Numerical and empirical models for service life assessment of RC structures in marine environment

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Abstract: The service life prediction of reinforced concrete (RC) structures in marine environment is essential in structural repair and health monitoring. In this paper, a numerical model for predicting the service life of reinforced concrete is first developed which considering the time-varying boundary of chloride concentration, critical chloride concentration and density of corrosion current. Based on the model, the effects of water cement ratio, reinforcement diameter, concrete cover thickness and critical chloride ion concentration on the service life and deterioration duration of RC structures are investigated. The key factors affecting the service life of reinforced concrete structures are determined. More importantly, based on regression analysis, a new simplified empirical model for predicting the service life of RC structures is also developed. It provides a fast assessment tool for practical engineers. Both the numerical model and empirical model are validated are suitable for practical engineering applications. The results show that with the increase of water cement ratio, the service life of reinforced concrete structure decreases exponentially. And with the increase of the thickness of the concrete cover, the service life, deterioration duration, and safety reserve increase linearly. However, the influence of the diameter of the reinforcing bar on the service life can be ignored..

Key words: Service life prediction; RC structures; Chloride diffusion; Critical chloride value; Corrosion current density.

1 Introduction

Reinforced concrete (RC) structures are widely used in normal construction projects , such as tall

buildings (Fu,2018;Fu,2021)and bridges (Fu ,2015;Fu 2016)offshore bridges, subsea tunnels, and harbour projects (Pillai *et al.*, 2019; Xu, Shi ; Shao, 2019a) and . For these types of projects, chloride ingress due to marine environment is one of the main factors causing the corrosion of steel bars (Marks, Glinicki and Gibas, 2015; Chang *et al.*, 2020). However, serious corrosion of steel bars causes the deterioration of structural capacity, causing serious challenges to the durability of RC structures (Alexander and Beushausen, 2019). Therefore, for marine projects, predicting the service life of the RC structure in marine environment has become an important design task for design engineers. The accurate prediction enables effective health monitoring and timely retrofitting of marine projects in their service life (Bouteiller, Marie-Victoire and Cremona, 2016; Dhandapani *et al.*, 2018). Even for projects under construction, service life prediction can provide important guidelines for designers.

Chloride ingress is particularly problematic to concrete (Nogueira, Leonel and Coda, 2012; Shaikh, 2018). Driven by the concentration difference, chloride ions and oxygen in the marine environment diffuse into the interior of concrete through its pores. Unfortunately, once the chloride concentration on the steel surface reaches the critical value, the passivation film on the steel surface will be destroyed. Consequently, the steel reinforcement members encased are subject to corrosive damages (Guo *et al.*, 2004). This erosion of the steel can cause a reduction in the RC structures' ability to resist tensile stresses. Hence, chloride ingress induced reinforcement corrosion is one of the main factors affecting the durability of concrete structures and at present, many scholars have carried out extensive research on this issue. Nathan D. Stambaugh *et al*. (Stambaugh, Bergman and Srubar, 2018) used the critical value of chloride ion concentration on the surface of steel bars as the service life assessment standard and studied the service life of RC structures in marine environments under different circumstances such as the location and the mix ratio (Khanzadeh-Moradllo *et al.*, 2015; Jung *et al.*, 2018; Mir *et al.*, 2019). However, they assumed that the chloride ion concentration on the concrete surface was constant and did not consider the time-varying characteristics of the chloride ion concentration on the surface (Huan, Zuquan and Xiaojie, 2015; Yang, Cai and Yu, 2017). S. Muthulingam *et al*. (Muthulingam and Rao, 2014) established a service life prediction model by considering the influence of wet-heat-diffusion coupling and the time-varying characteristics of the chloride concentration at the boundary. However, the model requires too many input parameters, so it is not practical. It can only predict the moment when the steel bar begins to rust, but it cannot predict when the RC structure will fail, that is, the failure life. Cao *et al* (Cao, 2014) and Zhu *et al*. (Zhu and Zi, 2017; Zhang *et al.*, 2019a) established a mechanical model

58 to predict the service life of RC structures. It is based on analysis of the corrosion mechanism of steel bars
59 considering the thickness of concrete cover (Enright and Frangopol, 1998), the critical value of the chloride
60 concentration (Enright and Frangopol, 1998; Bastidas-Arteaga *et al.*, 2009), and the chloride diffusion
61 coefficient (Pack *et al.*, 2010). Zheng *et al* (Zheng, Wong and Buenfeld, 2009) also developed a numerical
62 model to assess the influence of ITZ on the steady-state chloride diffusion. Based on the finite difference
63 method of Crank Nicolson, Song *et al*. (Song *et al.*, 2009) and Petcherdchoo *et al*. (Petcherdchoo, 2015)
64 studied the effect of retrofitting agents on the service life of RC structures. Jones *et al*. studied the
65 effectiveness of using filler to repair concrete cracks on prolonging the service life of RC structures. These
66 studies show that when micro cracks appear on the surface of concrete, repair agents can greatly prolong the
67 service life of RC structures. Furthermore, Attari *et al*. established a failure probability model for RC
68 structures. In these studies, when the failure probability reached 10%, the RC structure is considered to have
69 reached the service life, and the cracks in the RC structure have reached an acceptable limit.
70 Although many service life prediction models for RC structures have been developed, there are still
71 many challenges have not been resolved. For example, most of the existing models only use the critical
72 chloride concentration as the basis for predicting service life. However, the critical chloride concentration is
73 only the indication of beginning of steel bar corrosion (Zhao, Karimi, *et al.*, 2011). The life cycle performance
74 of reinforced concrete structures after reinforcement corrosion is rarely concerned in the existing service life
75 models. (Pan, Chen and Ruan, 2015). Most importantly, most of the existing models calculated the service
76 life of RC structures by solving complex partial differential equations, which greatly increases the
77 computational cost and is difficult to use in practical engineering. Moreover, the chloride concentration at
78 the boundary of concrete is time-dependent rather than constant, which will directly affect the distribution of
79 chloride in concrete.
80 Therefore, the focus of this research is to address above issues. The main purpose of this research is to
81 establish a practical models for practising engineers,allow them to use easily quantifying engineering
82 parameters for predicting the service life of RC structures. Firstly, a complex numerical model to predict the
83 service life of RC structures is established by diffusion-corrosion theory. The model verifications show that
84 both the chloride ion concentration and service life predictions agree well with the measured values.
85 Secondly, based on proposed model, the influence of factors such as the thickness of the cover, the water-
86 cement ratio, the critical value of chloride ion concentration, and the diameter of the reinforcement on the

service life of the RC structure are analysed. Finally, through a two-stage regression simulation of the service life of RC structures under 300 different conditions, an empirical model for predicting the service life of RC structures is established. By comparing with the numerical simulation results, the empirical model is in good agreement with the numerical model. The models proposed in this paper provides important theoretical support for life assessment of existing projects and optimization of service life design of projects to be built.

2. Theoretical background

2.1 Chloride diffusion model

After decades of theoretical and experimental research by many scholars (Hobbs, 1999; Zeng, 2007; Wang *et al.*, 2018; Zheng *et al.*, 2018; Wang, Gong and Wu, 2019), the diffusion of chloride ions in concrete in line with Fick's second law has become a widely used. And the governing equation for the diffusion of chloride ions in concrete is expressed as:

$$\frac{dc}{dt} = \frac{\partial c}{\partial x}\left(D_c \frac{\partial c}{\partial x}\right) + \frac{\partial c}{\partial y}\left(D_c \frac{\partial c}{\partial y}\right) \tag{1}$$

where c is chloride ion concentration (Mass ratio of chloride ion to concrete, %), D_c is chloride ion diffusion coefficient (m^2 / s), respectively.

2.1.1 Chloride diffusion coefficient

It can be seen from Eq. (1) that the chloride ion diffusion coefficient is a key parameter that determines the diffusion rate of chloride ions in concrete. The chloride ion diffusion coefficient is not only related to the factors such as concrete types, pore structure, water-cement ratio, hydration degree, *etc*., but also to the external environment, such as temperature (Bažant and Najjar, 1972), humidity (Muthulingam and Rao, 2014), current time (Zeng, 2007). However, to simplify it, in this paper, the chloride ion diffusion coefficient is calculated with only considerations of the effects of water-cement ratio, temperature, humidity, and aging. Its expression is (Muthulingam and Rao, 2014; Chen *et al.*, 2019)

$$D_c = \underbrace{\frac{2\times\varphi_p^{2.75} D_p}{\varphi_p^{1.75}(3-\varphi_p)+n(1-\varphi_p)^{2.75}}}_{\text{Water-cement ratio}} \cdot \underbrace{exp\left[\frac{U_c}{R}\left(\frac{1}{T_{ref}}-\frac{1}{T}\right)\right]}_{\text{Temperature}} \cdot \underbrace{\left[1+\frac{(1-h)^4}{(1-h_c)}\right]^{-1}}_{\text{Humidity}} \cdot \underbrace{\left(\frac{t_{\text{ref}}}{t}\right)^m}_{\text{Curing age}} \tag{2}$$

where U_c is the activation energy for chloride ion diffusion, t_{ref} is the average exposure time, R is the gas constant, T_{ref} is the absolute ambient temperature, h is humidity, h_c is critical humidity (0.75), D_p is the diffusion coefficient of chloride ions in water, n is an empirical constant (using 14.44 as reference (Du,

Jin and Ma, 2014)), m is the time decay index, and f_p is the porosity of the cement slurry, respectively. f_p can be expressed as(Chen *et al.*, 2021):

$$\varphi_p = \frac{w/c-0.17\alpha}{w/c+0.32} \tag{3}$$

where a is degree of hydration of cement slurry, and w/c is water to cement ratio, respectively. The value of the degree of hydration of cement slurry α in formula (3) can be calculated by

$$\alpha=1-exp(-3.15\times w/c) \tag{4}$$

2.1.2 Surface chloride ion concentration

The surface chloride ion concentration on the concrete is another key factor affecting the chloride ion concentration inside the concrete. In the numerical solution, the surface chloride ion concentration is also called the boundary condition. In the marine environment, chloride ions are transmitted to the surface of offshore engineering concrete structures through the flow of the air, and then diffuse into the concrete through the pores of the concrete (Yang, Cai and Yu, 2017). Fig. 1 shows statistics of chloride ion concentration on the surface of marine engineering concrete structures in different coastal areas by different scholars (Meira *et al.*, 2007; Stipanovic Oslakovic, Bjegovic and Mikulic, 2010; Huan, Zuquan and Xiaojie, 2015). It can be seen from the Fig. 1 that the surface chloride ion concentration ranges from 0.1% to 2.5%. There are many factors that affect the chloride ion concentration on the concrete surface, such as temperature, humidity, cement type, and water-binder ratio. Yang et al. and Chen et al. (YANG Lufeng, CHEN Chang, 2019) obtained the regression equation of surface chloride ion and time function through regression analysis of 372 sets of surface chloride ion concentration data. It is worth noting that Eq. (5) is based on the test results of ordinary Portland concrete. Therefore, Eq. (5) is only applicable to ordinary Portland concrete, but not to special concrete, such as fly ash concrete, slag concrete, etc.

$$C_s(t) = \frac{5.3t}{1+0.7047t}\times w/c \tag{5}$$

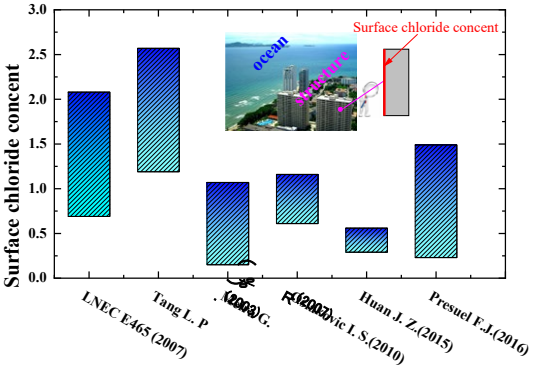


Figure 1 Statistics of Surface chloride ion concentration

2.2 Rebar corrosion

2.2.1 Critical chloride ion concentration

Chloride ions accumulate on the surface of the steel bars over the time. When the concentration of chloride ions on the surface of the steel bars reaches certain value, the steel bar begins to corrode. This value is called the critical chloride ion concentration. The critical chloride ion concentration indicators include free chloride ion concentration, total chloride ion concentration, and the ratio of free chloride ion concentration to hydroxide concentration (Cao *et al.*, 2019). In this paper, the total chloride ion concentration is used as an index to measure the critical chloride ion concentration. Due to the differences in measure methods and the discrete type of concrete materials, the critical chloride ion concentration cannot be determined at present. The critical chloride ion concentration currently reported is between 0.079% and 0.2% (Zhao, Hu, *et al.*, 2011). The critical chloride ion concentration from 51 existing literature is collected in this paper. Their statistical distribution is shown in Fig. 2. From the Fig. 2, the critical chloride ion concentration distribution is relatively scattered. Therefore, the mean value of 0.10098% is used in this paper as the critical chloride ion concentration.

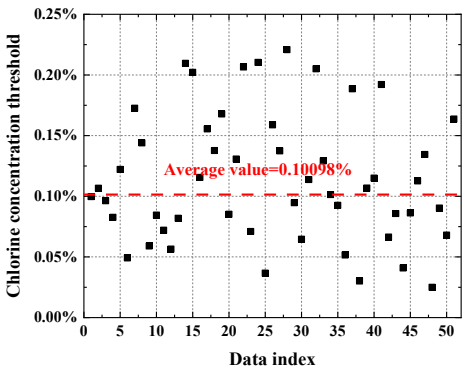


Figure 2 Statistics of Critical chloride ion concentration

2.2.2 Corrosion current density

The chloride ion concentration is not constant across the whole volume of concrete. The chloride ion concentration near the erosion surface is high, and the chloride ion concentration away from the erosion surface is low (Pan, Chen and Ruan, 2015). Therefore, the chloride ion concentration on the surface near the cover first reaches the critical chloride ion concentration, and the passivation film was damaged (Li, Wang and Li, 2019). Research in Literature (Cao, 2014) shows that there is a potential difference between the active

area formed after the passivation film on the steel bar is damaged and the inert area where the passivation film is not damaged, and a macroscopic electrochemical corrosion is formed. At the same time, there is also a Micro corrosion current, the total corrosion current density can be expressed as (Zhu and Zi, 2017):

$$i_{corr} = i_{mic} + i_{mac} \tag{6}$$

where i_{corr} is the total corrosion current density, i_{mic} is the micro battery corrosion current density, and i_{mac} is the macro battery corrosion current density, respectively.

At present, many empirical, theoretical, and numerical models have been established to calculate the corrosion current density of steel bars. In this paper, the Probabilistic mode of Papakonstantinou *et al.* (Papakonstantinou and Shinozuka, 2013) is adopted, with the expression:

$$ln\,1.08 i_{corr} = 7.89 + 0.7771\,ln(1.69 c_t) - \frac{3006}{T} - 0.000116 R_c \tag{7}$$

where i_{corr} is the corrosion current density, c_t is total chloride ion concentration, and R_c is resistance of the concrete cover, respectively.

The empirical formula given by Liu *et al.* (Liu and Weyers, 1998) for resistivity of concrete cover is:

$$ln\,R_c = 8.03 - 0.549\,ln(1 + 1.69 c_t) \tag{8}$$

2. 3 Determination of service life

In general, when the chloride ion concentration on the surface of the steel bar reaches the critical chloride ion concentration, the marine engineering concrete structure is considered to have reached the service life. The limit state function at this stage can be expressed as

$$G_1(c,t) = C_{cri} - C(max,t) \tag{9}$$

where $G_1(c,t)$is the limit state function, $c_{cri}$is the critical chloride ion concentration, and $c(max,t)$ is the maximum chloride ion concentration on the steel bar surface at the ingress time of *t*, respectively.

It is worth mentioning that when the maximum chloride ion concentration on the surface of the steel bar reaches the critical chloride concentration, the offshore engineering concrete structure doesn't fail, and only the steel barssbegin to rust (Zhao, Hu, *et al.*, 2011; Zhao *et al.*, 2016). The radial expansion stress is developed during the corrosion process. When the radial expansion stress starts to caused damages of the the concrete cover, the cover will crack and peel, and the structure will fail (Zhao, Karimi, *et al.*, 2011). In this paper, it is called the structural failure life. The limit state function can be expressed as:

$$G_2(lim,t) = \rho_{cr} - \rho(lim,t) \tag{10}$$

where ρ_{cr} is the steel rebar erosion rate at failure of the structural concrete (%), it is calculated as:

$$\rho_{cr} = \frac{2(\delta_1+\delta_2)}{r_0} \quad (11)$$

where δ_1 is the depth of rust generated by filling the pores in the transition zone between the steel bar and concrete at the interface between the corrosion products is 12.5 um; δ_2 is the depth of rust producing radial pressure, it is worked out based on the theory of thick-walled cylinders (Xu, Shi and Shao, 2019b), and can be expressed as:

$$\delta_2 = \frac{r_0}{E_c}\left[\frac{(r_0+c)^2+r_0^2}{(r_0+c)^2-r_0^2} + v_c\right] \cdot [0.3 + 0.6\, c/(2r_0)] \cdot ft \quad (12)$$

where r_0 is the reinforcement radius (mm), v_c is the Poisson's ratio of the concrete cover, Ec is elastic modulus of concrete (MPa), and f_t is tensile strength of concrete (MPa), respectively.

$\rho(lim,t)$ is the corrosion rate of steel bars at time *t* (%). According to Faraday's law, the distribution of corrosion depth $u_d(\theta,t)$around steel bars can be expressed as (Alexander and Beushausen, 2019; Chen *et al.*, 2019; Zhang *et al.*, 2019):

$$u_d(\theta,t) = \int_{t_c}^{t} 0.0116 \cdot i_{corr}(\theta,t)dt \quad (13)$$

The mass loss of rebar can be expressed as:

$$M_S = \rho_s \int_0^{2\pi} u_d(\theta,t)\, d\theta \quad (14)$$

Where ρ_s is the density of the rebar（kg/m^3）:

So：

$$\rho(lim,t) = \frac{\rho_s \int_0^{2\pi} u(\theta,t)d\theta}{\rho_s \cdot \pi \cdot r_0^2} \times 100\% = \frac{\int_0^{2\pi} u(\theta,t)d\theta}{\pi \cdot r_0^2} \times 100\% \quad (15)$$

In the summary, the flow chart of service life prediction for RC structures is shown in Fig.3.

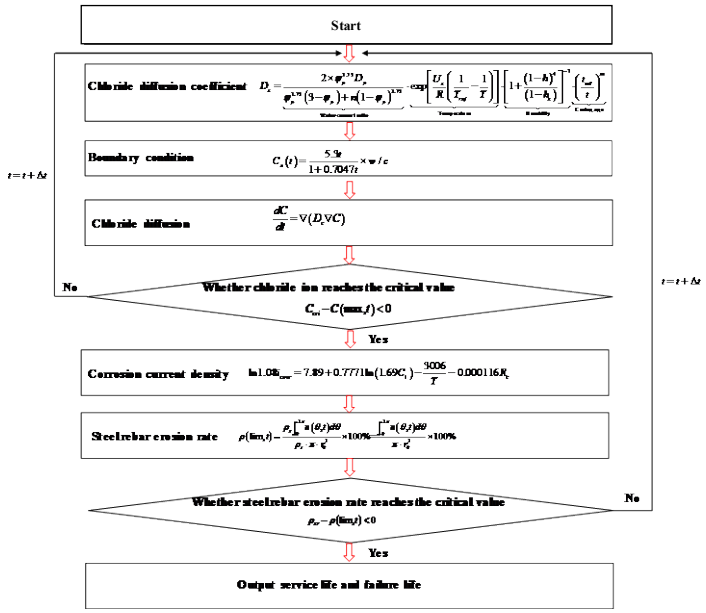


Figure 3. The Flow chart of the derivation of the proposed multiphase numeric model.

3. Numerical Model validation

The numerical model proposed in this paper comprises two stages modelling. The first stage is the diffusion of chloride ions, and the second stage is the corrosion of steel bars. Therefore, the model verification in this section is also divided into two aspects: chloride ion diffusion verification and service life. The parameters used in the simulation are listed in Table 1. In the process of numerical simulation, the finite difference method (FEM) is adopted to solve the chloride ion diffusion equation (Eq.1) to obtain the distribution of chloride ion concentration in concrete. Once the chloride concentration on the steel surface reaches the critical chloride concentration, the concrete structure will reach its service life. Secondly, the steel corrosion rate is calculated through the Eq (15). Once the steel corrosion rate reaches the critical steel corrosion rate, the concrete structure will reach its failure life.

Table 1. Numerical simulation parameters.

Symbol	Parameter value	Mean
U_c	44.6 $[K \cdot J/mol]$	the activation energy for chloride diffusion

t_{ref}	28 [d]	Reference time of chloride ingress
R	8.314[$J/K \cdot mol$]	the gas constant
h_c	0.75 [--]	the critical humidity
h	1	humidity
D_p	1.07×10^{-10} [m^2/s]	the diffusion coefficient of chloride in water
m	0.2	the time decay index of chloride diffusion
ρ_s	7500 [kg/m^3]	the density of the rebar
T_{ref}	293 [K]	reference temperature
δ_1	12.5 um	the depth of rust generated by filling the pores
r_0	8mm to 13mm	the reinforcement radius
Ec	30 [GPa]	elastic modulus of concrete
f_t	1.43 [MPa]	tensile strength of concrete
v_c	0.2	the Poisson's ratio of the concrete
c	40mm to 70mm	thickness of reinforced concrete cover
w/c	0.45, 0.55, 0.65	the water to cement ratio

3.1 Chloride diffusion verification

The experimental data of W. Chalee *et al*.(Chalee, Jaturapitakkul and Chindaprasirt, 2009) will be used to compare with the numerical simulation in this paper. The size of the concrete cube specimen was 200mm × 200mm × 200 mm, and the water-cement ratio was 0.45, 0.55, 0.65. And the concrete is immersed in seawater, which indicates that the concrete is saturated. Therefore, relative humidity of the concrete is 1 in numerical simulation. In addition, the average value of the external ambient temperature is 293 K. The comparison between numerical simulation results and test results is shown in Figure 4. Obviously, the chloride concentration curve obtained by numerical simulation is very close to that obtained by experiment,

which indicates that the chloride diffusion model is reliable.

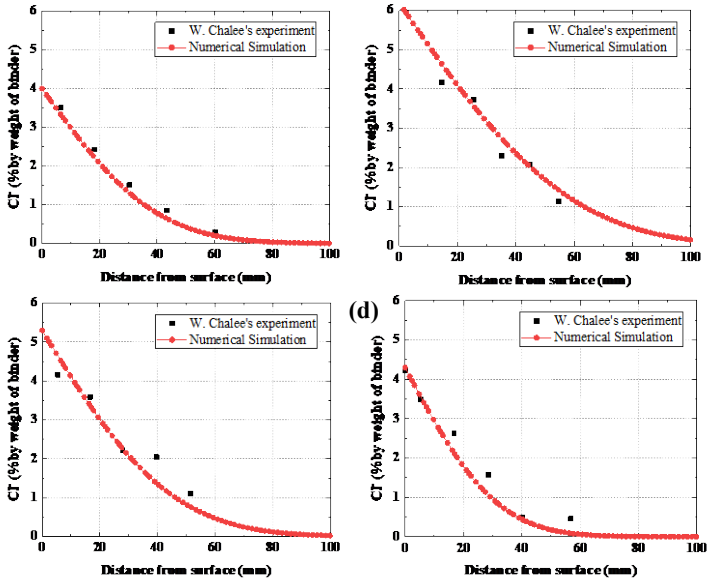


Figure 4 Chloride diffusion verification (a) w/c=0.65, time=2 years; (b)w/c=0.65, time=5 years; (c) (c) w/c=0.5, time=5 years;(d) w/c=0.45, time=5 years.

3.2 Service life verification

The service life prediction model proposed in this paper is compared with Moraddllo *et al*. (Khanzadeh Moradllo, Shekarchi and Hoseini, 2012) and Aruz *et al*. (Petcherdchoo and Chindaprasirt, 2019). The thickness of the concrete cover is 50mm and 60mm, and the water-cement ratio is selected as 0.55. In addition, the concrete is saturated, *i.e*. the relative humidity is 1. The average temperature of the environment is 293K. Reinforcement diameter is 10mm. Fig. 5 shows the comparison of the service life of the three models, it can be seen that the differences in the service life predictions of the three models are small, which indicates that the numerical model established in this paper has a certain degree of reliability.

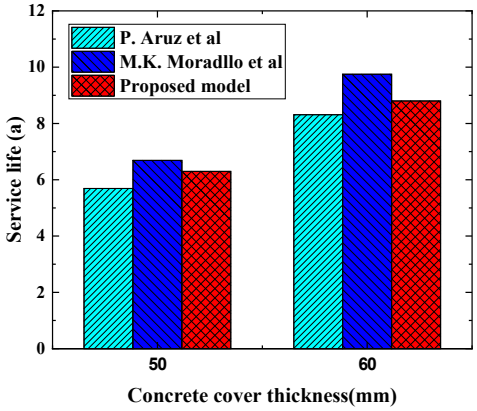


Figure 5 Service life verification

4. Parametric analysis using the new numerical model

Using the proposed numerical model, intensive parametrical studies are made, which are show as follows:

4.1 Influence of different water-cement ratios

The water-cement ratio for different concrete strength grades is different. However, different water-cement ratio has great influence on the chloride diffusion coefficient and the chloride ion concentration on the concrete surface, especially for the chloride diffusion coefficient(Ishida, Iqbal and Anh, 2009). Therefore, the water-cement ratio has a very important influence on the durability of RC structures (Pack *et al.*, 2010). Fig. 6a shows the service life of RC structures in the marine environment as a function of water-cement ratio. It can be seen from the Fig. 6a that the water-cement ratio has a very important effect on the service life of the marine engineering concrete structure. For example, when the water-cement ratio is 0.36, the service life is 46.1 years. However, when the water-cement ratio is increased to 0.55, the service life is only 6.3 years. Therefore, in marine engineering, using a low water-cement ratio can effectively increase the service life of the structure. Besides, Fig. 6a also shows the relationship between the deterioration duration and the water-cement ratio. The deterioration duration also decreases exponentially as the water-cement ratio increases. Moreover, as the water-cement ratio increases, the safety reserve decreases more slowly. The larger the water-cement ratio is, the longer the safety reserve period is, and the safety reserve period varies from 5.8 years to 9.8 years. Fig. 6b shows the change of the maximum chloride ion concentration on the surface of the steel bar with time under different water-cement ratios. It can be seen from the Fig. 6b that under the same ingress time, as the water-cement ratio increases, the chloride ion concentration gradually decreases. For example, when water-cement ratio of 0.55, the maximum chloride ion concentration on the surface of the steel bar increased rapidly within 0 to 20 years, and then increased slowly.

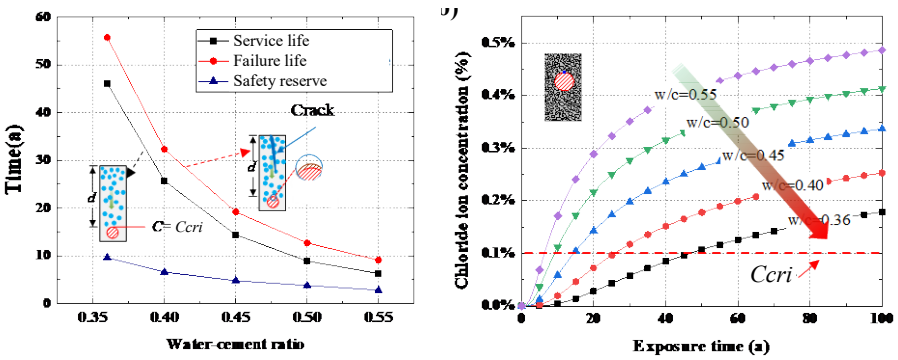


Figure 6 Effect of water-cement ratio on service life and chloride concentration distribution. (a) service life; (b) chloride concentration distribution

4.2 Thickness of concrete cover

The thickness of the concrete cover is an important parameter for structural design. For different environments, the requirements for the thickness of the concrete cover are different in the Code for durability Design of concrete structures. Therefore, it is necessary to study the effect of concrete cover thickness on service life. Fig.7a shows the values of three indicators of service life, failure life, and safety reserve under different concrete cover thicknesses. It can be seen from the Fig.7a that with the increase of the concrete cover thickness, the service life, deterioration duration and safety reserve all increase. For example, when the thickness of the cover is 40 mm, the service life is only 15.2 years. However, when the thickness of the concrete cover increased to 70 mm, the service life increased to 55.7 years, which was an increase of 3.67 times compared to the 40 mm thickness of the concrete cover.

Further research found that with the increase of the thickness of the cover, the range of the change in the safety reserve period was small and had a linear relationship with the thickness of the concrete cover. However, deterioration duration increases greatly with the increase of the thickness of the concrete cover. Fig. 7b shows the depth of the corrosion of the steel bar when the cover is cracked under different thicknesses of the concrete cover. It can be seen from the Fig. 7b that the corrosion geometric form of the steel bar with different cover thickness is similar, but the peak of the corrosion depth increases with the thickness of the cover and increase. For instance, when the thickness of the concrete cover is 40 mm, the depth of rust is 82.3 *um*, however, when the thickness of the concrete cover is 70 *u*m, the depth of rust is 100.4 *um*. Moreover, the corrosion depth curve of the steel bar in this paper is similar to the numerical model of Jinxia (Xia *et al.*, 2019), and this corrosion curve is similar to the corrosion mode of the entire steel bar observed through field exposure test experiments (Sun *et al.*, 2002; Poupard *et al.*, 2006; Kessler *et al.*, 2016).

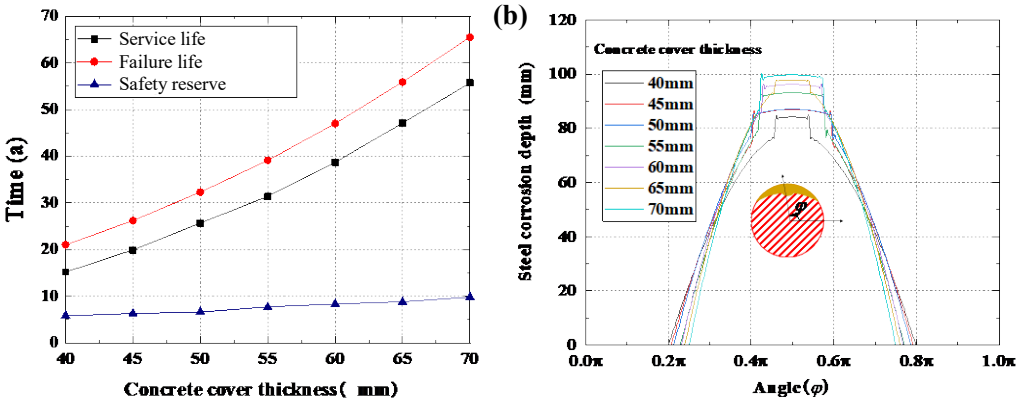


Figure 7 Influence of concrete cover thickness on send corrosion layer depth. (a) service life (b) corrosion layer depth.

4.3 Influence of critical chloride ion concentration

The critical chloride ion concentration is another important factor affecting the corrosion of steel bars. For different types of steel bars, cement types and service environments, the critical chloride ion concentration is not same. The critical chloride ion concentration obtained by many scholars has a very large value (Cao, Y. *et al*. 2019, Zhang, K. *et al*. 2019). Therefore, in this section, the influence of different critical chloride ion concentrations on the service life of RC structure is studied with a water-cement ratio of 0.4. As shown in Fig 8, as the critical chloride ion concentration increases, both the service life and the deterioration duration of the RC structure increase. More importantly, it turns out that the critical chloride ion concentration has a linear relationship with the service life, which is consistent with the results of S. Muthulingam *et al*. (Muthulingam and Rao, 2014). For instance, for every 0.01% increase in the critical chloride ion concentration, the RC structural service life increases by 2.5 years.

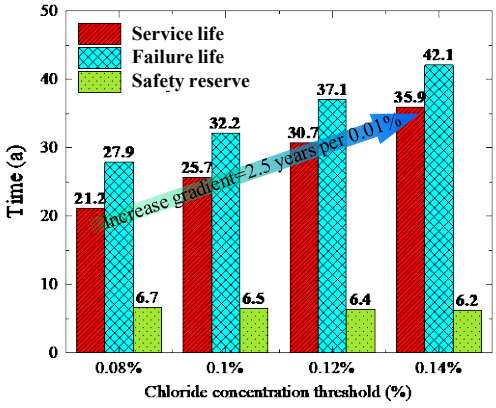
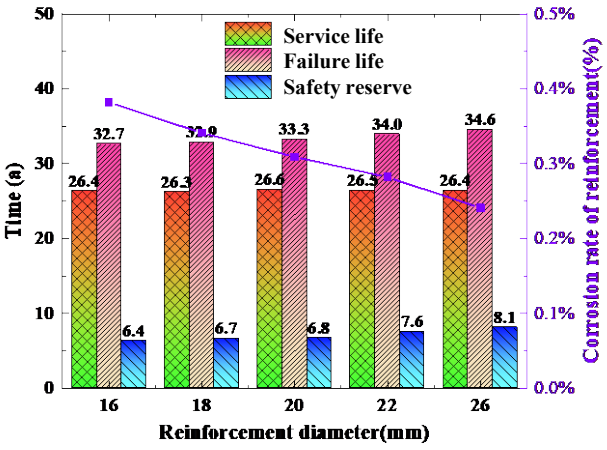


Figure 8 Effect of critical chloride ion concentration on service life

306 *4.4 Effect of Rebar Diameter*

307 For different types and functions RC structures, the rebar diameter in the RC structure is also different.
308 Therefore, it is of great significance to study the impact of the rebar diameter on the service life of marine
309 RC structures. Fig. 9 shows a histogram of the service life, failure life, and safety reserve of marine RC
310 structures in the range of rebar diameters from 16 mm to 26 mm. It can be seen from the Fig. 9 that the
311 influence of the rebar diameter on the service life could be ignored (*e.g.*, the difference between the maximum
312 and the minimum service life for different rebar diameter is only 0.5 year). This is mainly because the service
313 life mainly depends on the critical chloride concentration and thickness of concrete cover. Additionally, as
314 the diameter of the steel bar increases, the deterioration duration and safety reserve both increases, but the
315 upward trend is also slight. For example, when the rebar diameter is 16 mm, the deterioration duration and
316 safety reserve are 32.7 years and 6.4 years, respectively. And when the rebar diameter changes to 26mm, the
317 deterioration duration and safety reserve of the RC structure are 34.6 years and 8.1 years, respectively. Fig.
318 9 also shows the corrosion rate of steel bars when the structure fails under different the rebar diameters. It is
319 worth mentioning that as the rebar diameter increases, the corrosion rate of the rebar decreases significantly.
320 For example, when the rebar diameter is 16mm, the corrosion rate of the rebar is 0.382%; however, when the
321 rebar diameter is 26 mm, the rebar corrosion rate is only 0.241%.



322

323 **Figure 9** Effect of Rebar Diameter on service life

324 **5 A simplified empirical model for service life prediction**

325 According to the discussion in Section 4, it can be seen that the rebar diameter has a small effect on the
326 service life of the structure. And the thickness of the cover, the water-cement ratio and the critical chloride
327 ion concentration all have significant impact on the service life of the concrete structure. The cover thickness

and water-cement ratio are important parameters in engineering design. Therefore, in this paper, 300 groups RC structures with different water-cement ratios, concrete cover thickness are simulated to predict their service life. These 300 groups of data are divided into two categories. First: the thickness of the cover: 40mm, 45 mm, 50 mm, 55 mm, 60 mm, 70 mm, and the water-cement ratios 0.36, 0.40, 0.50, and 0.55. Second: the cover thickness is 65 and the water-cement ratio is 0.45 as a control group. A two-stage data fitting and regression analysis method are used to establish an empirical service life prediction model. In the first stage, the functional representing the relationship between the thickness of the cover and the service life is obtained through regression analysis, as shown in formula (16), where A and B is the undetermined coefficient related to water-cement ratio. In the second stage, through regression analysis, the relationship between the undetermined coefficients A and B and the water-cement ratio is obtained, as shown in formula (17).

$$f(w/c, cd) = A + B \times cd \tag{16}$$

Where A and B is fitting parameters; wc is water-cement ratio; cd is the thickness of concrete cover.

$$f(wc, cd) = \text{-}4.0+\exp\left(-\frac{326w/c}{19} + 10.364\right) + \left[\frac{2}{11}\text{-}\exp\left(-\frac{137w/c}{8} + 6.945\right)\right] \times cd \tag{17}$$

However, in the process of numerical simulation, we assume that the ambient temperature is 293 K and the concrete is saturated. Therefore, the applicable condition of formula (17) is saturated concrete with an ambient temperature of 293 K.

Fig. 10 shows the comparison between the service life prediction model proposed in this paper and the numerical simulation results. It can be found that the numerical simulation results are distributed near the prediction model curve, which indicates that the proposed model in this paper is reliable.

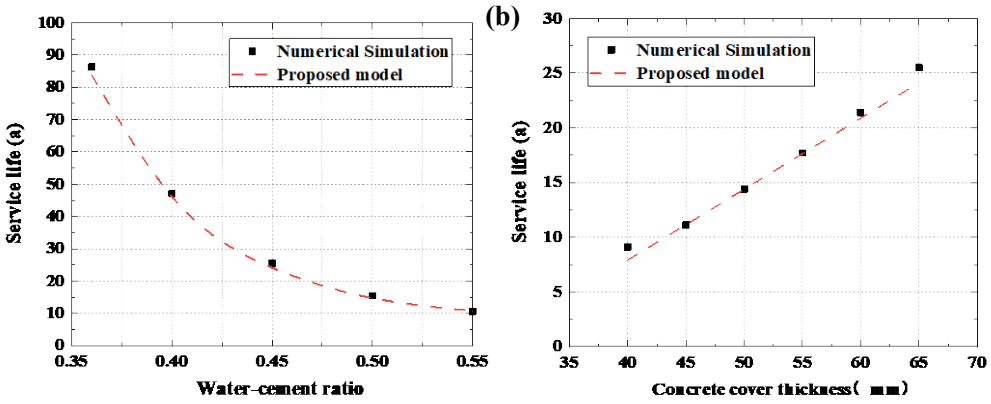


Figure 10 Validation of Practical service life prediction model (a) Cover thickness=65mm; (b) Water cement ratio=0.45

6 Conclusion

In this paper, both numerical and empirical models for predicting the service life of RC structures in the marine environment are proposed. The proposed numerical analysis model not only considers the service life of RC structures, but also the deterioration duration. Moreover, the effects of water cement ratio, rebar diameter, concrete cover thickness and critical chloride ion concentration on the service life and deterioration duration of RC structures are comprehensively analysed, and the key factors affecting the service life of RC structures are determined. The following conclusions can be drawn:

(1) With the increase of water cement ratio, the service life of RC structure decreases exponentially. When the water-cement ratio is 0.36, the service life is 46.1 years. However, when the water-cement ratio is increased to 0.55, the service life is only 6.3 years.

(2) With the increase of the thickness of the concrete cover, the service life, failure life, and safety reserve all linear increase; Thickness of corrosion layer with different cover thickness is similar, but the peak of the corrosion depth increases with the thickness of the cover increase.

(3) As the critical chloride ion concentration increases, both the service life and the deterioration duration of the RC structure increase. More importantly, it turns out that the critical chloride ion concentration has a linear relationship with the service life.

(4) The influence of the rebar diameter on the service life can be ignored. It is worth mentioning that as the rebar diameter increases, the corrosion rate of steel bars decreases significantly.

(5) Various factors (water-cement ratio, protective layer thickness, rebar diameter, *etc*.) have a small impact on the safety reserve period. The safety reserve period of RC structure is generally less than 10 years.

(6) Through regression analysis of 300 sets of simulation data, the proposed empirical forecasting model has good reliability in the service life prediction of RC structures and is suitable for practical engineers.

Availability of data and materials

All data that support the findings of this study are available from the corresponding author upon reasonable request.

Competing interests

The authors declare no conflict of interest.

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