Durability of Reinforced Concrete Structures under Coupling Action of Load and Chlorine Erosion

Yang Li[1, *], Dongwei Yang[1] and Jiangkun Zhang[1]

Abstract: Diffusion behavior of chloride ion in reinforced concrete under bending moment was studied by taking the ratio of bending moment to ultimate flexural capacity as load level indicator. The function relationship between load level and chloride ion diffusion coefficient was established, based on that the limit state equation of the chloride ion critical concentration and chloride ion concentration on surface of the steel bar was established. Then by applying Monte-Carlo method the corrosion probability of reinforcement under different load levels in splash zone was calculated. Calculation results demonstrated that compared with the durability reliability index considering loading effect, the reliability index without considering loading effect could be 100% higher. In consideration of requirement for concrete durability, some revision suggestion was put forward. It was recommended that for beam members with different design life in splash zone, the corresponding minimum cover thickness should be adjusted properly as well as water-cement ratio limit.

Keywords: Concrete durability, reliability index, coupling effect, chloride ion diffusion.

1 Introduction

In coastal areas [Moreno, Pellicer, Adam et al. (2017)], concrete structures are not only subjected to environmental attacks (e.g. the penetration and diffusion of chloride ions) but also wind loads, vehicle loads, wave loads and even seismic loads. At present, the generally accepted research result shows that: The load may not only change the micro-/meso-structure of concrete, but even cause new micro-cracks. This leads to the change of the penetration and diffusion boundary conditions of chloride ions, and finally the change of the permeability and diffusivity of chloride ions. However, there is less considering of the loading effect in the present research on the durability design method of reinforced concrete structures [Zhong and Jin (2016)]. Based on a large number of chloride ion permeation model and steel corrosion model, time dependent reliability and service life prediction of concrete structure were studied deeply in document [Gao, Lu, Yuan et al. (2016); Haque and Kawamura (1993); Wu, Li, Wang et al. (2016); Argiz, Moragues, Menéndez et al. (2017); Yang and Wang (2018); Alkam and Alqam (2015); Safehian and Ramezanianpour (2013)]. But in this research loading effect has not been considered as major factor affecting durable reliability indicator. At present, a large

[1] School of Civil Engineering and Environment, Hubei University of Technology, Wuhan, Hubei, 430068, China.

* Corresponding author: Yang Li. Email: liyang01245@126.com.

number of experimental studies have been carried out on the coupling action of chlorine erosion and load including compression [Tegguer, Bonnet, Khelidj et al. (2013)], static bending [Lei, Peng and Shi (2014); Wang and Zhou (2013)], splitting [Park, Kwon and Jung (2011)] and repeated compression [Lee, Hyun, Kim et al. (2014); Zhang, Jia, Meng et al. (2014)]. Meanwhile the actual engineering components and induced cracking components were also studied [Da Costa, Fenaux, Fernández et al. (2013); van den Heede, Maes, De Belie (2014); Cui, Lu, Liu et al. (2013)]. All these research were conducted from two aspects of lower stress level or higher stress level. However, in existing research there are two main shortcomings: Firstly, there is short of unified theory and numerical models about the influences of higher/lower stress level on chloride ions diffusion action [Du, Liu and Zhang (2016)]. Secondly, as the present main indicators of loading performance, concrete stress (ratio), strain (ratio) and crack are all difficult to be accurately quantified in the actual project design, which pose an impediment to the analysis of structure durability reliability with considering loading effect.

In response to this situation, the ratio of load to ultimate bearing capacity was used as the load level index, thus the unified theory and numerical model about the effect of higher/lower level load on chloride ion diffusion action is established. By test research of chloride ion diffusion phenomenon in reinforced concrete, the existing chloride ion diffusion model under loading is further perfected. Based on this improved model, the limit state equation of critical chloride ion concentration considering coupling effect of load and chloride ion diffusion was established. And then the probability of the initial rust in the concrete under load was calculated. The calculation results can provide a method for appraising time dependent reliability of existing reinforced concrete structures and revising the code contents concerning concrete durability design.

2 Chloride ion corrosion model under loading

Based on Fick's second law, by analyzing a large number of experimental data, the chloride ion diffusion coefficient was found to be changed with time. And the time-chloride diffusion coefficient model was as follows [Mangat and Limbachiya (1999)]:

$$D(t) = D_0\left(\frac{t_0}{t}\right)^{\alpha} \tag{1}$$

Where D_0 is the chloride ion diffusion coefficient of concrete exposure to the chloride ion environment after the time t_0; α is the coefficient related to water-cement ratio of the concrete as well as the mineral admixture type and proportion.

For beam members, at low stress level the bending moment is generally proportional to the stress of concrete; whereas, at high stress level, the main factors influencing chloride ions penetration in concrete are the width and depth of concrete cracks which also have a proportional relationship with load. According to this, on the basis of Eq. (1), the following solution model [Wang and Zhou (2013)] of chloride ion transport is established by taking the ratio of load to ultimate bearing capacity as load level:

$$C(x,t)=C_0+\left(C_s-C_0\right)\left[1-\mathrm{erf}\left(\frac{x}{2\sqrt{\frac{K_e f(\delta)D_0 t_0^{\alpha}t^{1-\alpha}}{1-\alpha}}}\right)\right] \tag{2}$$

Where C (x, t) is the percentage of chloride ion concentration in the depth of x from the surface of the concrete at time t; C_0 is the initial chloride ion concentration in the concrete (in %); C_s is the surface chloride concentration (in%); x is the chloride ion diffusion depth(m); K_e is the environmental influence coefficient; δ is the ratio of the load effect of the concrete specimen to the ultimate bearing capacity of the concrete specimen, load ratio for short; $f(\delta)$ is load effect coefficient; Other variables have the same meanings as that in Eq. (1).

It can be seen from Eq. (2) that the diffusion coefficient here considers three factors: environmental impact, load effect and time-varying effect. For the purpose of showing a clearer difference of the new diffusion coefficient provided in this paper from the traditional one without considering loading effect, the model of chloride diffusion coefficient is specially proposed as follows:

$$D(t)=\frac{K_e f(\delta)D_0(\frac{t_0}{t})^{\alpha}}{1-\alpha} \tag{3}$$

In next Chapter $f(\delta)$ value in Eq. (3) will be fitted by test data analysis.

3 Experimental study on chloride erosion in concrete beam under load

3.1 Experimental conditions

The concrete beam specimen size is 100 mm×150 mm×500 mm under sustained bending moment. The ultimate flexural capacity of concrete beams is 3.5 kN·m measured by testing machine. In order to realize the coupling action of load and chloride erosion, self-anchoring method by three dividing point loading was used. The test load levels were 30% and 50% of the ultimate flexural capacity respectively. As shown in Fig. 1, two specimens formed one group. On each side of the specimen, two permeable surfaces were left as the tension surface and the compression surface respectively. High strength screws and nuts made of stainless steel was used. The loading device was pre-treated for corrosion proofing. The gap between screw and the bolt was sealed with epoxy resin.

Figure 1: Experimental loading device

Table 1: List of test specimen

Sample	Quantity	Sample number	Quantity	Sample number	Quantity
C-0.0-30	1	C-0.0-90	1	C-0.0-150	1
C-0.3T-30	1	C-0.3T-90	1	C-0.3T-150	1
C-0.3C-30	1	C-0.3C-90	1	C-0.3C-150	1
C-0.5T-30	1	C-0.5T-90	1	C-0.5T-150	1
C-0.5C-30	1	C-0.5C-90	1	C-0.5C-150	1

Note: C means the condition that fully immersed in 3.5% NaCl solution; 0.3 T means the condition that immersed in 3.5% NaCl solution and imposed 0.3 times load at the same time; 0.5 T means immersed in 3.5% NaCl solution and imposed 0.5 times load at the same time. The number following 30, 90, 150 indicates the time of Immersion test (days).

3.2 Experimental material

The specimens used for the test are reinforced concrete beams. The detail of the material parameters is shown in Tab. 2. There were 4 HRB335 steel bars with diameter of 10 mm in every specimen. The thickness of the concrete cover was 25 mm.

Table 2: Concrete mix proportion

Grade of concrete	Water -cement ratio	Water consumption (in kg/m³)	Cement consumption (in kg/m³)	Sand consumption (in kg/m³)	Gravel consumption (in kg/m³)	28 days compression strength (in MPa)
C25	0.44	175	398	566	1261	30.1

3.3 Method of test data processing

The specimens under bending moment were immersed in chloride solution in 2.4 m×3.2 m×0.8 m pool filled with NaCl solution with mass fraction of 3.5%, which are shown in Fig. 2. In order to keep the concentration of NaCl solution be around 3.5%, the NaCl solution was renewed during experimental period per fifteen days. Immersion time was 30, 90, 150 days respectively.

After soaking for 30, 90, 150 days, the corresponding specimens were taken out and dried for two days by Large-scale high temperature test chamber. A small-sized power drill was used to get powder from different depths of the specimens. Ion selected electrode method was used to test the chloride percentage. Before testing, the chloride electrode was marked in the standard solution and the standard potential curve could be drawn. Then by immersing the calibrated electrode into the concrete powder solution and measuring the magnitude of voltage, the corresponding chloride concentration could be gotten from the standard potential curve, and the chloride mass fraction could be derived.

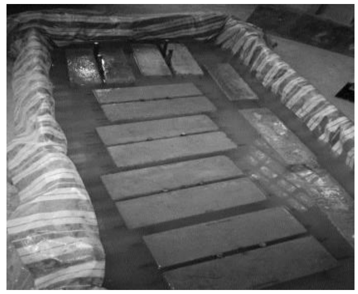
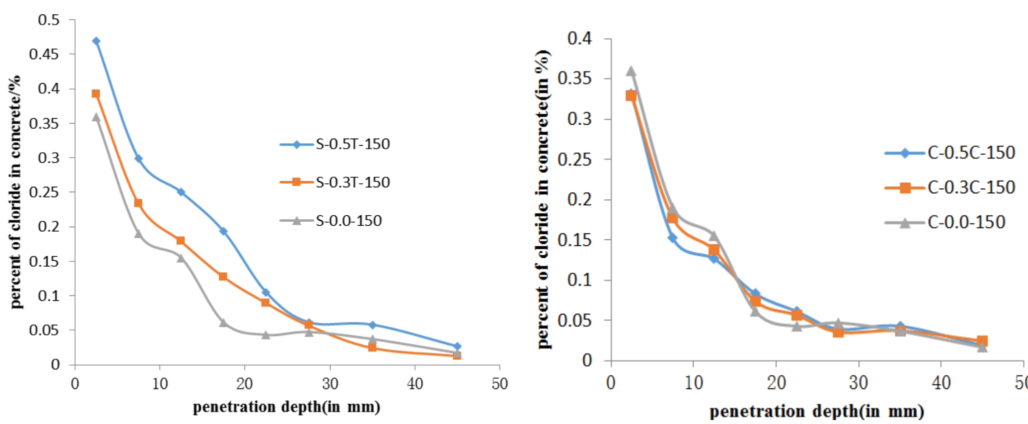


Figure 2: Test specimen immersed in chloride solution

4 Chloride diffusion coefficient of concrete under load

4.1 Test result

In order to express the chloride diffusion phenomenon more clearly, the percentage of chloride in the concrete powder measured at the depth of 5 mm~50 mm from the cover surface with immersion time of 150 days drawn as shown in Fig. 3. By analysis, it can be found that the chloride diffusion coefficient under 30%, 50% load level was on average 1.3, 1.47 times of that under unload condition in the tensile zone. Whereas in the compression zone, the chloride diffusion coefficient under 30%, 50% load level was on average 0.99, 0.92 times of that under unloading condition respectively [Kubissa, Jaskulski, Koteš et al. (2016)].



(a) Tension zone (b) Compression zone

Figure 3: Chloride ion penetration in concrete for 150 days

4.2 Calculation of diffusion coefficient

Generally, diffusion can be taken as the main transport form of chloride ions in soaking concrete. Thus chloride ion diffusion coefficient can be taken as the basic parameter to demonstrate the diffusivity of chloride. The analytical solution model [Mangat and Limbachiya (1999)] according to Fick's second law is given by:

$$C(x,t)=C_0+\left(C_S-C_0\right)\left[1-\mathrm{erf}\left(\frac{x}{2\sqrt{D_C t}}\right)\right] \tag{4}$$

Where D_c is the chloride diffusion coefficient (in m^2/s), Other symbols have the same meaning as above, where C_0 is taken to be 0 here.

By substituting the test value of chloride ion content from each layer into Eq. (4), with nonlinear least square method provided by fitting toolbox in Matlab, chloride ion diffusion coefficient and the surface chloride concentration could be obtained respectively. Considering the difference of surface concentration of the specimen, that means even for specimen under the same level of load, the variation of chloride ion diffusion coefficient could not be obvious. Thus, for each specimen in the same test group, the chloride diffusion coefficient was regressed to that in the same surface concentration, as listed in Tab. 3.

Table 3: Diffusion coefficients under same surface concentration

Sample	Corrosion time (in days)	Surface concentration C_s (in %)	Diffusion coefficient D_c (in 10^{-12} m^2/s)	R^2	Remark
C-0.0-30	30	0.3287	22.390	0.985	unloading
C-0.0-90	90		13.130	0.924	
C-0.0-150	150		9.378	0.907	
C-0.3T-30	30	0.3410	34.880	0.964	0.3 M_U, tensile zone
C-0.3T-90	90		12.310	0.909	
C-0.3T-150	150		15.772	0.932	
C-0.3C-30	30	0.3051	21.736	0.956	0.3 M_U, compressive zone
C-0.3C-90	90		12.726	0.964	
C-0.3C-150	150		10.833	0.931	
C-0.5T-30	30	0.4012	28.233	0.962	0.5 M_U, tensile zone
C-0.5T-90	90		22.852	0.917	
C-0.5T-150	150		19.270	0.920	
C-0.5C- 30	30	0.2729	16.763	0.951	0.5 M_U, compressive zone
C-0.5C-90	90		13.413	0.894	
C-0.5C-150	150		13.063	0.865	

4.3 Chloride diffusion model considering effect of load

As can be observed from Tab. 3, for concrete specimen under the same load level D_c obtained by regression is not a constant but decreasing with time when other factors are constant. According to Eq. (1), by applying the D_c data of the same sample curing for 28-day, D_0 can be obtained as shown in Tab. 4.

Table 4: Diffusion coefficient of initial chloride ion under load

Sample	Surface concentration C_s (in %)	Diffusion coefficient D_0 (in 10^{-12} m^2/s)	R^2	Remark
C-0	0.3287	23.03	0.916	Tensile zone
C-0.3T	0.3410	32.00	0.905	
C-0.5T	0.4012	33.83	0.890	
C-0	0.3287	23.03	0.916	Compressive zone
C-0.3C	0.3051	22.87	0.915	
C-0.5C	0.2729	21.24	0.880	

By using the values in Tab. 4, the influence coefficient $f(\delta)$ can be obtained by mathematical fitting method as follows:

In tensile zone:

$$f(\delta)=0.9664\delta+1.0285 \tag{5}$$

In compressive zone:

$$f(\delta)=-0.145\delta+1.0104 \tag{6}$$

From Eq. (5) and Eq. (6), it could be found that: for the flexure member, when bending load is within 0.5 times of its ultimate bearing capacity, the diffusion coefficient of chloride ion in tension zone is higher than that in compression zone. Although previous studies have demonstrated that: when the concrete compression stress reaches to a certain value, the chloride ion diffusion coefficient is increasing due to concrete crushing [Wang and Yan (2014)]. But in general, the corrosion of reinforcement in tensile zone will generally lead to more serious consequence. Thereby, when calculating the durability reliability index of bending member, Eq. (5) will be chosen to calculate $f(\delta)$.

5 Durability reliability index calculation considering load effect

5.1 Definition of the ultimate states

Initial corrosion of steel reinforcement can be taken as the mark of structure "out of service" for durability [Li and Lin (2007)], which means the concentration of chloride on the steel bar surface reaches to the critical concentration C_{cr}. Based on this, the durability limit state design expression considering load effect can be taken as follows [Wu, Li, Wang et al. (2016)]:

$$S=C(d,t)=C_0+\left(C_s-C_0\right)\left[1-\operatorname{erf}\left(\frac{d}{2\sqrt{\dfrac{K_e f(\delta)D_0 t_0^{\alpha}t^{1-\alpha}}{1-\alpha}}}\right)\right] \tag{7}$$

In which the resistance R is regard as the critical concentration $R=C_{cr}$. Then the limit state equation can be obtained as follows [Cao (2016)]:

$$Z=g(R,S)=C_{cr}-C(d,t)=0 \tag{8}$$

5.2 Durability reliability index calculation

5.2.1 Example

At present, many domestic and foreign scholars have studied the uncertainties of material and environment variables on the basis of a large number of experimental data, and determined the statistical parameters of each random variable in the model. In this paper, based on the existing research results [Cao (2016)], the distributions of major parameters are shown in Tab. 5.

Table 5: Parameter statistics of major random variables

Variable	Mean value range	Variation coefficient	distribution
d (in mm)	30~70	0.16	Normal
w/c	0.25~0.5	-	-
t (in year)	5~100	-	-
C_{cr} (in %)	0.818	0.494	Lognormal

In view of the value range about load ratio δ, it should be considered from several aspects as follows: (1) The influence of partial coefficient in the design should be considered. (2) The effect of long-term load on the chloride diffusion should be mainly considered, that is the actual live load effect should be obtained according to the quasi-permanent value. Taking the standard value of permanent load G and live load Q as example, the expression of δ can be given by:

$$\delta=(G+\psi_q Q)/[\gamma_d(\gamma_G G+\gamma_Q Q)] \tag{9}$$

Where, γ_G is the partial coefficient of dead load, taken as 1.05 when dead load is adversed to structure; γ_Q is the partial coefficient of live load taken as 1.2; γ_d is the structure coefficient taken as 1.2. Ψ_q is the quasi-permanent value coefficient usually taken at the range of 0.4~1.0. Besides, the ratio of variable load to permanent load can be taken at the range of 0~2. As a result, the range of δ can be taken at the range of 0.4~0.8.

5.2.2 Analysis of relationship between major parameters and reliability index

Combined the Eq. (5), Eqs. (7-8) and calculation conditions above, by using the Monte-Carlo method, the durability reliability index β for concrete members under different load levels was simulated based on matlab software. Firstly, generate a random array of n critical concentration C_{cr} values subject to lognormal distribution. Secondly, generate random arrays of n d values subject to normal distribution. Thirdly, according to Eq. (7), calculate random arrays of n C values. Fourthly, according to Eq. (8), calculate random arrays of n Z values and find the times m that Z values in the array being higher than 0. Finally, get failure probability p_f which is m/n, and then calculate reliability index β, that is $\Psi^{-1}(1- p_f)$, in which Ψ^{-1} is the inverse of standard normal probability function [Wang, Yang and Jivkov (2015)]. In order to express this influence clearly, make the corresponding parameter values change, meanwhile kept the rest values constant given by: d=50 mm, w/c=0.35, t=30 years. Other parameters were taken according to splash zone condition [Medeiros-Junior, Lima and Brito (2015)] as: C_s= 4.5%, K_e=0.4. The initial percentage of chloride was taken as: C_0=0.01%; According to Li et al. [Li and Fang

(2013)] D_0 was taken as $D_{28}=10^{(-12.06+2.4w/c)}$, in which *w*/*c* means water-cement ratio. Based on above analysis method, the dependence of reliability index on the depth, water cemment ratio and time were gotten respectively, as shown in Figs. 4-6.

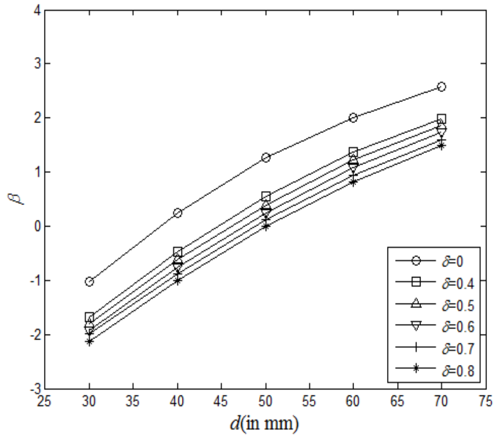


Figure 4: *d*-*β* curve

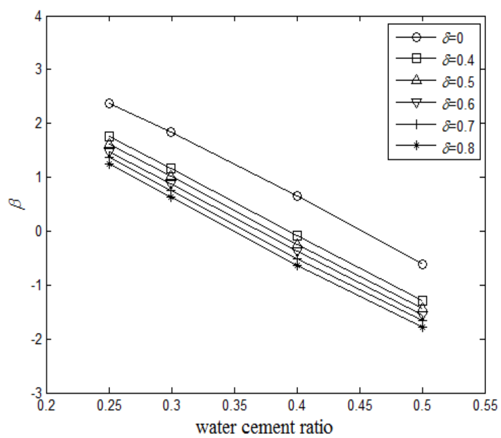


Figure 5: Water cement ratio-*β* curve

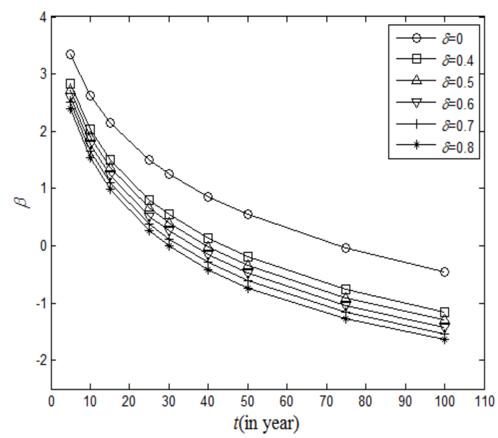


Figure 6: *t*-*β* curve

Analysis of calculation results:

(1) As can be seen from Fig. 4, *β* value is gradually increasing with *d* form 30 mm to 70 mm at the same load level, with the average increase being almost 196%. That means reliable index *β* is sensitive to concrete cover *d*. According to GB/T50476-2008, the minimum concrete cover of concrete beam with service life of 30 years in not hot splash zone should be above 50 mm. Fig. 3 indicates that the corresponding *β* could reach to 1.26 without considering load effect. However, if the load effect is taken account, *β* will decrease to around 0 when δ=0.8. It should be noted that according to reference Wang et al. [Wang and Yan (2014)] the target reliability index range about concrete durability design should be 0~1.5.

(2) As can be seen from Fig. 5, when the water-cement ratio decreases from 0.5 to 0.25 at the same load level, the average increase percent of the reliability index β can reach to 160%, indicating its high sensitivity to water-cement ratio. According to GB/T50476-2008 [GB/T50476-2008 (2008)], the maximum water-cement ratio of concrete beam with service life of 30 years in not hot splash zone should not exceed 0.4. Under this condition β will decrease to around -0.8 when δ=0.8.

(3) As can be seen from Fig. 6 at the same load level, the difference between β values of the structure used for 5 years and 100 years can be up to 4~5. It indicates the durability index remarkably decreases with time. Meanwhile, it can be found out that when other factors are kept constant, with the load level δ increasing, the corresponding β shows significant difference, taking t=30 years as an example, when δ increases from 0 to 0.8, β decreases from 1.27 approximately to 0.

In summary, the influence of load level on structure durability reliability index is significant. In the same condition, the durability reliability index considering load effect decreases by more than 100% compared with not considering load effect. Above all the load effect should be considered in the structure durability design.

5.2.3 Revised suggestion for durability design method considered load level

Combined with the durability reliability index at different load levels from Figs. 4-6, reference can be provided for revising the regulation of code. Taking the calculation conditions provided in Section 4.2.1 as example, the reliability index for different design working life with the low requirements (that means minimum concrete cover, maximum water-cement ratio, etc. given in GB/T 50476-2008 were chosen) is given by Tab. 6.

Table 6: Reliability index β of existing codes considering load effect

Design working life (in year)	30	50	100
Minimum concrete cover thickness (in mm)	50	60	65
Maximum water cement ratio	0.40	0.40	0.36
Reliability index β (δ=0.4)	-0.08	-0.02	-0.11
Reliability index β (δ=0.8)	-0.63	-0.54	-0.65

It should be noted that the durability failure defined in this paper is the reliability index of initial rust on reinforcement surface, which means the member will be not totally invalid under such durability failure. Therefore, the target reliability index at this stage can be properly reduced. It is suggested to take target reliability index between 0~1. Thereby, for the structure under long-term high stress level (that means δ is close to 0.8), it is suggested that the minimum concrete cover should be increased properly, and the maximum water-cement ratio should be deceased, the reliability index β under above suggestion will be improved to above 0, as shown in Tab. 7.

Table 7: Reliability index β for code with revised suggestion provided by this paper

Design working life (in year)	30	50	100
Revised minimum concrete cover thickness (in mm)	60	65	75
Revised water-cement ratio	0.36	0.36	0.36
Reliability index β (δ=0.4)	1.24	0.88	0.54
Reliability index β (δ=0.8)	0.70	0.33	-0.02

6 Conclusion

This study investigated the coupling effect of chloride and load on reinforced concrete bending beam. Within the scope of this investigation, the structural durability reliability index considering chloride penetration and loading effect was calculated resulted in the following conclusions:

(1) Chloride ions diffusion coefficient in tension zone under bending moment of 30% and 50% ultimate capacity was respectively 1.39, 1.47 times of that in unloaded member. Whereas the chloride ions diffusion coefficient in compression zone under bending moment of 30% and 50% ultimate capacity was respectively 0.99, 0.92 times of that in unloaded member.

(2) From the purpose of controlling probability of initial rust, the concrete cover thickness *c* should be improved and the water cement ratio should be decreased properly. It was recommended that for beam members with the relevant design life of 30 years, 50 years and 100 years in splash zone under long-term loading level, the corresponding minimum protective layer thickness should be improved to 60 mm, 65 mm and 75 mm respectively, and the corresponding maximum water-cement ratio limit should be controlled to be 0.36.

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Reference

Alkam, M. K.; Alqam, M. (2015): Prediction of the service life of a reinforced concrete column under chloride environment. *Advances in Materials Science & Engineering*, vol. 2015, pp. 1-8.

Argiz, C.; Moragues, A.; Menéndez, E. (2017): Use of ground coal bottom ash as cement constituent in concretes exposed to chloride environments. *Journal of Cleaner Production*, vol. 170, pp. 25-33.

Cao, Y. (2016): Chloride transport and reliability-based service life prediction of concrete under load. *China Building Materials Academy.* (in Chinese)

Cui, Z.; Lu, C.; Liu, R.; Hu, B. (2013): Analysis of the chloride ion erosion in flexural cracked beam and its durability service life. *International Journal of Computer Trends and Technology*, vol. 4, no. 5, pp. 1446-1449.

da Costa, A.; Fenaux, M.; Fernández, J.; Sánchez, E.; Moragues, A. (2013): Modelling of chloride penetration into non-saturated concrete: Case study application for real marine offshore structures. *Construction and Building Materials*, vol. 43, pp. 217-224.

Du, X.; Liu, J.; Zhang, R. (2016): Review on effect of external mechanical loadings on chloride penetration and diffusion into concrete. *Journal of Building Structures*, vol. 37, no. 1, pp. 107-125. (in Chinese)

Gao, Y.; Lu, C.; Yuan, S. (2016): Application analysis of probability model for chloride ion erosion distribution in marine concrete structure. *Hydro-Science and Engineering*, vol. 1, pp. 37-43. (in Chinese)

GB/T50476-2008 (2008): *Code for durability design of concrete structures*. China Building Industry Press, Beijing. (in Chinese)

Haque, M. N.; Kawamura, M. (1993): Carbonation and chloride-induced corrosion of reinforcement in fly ash concretes. *Materials Journal*, vol. 89, no.1, pp. 41-48.

Kubissa, W.; Jaskulski, R.; Koteš, P.; Brodňan, M. (2016): Variability of sorptivity in the concrete element according to the method of compacting. *Procedia Engineering*, vol. 153, pp. 355-360.

Lee, B.; Hyun, J.; Kim, Y.; Shin, K. J. (2014): Chloride permeability of damaged high-performance fiber-reinforced cement composite by repeated compressive loads. *Materials*, vol. 7, no. 8, pp. 5802-5815.

Lei, M.; Peng, L.; Shi, C. (2014): An experimental study on durability of shield segments under load and chloride environment coupling effect. *Tunnelling and Underground Space Technology*, vol. 42, pp. 15-24.

Li, G.; Fang, C. (2013): Durability simulation of concrete piers under the marine environment. *Concrete*, vol. 7, pp. 11-14. (in Chinese)

Li, M.; Lin, Z. (2007): Probabilistic model of corrosion initiation time of steel bar in concrete structure. *Journal of Hydraulic Engineering*, vol. 38, no. 5, pp. 630-636.

Mangat, P. S.; Limbachiya, M. C. (1999): Effect of initial curing on chloride diffusion in concrete repair materials. *Cement & Concrete Research*, vol. 29, no. 9, pp. 1475-1485.

Medeiros-Junior, R. A. D.; Lima, M. G. D.; Brito, P. C. D. (2015): Chloride penetration into concrete in an offshore platform-analysis of exposure conditions. *Ocean Engineering*, vol. 103, pp. 78-87.

Moreno, J. D.; Pellicer, T. M.; Adam, J. M.; Bonilla, M. (2017): Exposure of RC building structures to the marine environment of the Valencia coast. *Journal of Building Engineering*, vol. 15, pp. 109-121.

Park, S. S.; Kwon, S. J.; Jung, S. H. (2011): Analysis technique for chloride penetration in cracked concrete using equivalent diffusion and permeation. *Cement and Concrete Research*, vol. 41, no. 1, pp. 9-19.

Safehian, M.; Ramezanianpour, A. A. (2013): Assessment of service life models for determination of chloride penetration into silica fume concrete in the severe marine environmental condition. *Construction & Building Materials*, vol. 48, no. 11, pp. 287-294.

Tegguer, A. D.; Bonnet, S.; Khelidj, A.; Baroghel-Bouny, V. (2013): Effect of uniaxial compressive loading on gas permeability and chloride diffusion coefficient of concrete and their relationship. *Cement and Concrete Research*, vol. 52, pp. 131-139.

van den Heede, P.; Maes, M.; De Belie, N. (2014): Influence of active crack width control on the chloride penetration resistance and global warming potential of slabs made with fly ash+silica fume concrete. *Construction and Building Materials*, vol. 67, pp. 74-80.

Wang, J.; Yan, P. (2014): Probabilistic analysis of rebar rust in concrete under marine environment. *Journal of Jilin University Engineering and Technology Edition*, vol. 44, no. 2, pp. 352-357. (in Chinese)

Wang, X.; Yang, Z.; Jivkov, A. P. (2015): Monte Carlo simulations of mesoscale fracture of concrete with random aggregates and pores: A size effect study. *Construction & Building Materials*, vol. 80, pp. 262-272.

Wang, Y.; Zhou, H. (2013): Chlorine ion diffusion experiment in loaded concrete under salt spray environment. *Journal of Materials Science and Engineering*, vol. 31, no. 5, pp. 645-650. (in Chinese)

Wu, J.; Li, H.; Wang, Z.; Liu, J. (2016): Transport model of chloride ions in concrete under loads and drying-wetting cycles. *Construction & Building Materials*, vol. 112, pp. 733-738.

Yang, Y.; Wang, M. (2018): Pore-scale modeling of chloride ion diffusion in cement microstructures. *Cement and Concrete Composites*, vol. 85, pp. 92-104.

Zhang, L.; Jia, J.; Meng, G.; Zhu, W. (2014): Chloride diffusion in concrete subjected to compressive loading. *Magazine of Concrete Research*, vol. 66, no. 19, pp. 991-997.

Zhong, X.; Jin, W. (2016): Reliability design method for reinforced concrete structure based on durability. *China Civil Engineering Journal*, vol. 5, pp. 31-39. (in Chinese)