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Service life prediction of chloride-corrosive concrete under fatigue load

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Abstract. Chloride corrosion has become the main factor of reducing the service life of reinforced concrete structures. The object of this paper is to propose a theoretical model that predicts the service life of chloride-corrosive concrete under fatigue load. In the process of modeling, the concrete is divided into two parts, microcrack and matrix. Taking the variation of mcirocrack area caused by fatigue load into account, an equation of chloride diffusion coefficient under fatigue load is established, and then the predictive model is developed based on Fick's second law. This model has an analytic solution and is reasonable in comparison to previous studies. Finally, some factors (chloride diffusion coefficient, surface chloride concentration and fatigue parameter) are analyzed to further investigate this model. The results indicate: the time to pit-to-crack transition and time to crack growth should not be neglected when predicting service life of concrete in strong corrosive condition; the type of fatigue loads also has a great impact on lifetime of concrete. In generally, this model is convenient to predict service life of chloride-corrosive concrete with different water to cement ratio, under different corrosive condition and under different types of fatigue load.

Keywords: fatigue load; Chloride induced corrosion; microcrack area; fatigue damage; service life

1. Introduction

Chloride-induced corrosion has become the main factor in deteriorating the durability of reinforced concrete (Farahani and Taghaddos 2015). Chloride ion can react with the steel bar inside the concrete and cause expansion, ultimately leads to the cracking and spalling of concrete cover, and loss of steel cross-section area (Otieno and Beushausen 2016). According to estimation, it costs about 100 billions of dollars per year in the world to maintain and repair the chloride-corrosive concrete (Pour-Ali and Dehghanian 2015, Chen 2004). It is of great economic value and necessary to investigate the service life of chloride-corrosive concrete such that taking effective remedial action at an appropriate time.

When investigating the service life of chloride-corrosive reinforced concrete, it is necessary to try to be the practical environment to guarantee the accuracy of result. Reinforced concrete structures are often used as a stressed structure, especially the fatigue load. Fatigue load have great impacts on chloride transport in concrete. Up to date, the effect of Fatigue load on chloride ion diffusion in concrete has been considerably investigated and a great many of achievements have been reported. So far, the results can be divided into two parts, experiments and models.

In the experimental part, the effect of fatigue load on chloride ion diffusion is related to the type of fatigue loads, i.e., the fatigue load is fatigue compressive load, fatigue tensile load or fatigue flexural load. There is little effect on the chloride ion diffusion in concrete under some certain load times when the load is fatigue compressive load, but if the damage caused by fatigue compressive load exceeds a critical value, the diffusion rate would increase significantly (Saito and Ishimori 1995, Nakhi and Xie 2000, Gontar and Martin 2000, Song and Zhang 2016, Zhang and Ba 2012, Lee and Hyun 2014). When the load is fatigue tensile load, the chloride ion diffusion rate in concrete will significantly increase, especially when the stress level is higher than 30% of tensile strength (Fu and Ye 2016, Jiang and Zhu 2016). Fatigue flexible load, being the most common investigated fatigue load, has complex impact on chloride induced corrosion in concrete, on which mainly depends the position of concrete. The chloride ion diffusion rate would increase greatly in tensile stress section, while the chloride ion diffusion rate of the compressive stress section changes little because the stress level in fatigue compressive section is very low (Song and Zhang 2016, Zhang and Ba 2012, Chen and Zheng 2009, Jiang and Liu 2015, Wang and Sun

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2013, Van Mien and Stitmannaithum 2009, Ren and Huang 2015, Cusson and Lounis 2011).

In the model part, some scholars proposed some empirical models under fatigue load based on experiments to predict chloride content or service life of concrete (Zhang and Ba 2011, Ren and Huang 2015, Jiang and Sun 2010, Zhang and Ba 2013). In their opinion, chloride diffusion coefficient is related to fatigue load stress, and an equation between chloride diffusion coefficient and fatigue load stress was established in some of their papers. All of the empirical models employed the Fick's second law to characterize chloride transport in concrete. Also, some other scholars put forward some theoretical models. Van Mien (2011) proposed a chloride diffusion coefficient expression that considering fatigue load. Bastidas-Arteaga (2009) and Xiang (2007) introduced a reliability model to predict service life of concrete respectively. Van Mien (2009) proposed a model that can predict chloride content in concrete taking fatigue stress level and drying-wetting into account. He (2015) proposed a model under fatigue load based on principle of diffusion-limited aggregation. However, to the best of authors' acknowledge, these models still have some disadvantages, such as only suitable for some certain conditions (Zhang and Ba 2011, Ren and Huang 2015, Jiang and Sun 2010, Zhang and Ba 2013), ignoring the influence of fatigue load on chloride diffusion in concrete cover (Zhang and Ba 2013, He and Li 2015) that would overestimate the lifetime of concrete, and having no analytic solution and inconvenient to use to predict service life (Van Mien and Stitmannaithum 2011, Xiang and Zhao 2007, He and Li 2015).

To the view of above statements, this paper aims at putting forward a theoretical model that can predict and calculate chloride content and chloride corrosive service life of reinforcement concrete under fatigue load. In order to establish this model, some simple assumptions are made to obtain the expression between fatigue load and chloride diffusion coefficient, then the model is proposed based on Fick's second law. Finally, using previous studies to validate the proposed model, and discussing the influence of different water to cement ratios, aggressive conditions, and types of fatigue loads on chloride ions transport in concrete.

2. Chloride-corrosive theoretical model under fatigue load

2.1 Charactering the chloride diffusion coefficient by microcrack area

Concrete have original defects, such as microcracks and connected pores, naturally. These defects provide a channel for the transport of chloride ion inside concrete. According to the division of the author's previous paper (Yang and Guan 2019), the concrete can be divided into two parts, matrix and microcracks, as Fig. 1 shows. The micocrack represents the cracks caused by temperature, hydration and/or external load; the matrix represents all parts of concrete except micocracks.

Based on the above division, chloride ions enter into concrete through these microcracks and the interconnected pores of matrix, therefore, the total amount of chloride ions diffusion contain the amount from matrix and the amount from microcracks, which can be expressed as Eq. (1).

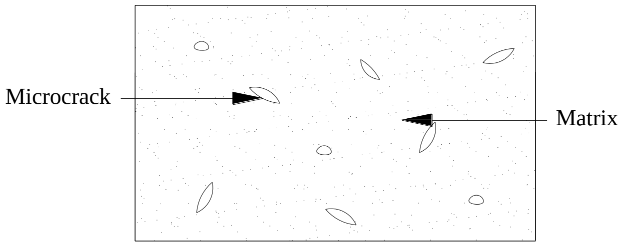

Fig. 1 The division of concrete area

$$J\left(A_m + A_c\right) = J_m A_m + J_c A_c \tag{1}$$

Where J is the total diffusion flux, J_m and J_c is the diffusion flux of matrix and microcracks respectively, A_m and A_c is the area of matrix and microcracks respectively.

According to diffusion theory (Xiao and Wei 1992), the diffusion flux can be expressed as

$$J = -D\mu \tag{2}$$

$$J_m = -D_m\mu \tag{3}$$

$$J_c = -D_c\mu \tag{4}$$

Where μ is the chloride ion chemical-potential gradient, D, D_m, and D_c is chloride diffusion coefficient of concrete, matrix and microcrack respectively.

Taking Eq. (2)-Eq. (4) into Eq. (1), which can be rewritten as

$$D = \frac{D_m A_m + D_c A_c}{A_m + A_c} \tag{5}$$

From Eq. (5) it can be found that the chloride diffusion coefficient of concrete can be described by microcrack areas.

As for undamaged concrete, original microcrack area is very small, and is much smaller than matrix area, which means $A_m \geq A_c$, and then Eq. (5) can be simplified as

$$D = D_m + \frac{A_c}{A_m} D_c \tag{6}$$

As we know, the chloride diffusion coefficient is related to crack width. When the crack width is less than the lower limit, crack width have no effect on chloride diffusion coefficient; when the crack width is greater than the upper limit, crack width also have no effect on chloride diffusion coefficient, the chloride diffusion coefficient can be considered as a constant and as the diffusion coefficient in water, which is much larger than diffusion coefficient in crack width less than lower limit (Jin and Yan 2010, Djerbi and Bonnet 2008). In present paper, D_m is considered as the diffusion coefficient in crack width less than lower limit, and D_c is considered as the diffusion coefficient in crack width greater than upper limit.

Fatigue loads can cause fatigue accumulative damage in concrete, which would extend and propagate the microcrack, thus increase the microcrack area. Consequently, the chloride diffusion coefficient increases too. According to Eq. (6), the chloride diffusion coefficient of damaged concrete can be expressed as

$$D^{'} = D_m + \frac{A_c^{'}}{A_m} D_c \tag{7}$$

Where $D^{'}$ is the chloride diffusion coefficient of damaged concrete, $A_c^{'}$ is the microcrack area of damaged concrete.

The microcrack areas of damaged concrete contain the original microcrack areas and increment of microcrack areas, which can be written as

$$A_c^{'} = A_c + \Delta A_c \tag{8}$$

Where ΔA_c is the increment of microcrack areas of damaged concrete.

Taking Eq. (8) into Eq.(7), which can be rewritten as

$$D^{'} = D + \frac{\Delta A_c}{A_m} D_c \tag{9}$$

where D is the chloride diffusion coefficient of undamaged concrete.

Eq. (9) shows that chloride diffusion coefficient of damaged concrete can be described by variation of microcrack areas.

2.2 Fatigue damage of concrete

According to the classical damage theory of Kachanov-Rabotnov, the damage variable of material can be interpreted as the effective area reduction caused by cracks (Murakami 1988), which can be expressed as

$$d = \frac{A - A^*}{A} = \frac{\Delta A}{A} \tag{10}$$

Where d is the damage variable of material, A is the original area of material, A^* is the effective area of damaged material, ΔA is the crack area of material.

Concrete usually have original microcracks and other cracks caused by some causes (such as prestress) before the fatigue load applied, thus have original damage based on the definition of Eq. (10). In present paper, on the purpose of investigating the effect of fatigue damage on chloride diffusion, defining that the original damage of concrete is 0, hence the crack area ΔA in Eq. (10). is the increment of microcrack area caused by fatigue load, therefore, the damage variable of concrete under fatigue load can be expressed as

$$d = \frac{\Delta A_c}{A_m} \tag{11}$$

Taking Eq. (11) into Eq. (9), which can be rewritten as

$$D^{'} = D + dD_c \tag{12}$$

It can be seen from Eq. (12) that chloride diffusion coefficient increases along with the increase of concrete damage variable. This is consistent with previous research results and the main difference between them might be the difference of the definition of damage variable.

Fatigue load would cause damage in concrete, the longer the fatigue load applied to concrete, the more microcraks initiated, thus the more damage the concrete became. According to linear cumulative damage theory, a widely used fatigue damage theory of materials, the damage of concrete is proportional to the number of fatigue loads (Yun and Kim 2005, Fatemi and Yang 1998, Christensen 2002), which can be expressed

$$d = \frac{n}{N_f} \tag{13}$$

Where n is the number of fatigue loads, N_f is the fatigue life times of concrete.

In Eq. (13), the number of fatigue loads n is the product of the frequency of the load and the time of action, which can be given as

$$n = f \cdot t \tag{14}$$

Where f is the frequency of the load; t is the time of action.

Taking Eq. (14) into Eq. (13) yields

$$d = \frac{ft}{N_f} \tag{15}$$

As the microcrack area of concrete increases with the increase of the number of fatigue loads, in this paper, assuming that the damage caused by microcrack areas increasing is equal to the damage caused by fatigue load numbers. In other words, the Eq. (15) is equal to Eq. (11), and then the Eq. (12) can be rewritten as

$$D^{'} = D + \frac{ft}{N_f} D_c \tag{16}$$

2.3 Model of chloride diffusion

It is well known that Fick's second law is the most widely used model to describe the process of chloride diffusion in saturated concrete. Indeed, the Fick's second law is insufficient to characterize the transport of chloride ion in concrete at atmospheric zone and tidal zone as the transport mechanism of chloride ion in these zone is very complicate, especially among outer several millimeters. However, due to its simple mathematical expression, many researchers still use Fick's second law to characterize chloride diffusion in interior concrete based on specific parameters (Liu and Ou 2017, Ann and Ahn 2009, Song and Lee 2008, Pack and Jung 2010). This method is effective and convenient to predict chloride content in interior concrete and predict service life of chloride-corrosive concrete. In present paper, the authors also based on Fick's second law to establish the predictive model under fatigue load, as Eq. (17) shows

$$\frac{\partial C}{\partial t} = D^{'} \frac{\partial^2 C}{\partial x^2} \tag{17}$$

Where C is the chloride content of concrete, a function of time and location, x is the location of diffusion direction, $D^{'}$ is the chloride diffusion coefficient of fatigue damaged concrete, giving in Eq. (16).

In order to solve the Eq. (17), initial condition and boundary condition have to be offered.

(1) Initial condition

The initial content of chloride ions in the concrete is C_0, which can be described as

$$C\left(x \geq 0, t=0\right)=C_0 \tag{18}$$

(2) Boundary condition

Some scholars suggest the surface chloride concentration (C_s) can be regarded as a constant (Life-365 2010, Lay and SchieBl 2003, Lindvall 1998, McGee 1999), which can be described

$$C\left(x=0, t \geq 0\right)=C_s \tag{19}$$

In the process of solving, rewriting Eq. (19) as

$$\frac{\partial C}{D^{'}\partial t}=\frac{\partial^2 C}{\partial x^2} \tag{20}$$

Making

$$\partial T = D^{'}\partial t \tag{21}$$

Substituting Eq. (21) into Eq. (22) gives

$$\frac{\partial C}{\partial T}=\frac{\partial^2 C}{\partial x^2} \tag{22}$$

Combined Eq. (18) and Eq. (19), Eq. (22) has a standard solution, as Eq. (23) shows

$$C\left(x,t\right)=C_0+\left(C_s-C_0\right)erfc\left(\frac{x}{2\sqrt{T}}\right) \tag{23}$$

Where $erfc$ (•) is complementary error function, $erfc(z)=\frac{2}{\sqrt{\pi}}\int_z^{\infty}e^{-x^2}dx$.

Integrating Eq. (21) gives

$$T=\int_0^t D^{'}dt=\int_0^t D+\frac{ft}{N_f}D_c dt=Dt+\frac{fD_c}{2N_f}t^2 \tag{24}$$

Substituting Eq. (24) into Eq. (23) yields

$$C\left(x,t\right)=C_0+\left(C_s-C_0\right)erfc\left(\frac{x}{2\sqrt{Dt+\frac{fD_c}{2N_f}t^2}}\right) \tag{25}$$

Eq. (25) is the proposed model that chloride ions transport in concrete under fatigue load. It can be found that this model is related to material property (D, N_f) and fatigue load parameters (f, N_f), and can be used to predict chloride content in concrete if the parameter values of material and fatigue load were gave.

3. Comparison with previous studies

In general, the chloride content of the location of embedded rebar exceeds the critical chloride content, meaning the rebar begins to corrosion, regard as the durability failure of concrete when durability designs (Kwon and Na 2009). In this paper, the authors also consider the time when the rebar embedded in concrete starts to rust as the service life of concrete. Professor Sun's Group have made a lot of efforts on chloride induced corrosion of concrete (Wang and Sun 2013, Jiang and Sun 2010, Sun and Jiang 2009) and proposed an empirical model, based on experiments and specific conditions of Qingdao Jiaozhou bay of China, to predict service life of reinforced concrete. In their model, the effect of fatigue load on chloride diffusion coefficient was also taken into account (Jiang and Sun 2010, Sun and Jiang 2009), as Eq. (26) shows. The fatigue life N_f in Sun's model was expressed as Eq. (27).

$$C\left(x,t\right)=C_0+\left(C_s-C_0\right)erfc\left(\frac{x}{2\sqrt{(3.2+0.8e^{0.023t-0.33})\times 10^{-12}t}}\right) \tag{26}$$

$$N_f=10^{\frac{a-S}{b}} \tag{27}$$

Where S is the fatigue load stress, a and b are the material parameters.

The parameter values of Sun's model were showed in Table 1 (chloride diffusion coefficient and material constant were acquired through experiments from the concrete same to Jiaozhou Bay undersea tunnel; the vehicle load frequency was the design traffic capacity of the undersea tunnel; surface chloride concentration was acquired from field investigation in previous structure; fatigue stress level was the estimated maximum fatigue stress level; concrete cover was the design value; initial chloride concentration was generally neglected and equals 0; Critical chloride content of corrosion was acquired from the undersea tunnel designing documents). Substituting these parameter values into Eq. (26), and Chloride diffusion coefficient in crack D_c equals 1.5×10^{-9} m^2/s (Jefremczuk 2004). The results predicted by the model proposed in present study, Sun's model and Fick's second law were shown in Fig. 2.

Table 1 Parameter values of Sun's model (Jiang and Sun 2010, Sun and Jiang 2009)

Parameters	Values
Chloride diffusion coefficient of concrete D/ $m^2\cdot s^{-1}$	4×10^{-12}
Material constant a	1.07
Material constant b	0.09
Vehicle load frequency f /times$\cdot d^{-1}$	70000
Fatigue stress level S*	0.2
Concrete cover /mm	70
Surface chloride concentration C_s /% by concrete weigh	0.1
initial chloride concentration C_0 /%	0
Critical chloride content of corrosion/% by concrete weigh	0.07

*Note: S=0.2 means the fatigue stress level is 20% of tensile strength of concrete

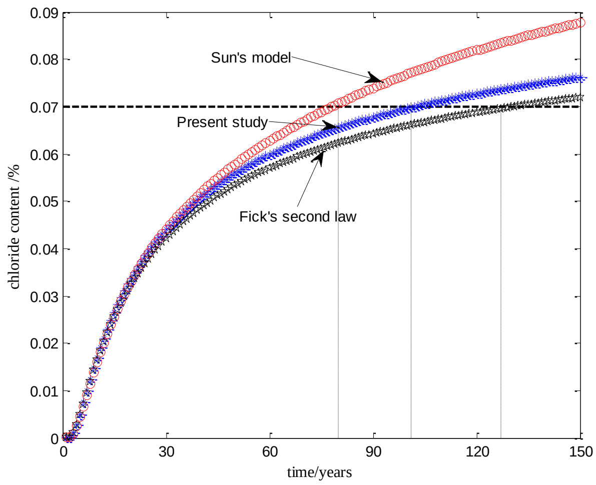

Fig. 2 Predictive service life of different model

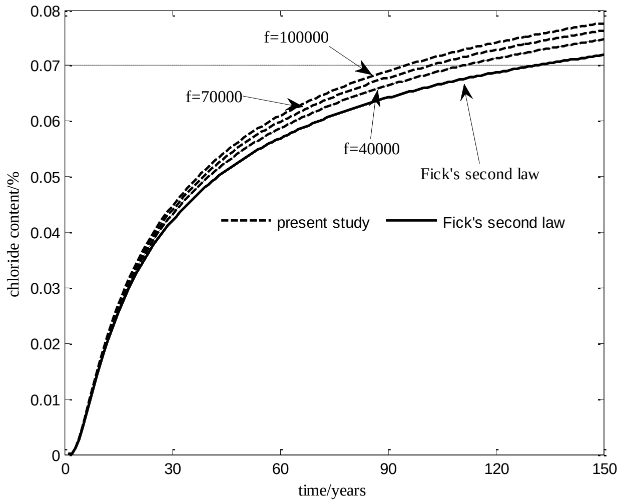

Fig. 3 Variation of chloride contents with time in various vehicle load frequencies

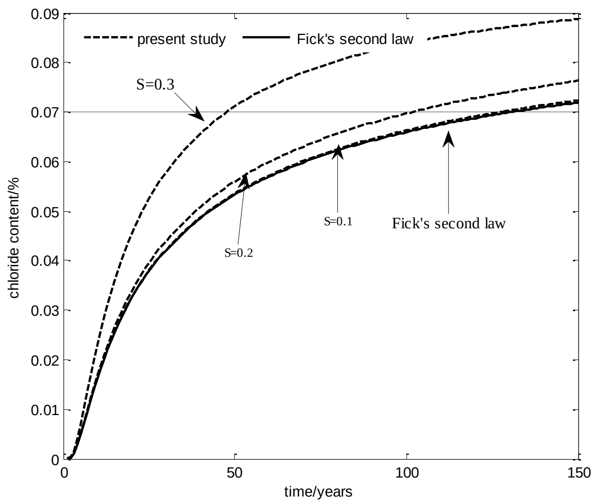

Fig. 4 Variation of chloride contents with time in various fatigue stress levels

*Note: S=0.1, 0.2, 0.3 means the fatigue stress level is 10%, 20%, 30% of tensile strength of concrete, respectively

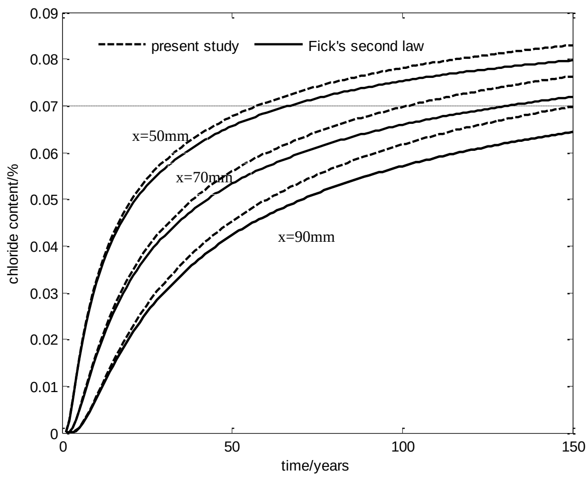

Fig. 5 Variation of chloride contents with time in various concrete cover thicknesses

The predictive service life of concrete structure in atmospheric zone using different model was shown in Fig. 2. It can be seen from Fig. 2 that fatigue damage decreases the service life of concrete dramatically, as the service life of this concrete is about 80a, 100a, and 130a predicted by Sun's model, the proposed model in present study and Fick's second law respectively. Fig. 2 also shows that there is little difference in chloride ions transport in early 20 years between the fatigue load and the no-load concrete, and the difference become significant after 50 years, which is also demonstrated in reference (Jiang and Sun 2010). However, there is still a difference between the results of Sun's model and present study, namely the predictive service life in Sun's model is shorter than present study. A possible explanation for this phenomenon may result from Sun's model considered the end of second stage of fatigue curve as the point of fatigue failure of concrete and ignored the third stage, hence the fatigue damage is overestimated. Consequently, the predictive service life is shorter compared to the result of present study.

Based on the parameter values of Table 1, the service life of concrete with different vehicle load frequencies, fatigue stress levels and concrete cover thicknesses were predicted and compared with the predictive results of Fick's second law. The results were showed as Fig. 3 to Fig. 5.

From Fig. 3, it can be found that, as expected, the service life decreases with the increase of vehicle load frequency. The service life is about 95a, 100a and 110a at vehicle load frequency of 100000 times/day, 70000 times/day and 40000 times/day respectively, all of them are shorter than Fick's second law predicted. The reason why different vehicle load frequencies do not have significant effect on service life is that: the fatigue load stress level is too low (S=0.2) in this study so that the fatigue life is very large, as a result, the fatigue damage is also low when chloride content reaches the critical value, since low fatigue damage have little influence on chloride ions diffusion (Jiang and Sun 2010).

From Fig. 4 it is reasonable to see that the service life decreases with the increase of fatigue stress level. When the stress level is 0.1, the service life predicted in the proposed

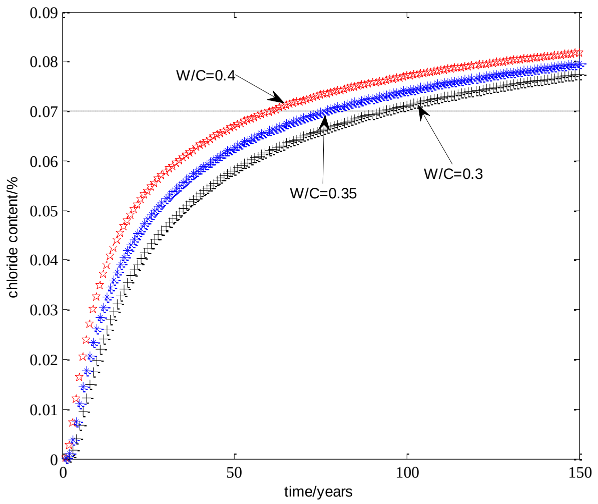

Fig. 6 Variation of chloride contents with time in different water to cement ratios

model is nearly closed to undamaged diffusion model, Fick's second law. The service life decreases dramatically when the stress level is 0.3, which is in accordance with reference (Fu and Ye 2016), reported that chloride diffusion coefficient would increase significantly under this stress level.

As Fig. 5 shows the service life predicted in present study under different cover thicknesses is always shorter than Fick's second law did. The thicker the concrete cover, the bigger the gap of their results. This phenomenon illustrates that fatigue load have much impact on service life of the thicker concrete covers.

According to the results and comprehensive analysis, it can be seen that the theoretical model proposed in this study is primary in accordance with practice conditions and is reasonable.

4. Parametric analysis

According to Eq. (25), it can be noted that there are two parameters, D and N_f, related to material properties; D_c can be considered as constant (Jefremczuk 2004), D_c=1.5×10^{-9}; f is related to vehicle load frequency or other loads frequency; and C_s is associated with corrosion conditions. The effect of concrete property, corrosion condition, and the type of fatigue load on service life of concrete was analyzed in this study.

4.1 Chloride diffusion coefficient

The influence of concrete properties on chloride diffusion coefficient has been investigated widely. The water to cement ratio, admixture, and concrete age of concrete all has an influence to the chloride diffusion coefficient in concrete. This paper would focus study the water to cement ratio on chloride-corrosive service life of concrete, other factors such as admixture and age will be discussed in further study. The chloride diffusion coefficient would increase with the increase of water to cement ratio (Life-365 2010, Lay and SchieBl 2003, Yan and Jin 2011, Jin and Guo-Jian 2011). A common used model was choosing to characterize the effect of water to cement ratio on chloride diffusion coefficient (Life-365 2010), as Eq. (28) shows. Taking this equation into Eq. (25).

$$D_{28} = 10^{(-12.06+2.4W/C)} \tag{28}$$

The service life of concrete with various water to cement ratio shows in Fig. 6 (when predicted, all parameter values of model come from Table 1 except the chloride diffusion coefficient). It can be found that the service life decreases from 95a to 60a when the water to cement ratio increases from 0.3 to 0.4. This is the partial reason choosing low water to cement ratio in practice and adding admixture in concrete, as admixture can reduce chloride diffusion coefficient of concrete (Life-365 2010, Yiğiter and Yazıcı 2007, Hisada and Nagataki 1999, Papadakis and Tsimas 2002).

Table 2 Value of surface chloride concentration (McGee 1999)

Level of aggressiveness	Description	C_s /% by weight of concrete*
low	structures placed at 2.84 km or more from the coast	0.015
moderate	structures located between 0.1 and 2.84 km from the coast without direct contact with seawater	0.048
high	structures situated to 0.1 km or less from the coast, but without direct contact to seawater	0.12
extreme	structures subject to wetting and drying cycles; the processes of surface chloride accumulation are wetting with seawater, evaporation and salt crystallization	0.30

*Note: The unit of C_s in reference is kg/m^3, and is transferred to % by weight in this paper, the density of concrete ρ=2400 kg/m^3

4.2 Surface chloride concentration

Corrosive condition determines the surface chloride concentration of concrete. Some efforts have been dedicated to the values of surface chloride concentration (Lay and SchieBl 2003, Lindvall 1998, McGee 1999), in general, the worse the corrosive condition, the greater the value of surface chloride concentration. The mean value of C_s of different level of aggressiveness is illustrated in Table 2 (McGee 1999).

The service life of various levels of aggressiveness shows in Fig. 7 (when predicted, all parameter values come from Table 1 except surface chloride concentration come from Table 2). It can be found that the service life of concrete under extreme and high level of aggressiveness is about 15a and 55a respectively, which is too short that looks unbelievable. To further understand this phenomenon, the authors compared these results with the results of Fick's second law predicted. It shows that there is not much

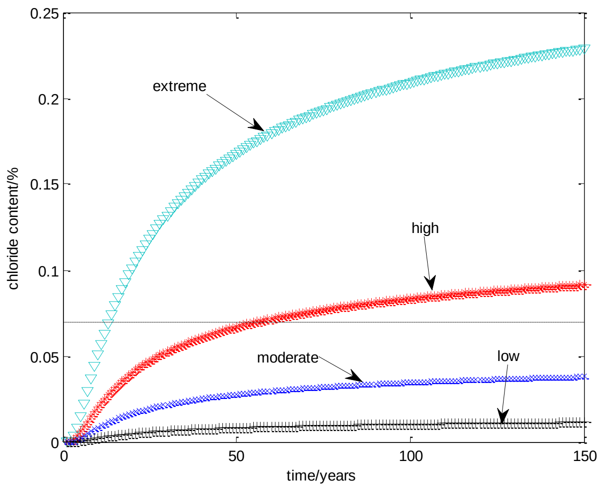

Fig. 7 Variation of chloride contents with time in different levels of aggressiveness

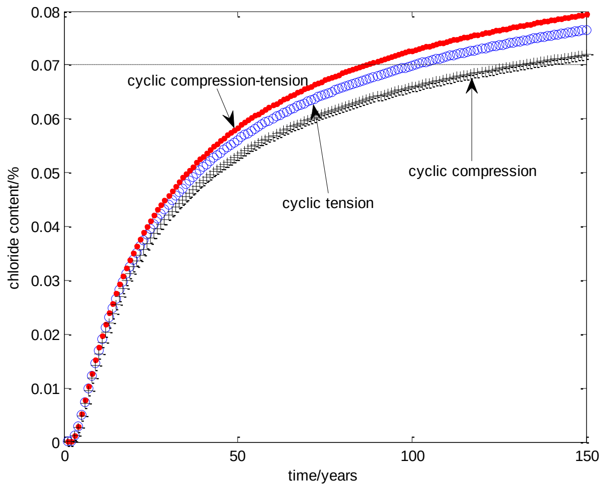

Fig. 8 Variation of chloride contents with time in different fatigue equations

difference between the results calculated by these two models, as the results predicted by Fick's second law are 16a and 60a corresponding to extreme and high level of aggressiveness. The reason why the service life is so short may be that: the total lifetime of reinforced concrete caused by chloride induced corrosion contains three parts, the time to corrosion initiation, time to pit-to-crack transition and time to crack growth. In general, the time to corrosion initiation, which means the time the chloride ion content of rebar surface reaches the critical value, is considered as the corrosion lifetime of concrete, the same to the present study. However, the total lifetime is relative short in extreme aggressive environment, especially the proportion of time to corrosion initiation in total lifetime decreases when the level of aggressiveness is increased (Bastidas-Arteaga and Bressolette 2009), as a result, the service life become very short in extreme level of aggressiveness in present study. Therefore, the stages of pit-to-crack transition and crack growth should not be neglected in severe corrosive environment and should be further studied.

4.3 Fatigue parameters

The fatigue life N of concrete can be predicted by the fatigue stress level S (Oh 1991), different type of load has a different influence on fatigue life. The expressions of S-N curves are demonstrated in Fib Model Code 2010 (Taerwe and Matthys 2013):

a. For cyclic compression

$$\log N_1 = \frac{8}{Y-1}\left(S_{c,\max}-1\right) \tag{29}$$

$$\log N_2 = 8 + \frac{8\ln(10)}{Y-1}\left(Y - S_{c,\min}\right)\log\left(\frac{S_{c,\max}-S_{c,\min}}{Y-S_{c,\min}}\right) \tag{30}$$

With

$$Y = \frac{0.45+1.8S_{c,\min}}{1+1.8S_{c,\min}-0.3S_{c,\min}^2} \tag{31}$$

Where:

i. If $\log N_1 \le 8$, then $\log N = \log N_1$

ii. If $\log N_1 > 8$, then $\log N = \log N_2$

b. For cyclic compression-tension with $\sigma_{ct,\max} \le 0.026\left|\sigma_{c,\max}\right|$

$$\log N = 9\left(1-S_{c,\max}\right) \tag{32}$$

c. For cyclic tension and tension-compression with $\sigma_{ct,\max} > 0.026\left|\sigma_{c,\max}\right|$

$$\log N = 12\left(1-S_{ct,\max}\right) \tag{33}$$

Where $S_{c,\max}$ is the maximum compressive stress level, $S_{c,\min}$ is the minimum compressive stress level, $S_{ct,\max}$ is the maximum tensile stress level, $\sigma_{c,\max}$ is the maximum compressive stress in MPa, $\sigma_{ct,\max}$ is the maximum tensile stress in MPa. The specific calculation methods of these parameters are shown in Fib Model Code (Taerwe and Matthys 2013).

To conduct a simple study about the effect of different type of fatigue load on chloride ions diffusion, the value of some parameters was simplified in present study. For cyclic compression, $S_{c,\min}$=0.2 (20% of compressive strength), $S_{c,\max}$=0.3 (30% of compressive strength); for cyclic compression-tension, $S_{c,\max}$=0.1 (10% of compressive strength); for cyclic tension, $S_{ct,\max}$=0.3 (30% of tensile strength), the vehicle load frequency f=4000 times/day, other parameters come from Table 1. Fig. 8 shows the service life of concrete in different fatigue life equations.

It can be seen from Fig. 8 that different types of loads have different service life, and the time order is: cyclic compression>cyclic tension>cyclic compression-tension. Obviously, it does not mean the service life of concrete subjected to cyclic compression-tension is always shorter compared to other types of loads, because the load frequency, corrosion environment and stress level also play an important part on it. Fig. 8 only illustrates that the type of loads have a great impact on chloride ion diffusion in concrete and some special attentions should be paid. This study also shows the model proposed in present study have the ability to describe chloride ion diffusion under different types of fatigue loads.

5. Conclusions

In this paper, the service life of chloride-corrosive concrete under fatigue load was investigated. The following conclusions can be obtained in this study:

(1) A new theoretical model is proposed. This model takes the variation of microcrack area and fatigue cumulative damage into account, introduces an expression of chloride diffusion coefficient under fatigue load, and is developed based on Fick's second law.

(2) Some works were done to compare the proposed model in this paper with previous studies, the results showed the proposed model is in accordance with practice conditions and is reasonable.

(3) Through the analysis of some parameters, the results showed: the service life of concrete decreases with the increase of water to cement ratio; chloride-contaminated environments have a great impact on service life of concrete, and the time to pit-to-crack transition and time to crack growth should not be neglected in strong corrosive condition; the type of fatigue loads has a different impact on chloride ion diffusion in concrete.

(4) This model has a simple form and is able to predict service life of concrete with different water to cement ratio, under different corrosive condition and under different types of fatigue loads. It can provide some reference values in concrete durability design.

In present studies, only the effect of fatigue load on chloride diffusion was investigated when modeling, the cement hydration, temperature and humidity also have a great impact on chloride diffusion, but have not considered. Therefore, in future studies, the authors hope to consider these factors into predictive model if possible.

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