IMPACT OF TARGET RELIABILITY OF DURABILITY DESIGN ON MAINTENANCE COST OF REINFORCED CONCRETE MEMBERS IN CHLORIDE ENVIRONMENT

Q. Li[1], H. Zhang[2], and L. Li[3]
[1]Department of Civil Engineering,
Tsinghua University, Beijing, 100084, China. Email: li_quanwang@tsinghua.edu.cn
[2]School of Civil Engineering,
University of Sydney, NSW 2006, Sydney, Australia
[3]Department of Science and Technology Development,
China Road & Bridge Corporation, Beijing, 100103, China

ABSTRACT

In reliability-based durability design of reinforced concrete (RC) structures, the depassivation of reinforcing steels is often taken as the durability limit state, and the target reliability index is a key parameter controlling the long-term durability performance of RC members. This study investigates the impact of target reliability of durability design in design phase on the life-cycle performance and the maintenance cost of RC structures. For this purpose, a chloride diffusion model for steel depassivation of RC members is firstly established; and then the cost models for maintenance of RC beam members are proposed. Based on the detailed section design and the durability limit state of steel depassivation, Monte-Carlo simulation is used to calculate the reliability index for the durability design of RC beam members; and then according to the defined maintenance inventions and associated costs, the maintenance costs for the whole service life are evaluated for different durability reliability indices. Finally, the impact of target reliability of durability design on the deterioration process and the maintenance cost is discussed.

KEYWORDS

Durability design; target reliability; maintenance cost; reinforced concrete members; chloride environment.

INTRODUCTION

Maintenance is essential to ensure the expected service life of reinforced concrete (RC) structures, especially for port structures which are subjected to the attack of chloride ions in marine environment. The maintenance cost of a port structure depends on the structural deterioration rate, allowable limit state intervention techniques, maintenance schemes and the generated user costs. Existing studies have investigated the impact of maintenance interval, discount rate, maintenance schemes and allowable limit states on maintenance cost (Val, 2005; Kendall et al., 2008; Chiu et al, 2010). And cost-based methods, e.g. life cycle cost analysis, have been extensively applied to optimize the maintenance works for RC structures (Singh and Tiong 2005; Bucher and Frangopol, 2006; Li et al. 2009). In reliability-based durability design of RC structures, the depassivation of reinforcing steels is often taken as the durability limit state, and the target reliability level has important impact on the deterioration rate, thus also on the maintenance cost. In Chinese code for durability design of RC elements, the target reliability of embedded steel bars remaining passivated is stipulated as 1.3 (CCES, 2005), while in European code the target reliability is 1.5 (Duracrete, 1998). Theoretically, the determination of target reliability should distinguish the expected service life of the structure, which could be done in the context of life-cycle cost, however up to now, no research work has been performed on the life-based durability design of reinforce concrete structures.

This paper investigates the impact of target reliability on the maintenance cost of RC structure of a marine port with a design service life of 30 years. The port of container wharf was built in 1998 and located in Guangzhou, China. The structure of wharf is a RC beam-slab system supported by high driven piles. The annual average temperature is between 22.3-23.1ºC with most elevated temperature as 28.4-28.8 ºC (July) and lowest temperature as 14.8-15.9 ºC (January). The annual average humidity is between 77-80% with important seasonal variation, and the seasonal humidity can reach 100% (spring and summer) and drop to 10% (winter). The main durability process for the RC structural members is identified as the chloride-induced corrosion of reinforcing steel bars. In this paper, the deterioration models and cost models are first established for the RC beams in the wharf. And then, the influence of target reliability of durability design for RC structures is investigated for its impact on the deterioration process of RC elements as well as the resulted maintenance costs. As a result, the optimized target reliability is discussed for the durability design of RC elements.

MODELS

Deterioration of RC members

The control process for the deterioration of RC members is chloride-induced corrosion of the embedded steel bars. The durability limit state is defined as the steel de-passivation, i.e. the external chloride ions penetrate into the concrete and accumulate at the steel surface, to a critical concentration high enough to initiate the steel corrosion. The analytical solution of Fick's second law is usually retained as engineering model (DuraCrete, 1998; fib, 2006), and the design equation for corrosion process can be expressed as:

$$G=\left\{C_0+\left(C_S-C_0\right)\left[1-erf\left(\frac{x}{2\sqrt{D_{\mathrm{Cl}}\left(t\right)\cdot t}}\right)\right]\right\}-C_{Cr}\geq 0 \tag{1}$$

in which C_0 is the initial chloride content in the concrete; C_S is a constant chloride concentration imposed on the surface; x is the thickness of concrete cover; D_{Cl} is the *apparent* chloride diffusion coefficient in concrete and *erf* is the mathematical error function. This apparent diffusion coefficient is found to be time-dependent (Bamforth, 1999), and a power law is recommended for its ageing behavior (Mangat and Molloy, 1994),

$$D_{\mathrm{Cl}}\left(t\right)=D_{\mathrm{Cl}}^{0}\left(\frac{t_0}{t}\right)^{a} \tag{2}$$

with D_{Cl}^0 stands for the diffusion coefficient at concrete age t_0, a for the exponential coefficient. In the calculation of D_{Cl}, t is taken as 30 years as $t > 30$ years

Cost models

The maintenance cost of a RC element during its service life can be is expressed as

$$C_m=\sum_{i=1}^{n}\left(\frac{C_{r,i}}{\left(1+r\right)^{t_i}}+\frac{C_{u,i}}{\left(1+r\right)^{t_i}}\right) \tag{3}$$

in which C_m is the total maintenance cost; $C_{r,i}$ is the cost of the *i*th maintenance intervention; $C_{u,i}$ stands for the user cost of *i*th maintenance by possible disturbance and stoppage of berth service; n is the number of maintenances during service life and t_i is the time (year) of the *i*th maintenance; r is the discount rate of currency. The discount rate r is determined by the social discount rate and the annual changing rate of producer price index (PPI). According to Cady (1983), the discount rate is assumed to adopt a step function:

$$r=\begin{cases}2.0\% & t_i=0\sim 30\text{ years}\\ 2.7\% & t_i=31\sim 60\text{ years}\\ 3.3\% & t_i=61\sim 90\text{ years}\\ 4.0\% & t_i>90\text{ years}\end{cases} \tag{4}$$

DETERIORATION AND MAINTENANCE

The exposure zones of RC elements in marine environment are classified as immerged zone, tidal zone, splash zone and atmospheric zone, as seen in Figure 1. In the paper, for purpose of simplicity, the maintenance plan concerns cross beams only. The design parameters of the cross sections are in Table 1.

The function in Eq.1 is used to calculate the failure probability of RC elements under chloride action. The basic parameters are C_0, C_S, C_{Cr}, D and a. These parameters all depend on concrete material composition and have statistical properties. Their statistical properties are obtained by on-site survey of similar port structures in Guangzhou and referring to durability standards (CCES 2005; fib 2006), and listed in Table 1.

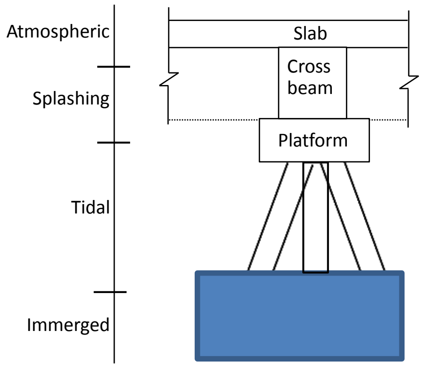


Figure1 Vertical view and exposure zone of RC elements in the wharf

Table 1 Design values and statistics of durability parameters

Design parameters			
Dimension (m)	Concrete	D_0 (10^{-12}m^2/s)	Concrete Cover (mm)
8.5×1.4×2.0	C45	4.5	70
Statistics of parameters in deterioration model			
Parameter	Distribution	Mean Value	Coefficient of Variation
C_0 (%binder)	Lognormal	0.06	0.1
C_S (%binder)	Lognormal	4.5	0.15
x (mm)	Normal	65, 70, 75	0.1
C_{Cr} (%binder)	Lognormal	0.45	0.2
D (10^{-12}m^2/s)	Lognormal	According to Eq.(2)	0.2
a (-)	Lognormal	0.4	0.1

Monte-Carlo simulation is used to obtain the failure probability of Eq. 1. The total number of samples is 100,000. The failure probability of the cross beam is shown in Figure 2, which increases as the service age grows.

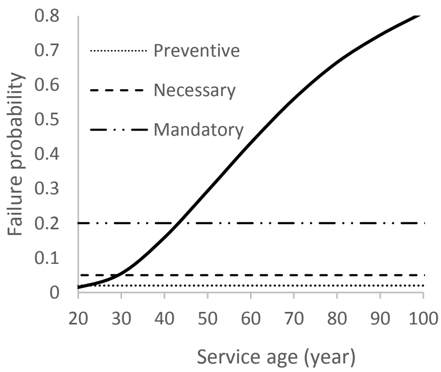


Figure 2 Failure probability of cross beam as the increase of service age

In practice, the maintenance intervention methods are decided based on the deterioration condition of RC members. The adopted intervention techniques depend strongly on the damage condition of members, which is dominantly affected by the corrosion extent of steel reinforcing bars, thus the corrosion extent of steel bars determines majorly the maintenance cost of RC members. Recognizing this, in this paper, three levels of intervention levels, named “preventive”, “necessary” and “mandatory” represented by failure probability of steel bar de-passivation, are defined in the maintenance planning of RC elements in the wharf, as seen in Table 2. The failure probabilities are 2%, 5% and 20% respectively corresponding to the “preventive”, “necessary” and “mandatory” maintenance levels, which are also shown in Figure 2. Table 2 lists the costs for the maintenance techniques considered in this study and the corresponding impact on port regular service of the three intervention levels. The maintenance cost is given as a “relative cost” which is calculated in terms of the price of new member including the design cost, material cost and construction cost. The user daily cost is estimated on the basis of the income of berths in last 10 years in this port, which is roughly 0.009 of the price of the new structure.

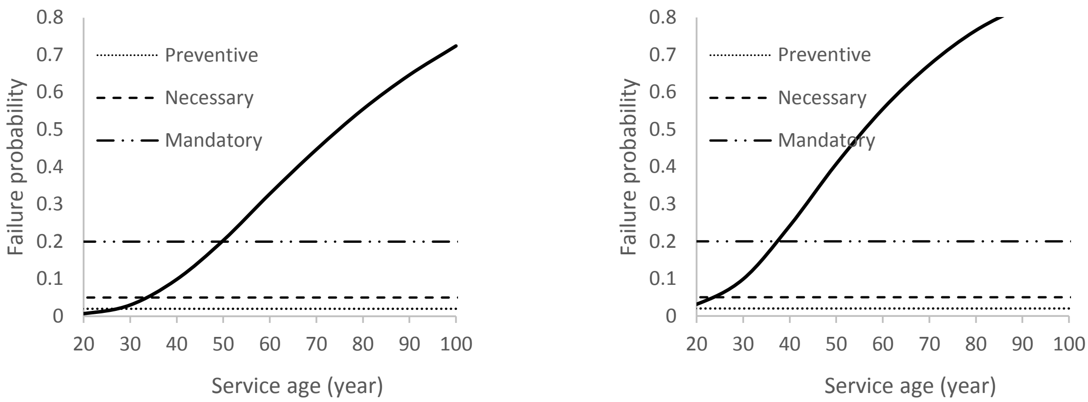
Table 2 Definition of 3 interventions

Maintenance level	Operations	Intervention cost	Service disturbance
Preventive, $P_f = 2\%$	Chloride extraction	0.88	Almost no disturbance
Necessary, $P_f = 5\%$	Chloride extraction & Surface treatment	1.14	Limited disturbance
Mandatory, $P_f = 20\%$	Cover reconstruction & Steel supplement	2.10	Close for 90 days.

According to the deterioration process shown in Figure 2, suppose that the port structure is expected to work for 100 years, the intervention times for the "preventive" level are 21year, 42year, 63year and 84year, respectively; for "necessary" level they are 29 year, 58year and 87year; for "mandatory" level they are 44year and 88year. With the intervention costs in Table 2, the maintenance costs for difference intervention levels are obtained. They are 1.04, 0.95 and 1.12 for the 3 intervention levels respectively. From the cost analysis, it can be seen that "necessary" maintenance achieves the lowest cost; "preventive" maintenance generates higher costs because of the very frequent operations; "mandatory" maintenance generates higher costs due to the associated high user costs caused by closed service during the heavy maintenance operations.

IMPACT OF TARGET RELIABILITY

The cross beams in the considered port structure has a reliability level of $\beta = 1.6$ (failure probability of 5.5%) for durability for design life of 30 years. If the target reliability increases to 1.9 (failure probability of 3%) or decreases to 1.3 (failure probability of 10%), with concrete diffusion coefficient remaining unchanged, the concrete cover thickness needs to increase to 75mm, or decreases to 65mm, respectively. For these two cases, the failure probabilities of the cross beam are obtained through Monte-Carlo simulation and shown in Figure 3.



(a) $\beta = 1.9$ (b) $\beta = 1.3$

Figure 3 Failure probability of cross beam with changed target reliability level

With the deterioration process in Figure 3 and the maintenance costs in Table 2, the maintenance intervals and costs for the three intervention levels are determined and given in Table 3. It can be seen that the "necessary" maintenance always achieves the lowest cost, which indicates that the optimum maintenance plan should be made referring to the "necessary" maintenance level. To investigate the impact of target reliability on the maintenance cost, more reliability indices are considered, and the associated maintenance costs are plot in Figure4. It is clearly seen that the maintenance cost decreases with the increase of durability reliability; in the range of durability reliability index being smaller than 1.6, the decrease of maintenance cost is relatively rapid, while in the range of durability reliability index being larger than 2.0, the decrease of maintenance cost is relatively slow. Therefore, it can be concluded that the optimum target reliability index should lie between 1.6 and 2.0, and the determination of it should refer to the increase in the construction cost as the target reliability index becomes larger.

Table 3 Maintenance levels and costs

Target reliability	Maintenance Level	Maintenance Interval	Intervention cost	User cost	Maintenance
1.3	Preventive	17	1.36	0	1.36
	Necessary	23	1.21	0	1.21
	Mandatory	37	0.97	0.38	1.35
1.6	Preventive	21	1.04	0	1.04
	Necessary	29	0.95	0	0.95
	Mandatory	44	0.81	0.31	1.12
1.9	Preventive	26	0.82	0	0.82
	Necessary	33	0.63	0	0.63
	Mandatory	49	0.50	0.18	0.68

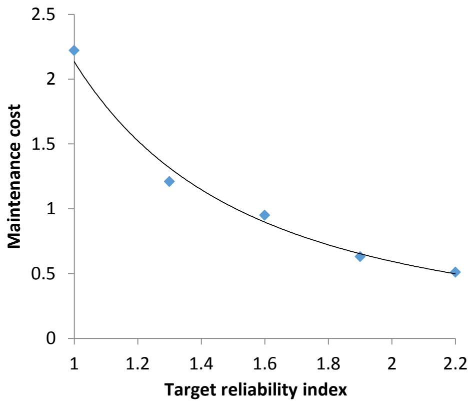


Figure 4 Dependence of maintenance cost on target reliability index

CONCLUSIONS

This paper establishes the deterioration model and maintenance cost model for the life-cycle cost analysis of RC elements in marine environments. Through Monte-Carlo simulations, taking the de-passivation of embedded reinforcing steel bars as durability limit state, the cost analyses for different durability reliabilities and maintenance levels are performed. The results show that the "necessary" maintenance, with failure probability of 5% for design life of 30 years as intervention threshold, always achieves the optimized maintenance cost; the maintenance cost decreases as the durability reliability becomes larger, but the optimum target reliability index lie between 1.6 and 2.0, and the determination of it needs to consider the change in the construction cost.

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