the time period to cracking, t_{cr} is calculated from Eq. (2.8):

$$t_{cr} = \frac{(W_{crit})^2}{2k_p} \tag{2.8}$$

$$k_p = 2.59 \cdot 10^{-6} \left(\frac{1}{\alpha}\right) \pi d i_{cor} \tag{2.9}$$

with: α – depends on the type of rust, $\alpha = 0.523$ (rust is $Fe(OH)_2$; $\alpha = 0.622$ for $Fe(OH)_3$; i_{cor} is the annual mean rust speed (mA/ft^2).

Liu and Weyers (1998) [13] proposed the corosion rate as follows:

$$i_{cor} = 0.926 \exp\left[7.98 + 0.7771 \ln(1.69C_t) - \frac{3006}{T} - 0.000116R_c + 2.24t^{-0.215}\right] \tag{2.10}$$

where: i_{cor} is corrosion rate (mA/cm^2); C_t is the total chloride content (kg/m^3 of concrete); T is the ambient temprature at the depth of the steel surface (K); R_c is the ohmic resistance of the cover concrete (Ω); t is the duration from corrosion initiation (years); The ohmic resistance of the cover concrete R_c, Liu (1996) [8] established a regression relationship between the concrete ohmic resistance and total chloride content for the field-exposed specimens as:

$$R_c = \exp\left[8.03 - 0.549 \ln(1 + 1.69C_t)\right] \tag{2.11}$$

Liu's mathematical model gave a pretty clear scientific ground. Liu's model has not yet considered the effect of load to period of corrosion propagation.

3. Model consider the effect of the load on the corrosion propagation time

3.1. Corrosion-induced cracked concrete cover without consider the effect of the load

Let ρ be the ratio of the steel mass loss (M_{loss}) to the original steel mass (M_s) per unit length:

$$\rho = \frac{M_{loss}}{M_s} \tag{3.1}$$

The basic assumptions: (1) The corrosion around the steel bar is uniform; (2) A thick-walled cylinder model is used for the concrete around the steel bar. The wall thickness is assumed to equal the thicknest concrete cover; (3) Tensile stress in thick- walled concrete cylinder caused by the expansive pressure is assumed to be uniform; (4) stress due to load is not considered.

At the time that corrosion cracked full concrete cover, the ratio of the steel mass loss to the original steel mass, ρ becomes ρ_c. The value of ρ_c, when considering corrosion products penetrated into open cracks, according to Chunhua Lu et al. [14]:

$$\rho_c = \left(1 + k\frac{c}{d}\right) \frac{\left\{\frac{2c}{d}\frac{f_{\text{ct}}}{E_{\text{cef}}}\left[\frac{(r_0+c)^2 + r_0^2}{(r_0+c)^2 - r_0^2} + v_c\right] + 1 + \frac{2\delta_0}{d}\right\}^2 - 1}{n-1} \tag{3.2}$$

where: c is thickness of concrete layer protecting steel (mm); d is the diameter of steel reinforcement (mm); E_{cef} is an effective elastic modulus of the concrete (MPa) $E_{\text{cef}} = 1/(1+\varphi)$ which φ is the creep coefficient of the concrete; $r_0 = d/2 + \delta_0$ (mm); δ_0 is thickness of the porous area around the steel bar, $\delta_0 = 12 \div 20$ μm [15]; $f_{\text{ct}}$is the tensile concrete strength (MPa); v_c – the Poisson coefficient of concrete; k is the coefficient denotes the degree of cracking filling by corrosive products ($0 < k < 1.0$); n is the volumetric expansion coefficient of the corrosive product.

3.2. Effect of load on cracking process caused by steel corrosion

In the bending and axial load-bearing reinforced concrete components associated with bending, the stress $\sigma_{\text{load}-x}$ in the concrete is perpendicular to the axis of the stirrupts (stirrupts placed perpendicular to the longitudinal reinforcement), Fig. 3.

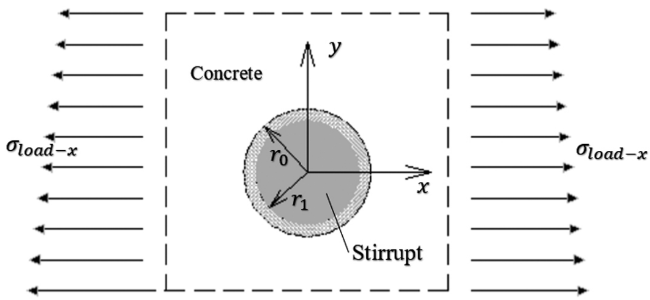

Fig. 3. Load-induced stresses have direction perpendicular to the axis of the stirrups

The tensile stresses in thick – walled concrete cylinder is assumed to be uniform, $\sigma_{\text{cor}-\text{x}}$ as Fig. 4.

The stresses $\sigma_{\text{load}-x}$ and $\sigma_{\text{cor}-\text{x}}$ in Fig. 3 and Fig. 4 are in the same direction, so the combined stresses due to load and corrosion cause cracking of the protective concrete as follows:

$$\sigma_{\text{load}-x} + \sigma_{\text{cor}-\text{x}} = f_{\text{ct}} \tag{3.3}$$

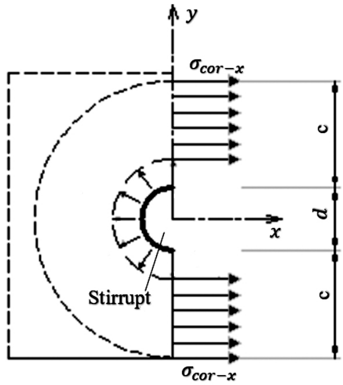

Fig. 4. The corrosion-induced tensile stress in the concrete

Modifying Eq. (3.2) by replacing f_{ct} with $f_{\text{ct}} - \sigma_{\text{load}-x}$, the ratio of the steel loss mass to the original steel mass $\rho_{c-\text{load}}$, when considering the effect of applied load is:

$$\rho_{c-\text{load}} = \left(1 + k\frac{c}{d}\right)\frac{\left\{\dfrac{2c}{d}\dfrac{(f_{\text{ct}} - \sigma_{\text{load}-x})}{E_{\text{cef}}}\left[\dfrac{(r_0+c)^2 + r_0^2}{(r_0+c)^2 - r_0^2} + \nu_c\right] + 1 + \dfrac{2\delta_0}{d}\right\} - 1}{n-1} \tag{3.4}$$

where: $\sigma_{\text{load}-x}$ is load-induced stress; it is positive when it is tensile stress; $\sigma_{\text{load}-x}$ is negative when it is compresion stress.

The corrosion-induced steel mass loss cause cracking concrete cover when considering the effect of applied load as:

$$\begin{aligned} M_{\text{loss}-\text{cr}} &= \rho_{c-\text{load}} M_s = \rho_{c-\text{load}}\frac{\pi}{4}\left(\frac{d^2}{10}\right)\rho_s \\ &= \rho_{c-\text{load}}\frac{\pi}{400}d^2 \cdot 7.85 = 0{,}0196\rho_{c-\text{load}}\pi d^2 \end{aligned} \tag{3.5}$$

3.3. A corrosion propagation time model consider the effect of the load

The amount of steel consumed is related to the magnitude of the current in electrochemical corrosion cells. Using Faraday's law to describe mass loss of steel due to corrosion:

$$M_{\text{loss}} = \frac{M I_{\text{cor}}}{zF}t \tag{3.6}$$

where: M_{loss} – the loss weight of consumed steel (g); M – the atomic weight of Fe, $M = 56$ g/mol; z – ionic valency; F – the Faraday's constant, $F = 96{,}500$ C/mol; t – the corrosion time (s); I_{cor} – the corrosion rate (A);

$$I_{\text{cor}} = 1 \cdot \frac{\pi d}{10} \cdot i_{\text{cor}} \cdot 10^{-6} = 10^{-7}\pi i_{\text{cor}} d \tag{3.7}$$

where: i_{cor} – the corrosion current density (μA/cm^2); d – the steel diameter (mm).

The loss mass of corrosion – induced steel, M_{loss} (g), when the corrosion time t in unit years:

$$M_{\text{loss}} = \frac{56 \cdot 10^{-7} \pi i_{\text{cor}} d}{2.5 \cdot 96,500} \cdot 365 \cdot 24 \cdot 3600t = 2.23 \cdot 10^{-3} i_{\text{cor}} dt \tag{3.8}$$

The mass loss of corrosion-induced steel will be accumulated over time. When M_{loss} is equal to $M_{\text{loss-cr}}$, the concrete cover will be full cracked.

$$M_{\text{loss-cr}} = 2.23 \cdot 10^{-3} i_{\text{cor}} dt = M_{\text{loss-cr}} = 0.0196 \rho_{c\text{-load}} \pi d^2 \tag{3.9}$$

When i_{cor} is unchanged over time, the corrosion propagation time t_{cr} when considering the end of those time is fully cracked concrete cover would be:

$$t_{\text{cr}} = \frac{0.0196 \rho_{c\text{-load}} \pi d^2}{2.23 \cdot 10^{-3} i_{\text{cor}} d} = 27.612 \frac{d}{i_{\text{cor}}} \rho_{c\text{-load}} \tag{3.10}$$

When i_{cor} is changed over time, the corrosion propagation time, t_{cr}, when considering the end of those time is fully cracked concrete cover would be:

$$\int_0^{t_{\text{cr}}} M_{\text{loss}} \partial t = M_{\text{loss-cr}} = 0.0196 \rho_{c\text{-load}} \pi d^2 \tag{3.11}$$

In Eq. (3.11) the corrosion current density i_{cor} will use Eq. (2.10). The Ohmic resistance of concrete layer protecting steel will use result of Lopez et al. [7]. R_c depends the relative humidity H:

$$R_c = 90.357 H^{-7.2548} \left[1 + \exp\left(5 - 50(1 - H)\right)\right] \tag{3.12}$$

In Eq. (2.10), C_t the total chloride content will change over time, C_t are based on Fick's second law of diffusion (consider initial chloride concentration of concrete is zero) as Eq. (3.13):

$$C(c,t) = \left\{ C_s \left(1 - \operatorname{erf} \frac{c}{2\sqrt{Dt}} \right) \right\} \cdot \frac{1}{100} \cdot \gamma_c \tag{3.13}$$

where: D – the chloride diffusion coefficient in concrete; C_s – the chloride concentration at the concrete surface; c – depth of concrete layer protecting steel bar; t is time ($t = t_1 + \Delta t$); γ_c is the concrete density.

3.4. Block diagram for t_{cr} calculation

The order of calculation t_{cr} can be performed according to the following diagram, Fig. 5. Material parameters such as compressive strength of concrete, tensile strength, elastic modulus can be determined experimentally or using empirical formulas of ACI 318-19, AASHTO LRFD 2017. Parameters such as chloride ion diffusion coefficient in concrete can be tested according to NT BUILD 492 or ASTM C1202-2019... or estimated by Life 365's formula.

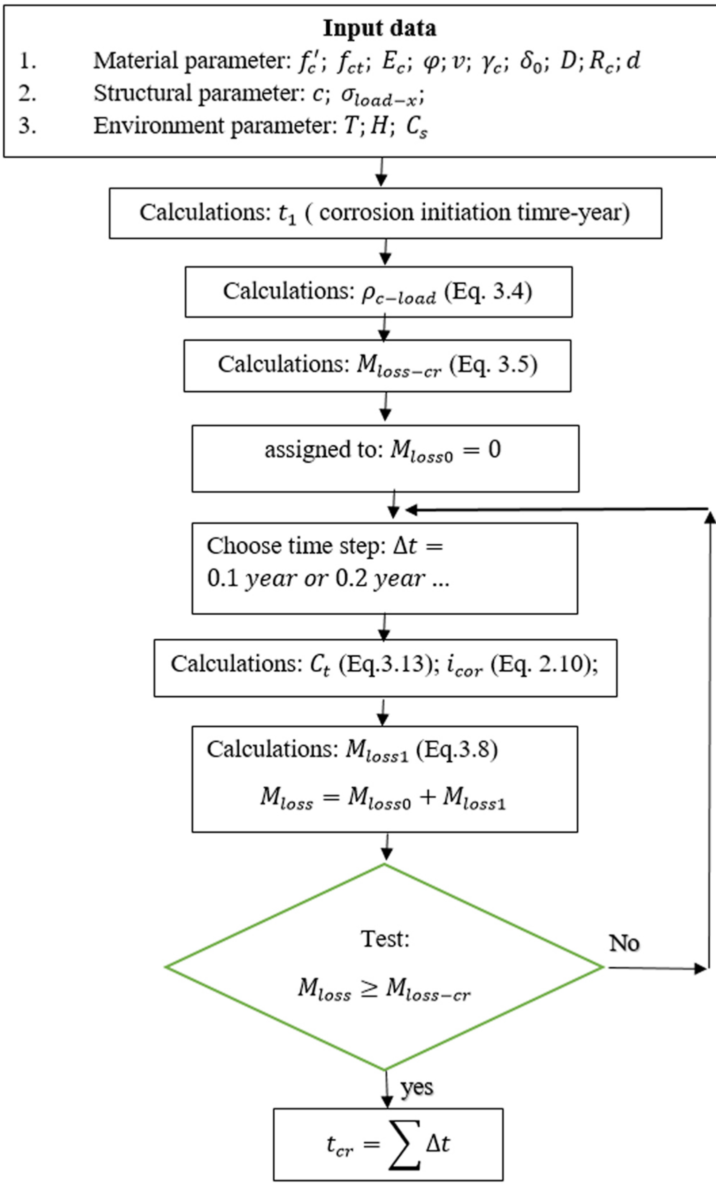

Fig. 5. Block diagram for t_{cr} calculation

3.5. Model validation

The Eq. (3.10) will be used to calculate Liu's test [8]. The general parameters for Liu's specimens: f'_c = 31.5 MPa; f_{ct} = 3.3 MPa; E_c = 27 000 MPa; φ = 2; v_c = 0.18; δ_0 = 12.5 µm.

The results from Table 2 show that the model gives results consistent with Liu's experiment (Fig. 5).

Table 2. Calculation result t_{cr} according to Eq. (3.10) with $k = 0.7$; $n = 2.5 \div 3.0$

Series	Bar diameter (mm)	Thickness of concrete cover (mm)	Corrosion current density μA/cm^2	Model predicted from Eq. (3.10) t_{cr} (years)	Liu's test (years)
1	16	47.50	2.35	1.53–2.04	1.84
2	16	69.60	1.80	3.09–4.12	3.54
3	16	27.18	3.77	0.57–0.75	0.72
4	12.7	52.07	1.81	2.58–3.44	2.38

3.6. The influence of parameters on corrosion propagation time

The survey example is a reinforced concrete structure with the following parameters:

The structural parameters: $c = 20 \div 50$ mm; The stirrup diameter: $d = 9.5$ mm; The normal stress due to load: $\sigma_{\text{load}-x} = -10 \div +3$ MPa.

The material parameters: $f_c' = 30$ MPa; $f_{\text{ct}} = 3.3$ MPa; $E_c = 30000$ MPa; $\varphi = 2$; $v_c = 0.18$; $\delta_0 = 12.5$ μm; $k = 0.7$; $\gamma_c = 2450$ kg/m^3. The ohmic resistance of concrete cover base Eq. (2.11): $R_c = 730.25\ \Omega$.

The environmental parameters: $T = 298$ K (25°C); $H = 75\%$; $D = 6 \cdot 10^{-12}$ m^2/s; $C_s = 0.6\%$.

The corrosion initiation time has been calculated to be 18 years.

Assuming that after 18 years the chloride diffusion coefficient is constant ($D = 6 \cdot 10^{-12}$ m^2/s; $C_s = 0.6\%$, the concrete density $\gamma_c = 2450$ kg/m^3). We will have the chloride content at the steel surface over time, which are based on Fick's second law of diffusion (when the initial chloride concentration of the concrete is zero), as Eq. (3.14):

Case $c = 50$ mm; $D = 6 \cdot 10^{-12}$ m^2/s; $C_s = 0.6\%$; $\gamma_c = 2450$ kg/m^3 are given as follows:

$$C(50, t) = 0.06 \left\{ 1 - \operatorname{erf} \frac{50 \cdot 10^{-3}}{2\sqrt{6 \cdot 10^{-12}\,(18 + t_{\text{cr}})}} \right\} \cdot 24.5 \tag{3.14}$$

3.6.1. The chloride concentration in concrete at the steel surface

The relationship between $C_{(50,t)}$ and t_{cr} according to Eq. (3.14) is shown in Fig. 6.

3.6.2. Corrosion current density

Time-dependent corrosion current density i_{cor} base on Eq. (2.10) with parameters of Eq. (3.14) as shown in Fig. 7.

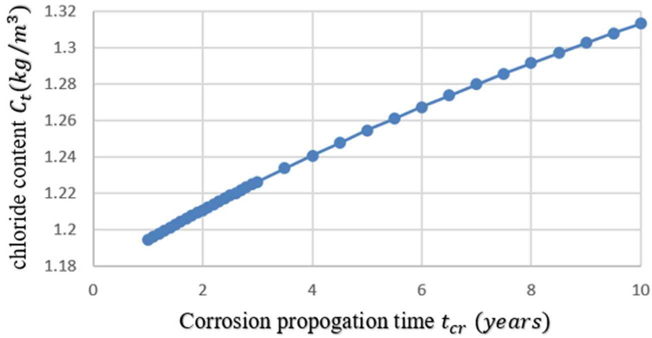

Fig. 6. The chloride content over time on the steel surface

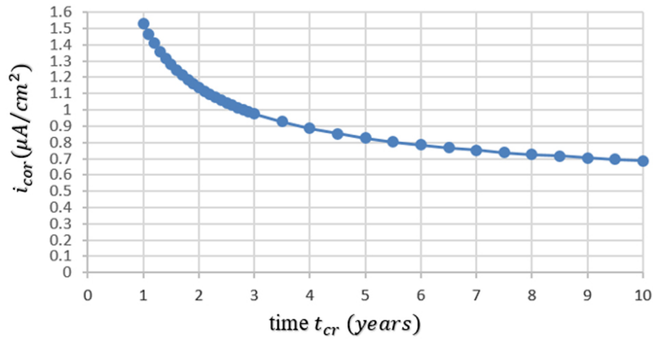

Fig. 7. The time-dependented corrosion current density

3.6.3. The loss mass of corrosion-induced steel

The build up of steel mass loss due to corrosion over time based on Eq. (2.9) as shown in Fig. 8.

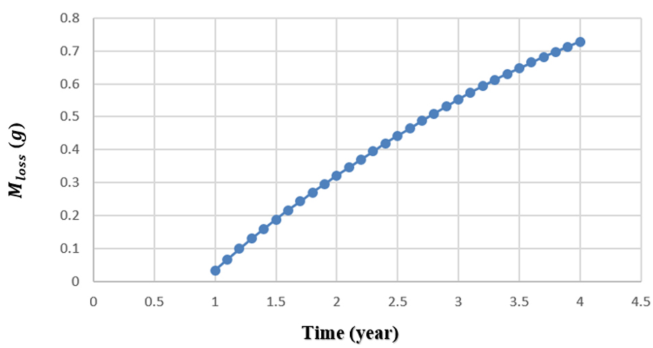

Fig. 8. The M_{loss} built up over time

3.6.4. The effect of load-induced stress on propagation time

The time of corrosion propagation considering the effect of stress is calculated based on Eq. (3.11) shown in Table 3.

Table 3. Calculation results with c = 25 mm

$\sigma_{\text{load}-x}$ (MPa)	–10	–8	–6	–4	–3	0	1	2	3
$\rho_{c-\text{load}}$	0.0382	0.0338	0.0294	0.0250	0.0228	0.0163	0.0141	0.012	0.01
$M_{\text{loss}-\text{cr}}$ g/cm	0.212	0.188	0.164	0.1393	0.1271	0.0907	0.0786	0.066	0.054
t_{cr} (years)	7.8	6.6	5.55	4.45	3.85	2.45	2.05	1.65	1.3

3.6.5. The influence of the depth of concrete layer protecting steel on propagation time

Investigate the influence of the depth of concrete layer protecting steel on $M_{\text{loss}-\text{cr}}$ in the above example when stress $\sigma_{\text{load}-x} = -3$ MPa; 0 MPa; 2 MPa is shown in Fig. 9.

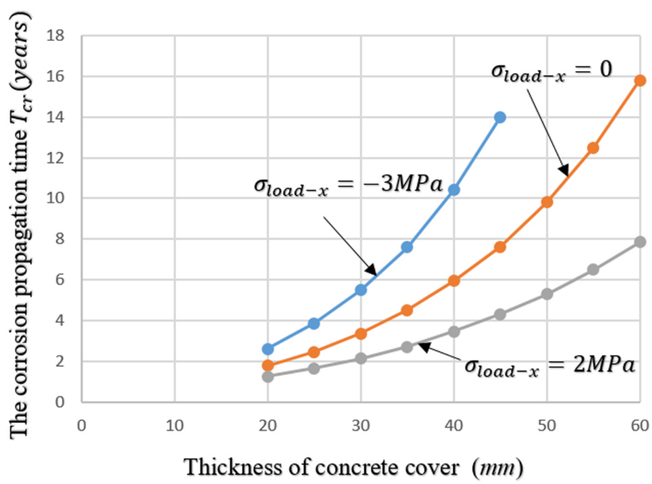

Fig. 9. Relationships between concrete cover thickness and t_{cr}

Comments from the model: The corrosion current densityi_{cor} is decreased over time, the first time i_{cor} decreases rapidly, the time after that i_{cor} decreases slowly; The $\rho_{c-\text{load}}$, $M_{\text{loss}-\text{cr}}$ and t_{cr} decrease as the stress due to the load increases; Corrosion propagation time decreases rapidly as load-induced stress increases from (–10 MPa) to (2 MPa); When the concrete cover thickness increases t_{cr} increases, it means the corrosion propagation time increases.

4. Conclusion

In reinforced concrete beam and column structures, the normal stress caused by load is usually perpendicular to the axis of stirrups. In one-way slabs and two-way slabs structures have two reinforcement types: the first type are flexural reinforcements and the second type are shrinkage and temprature reinfocements. The normal stress caused by load is also usually perpendicular to the axis of the these reinforcements. The corrosion-induced tensile stress has the same direction with load-induced stress in those structures. This influence have to consider in the reinforced concrete structures exposed chloride environment. Specifically, in this case, the corrosion propagation time must take to account the effect of load.

In the near future, we will conduct experimental studies to verify and adjust the model to suit the actual conditions at the site of construction structures.

Acknowledgements

This research is funded by University of transport and communications (UTC) under grant number T2021-CT-002.

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Received: 10.11.2021, Revised: 08.02.2022