Life-cycle cost analysis of cracking in a reinforced concrete beam under uniform chloride corrosion

Masoumeh Taghipour[1], Mehdi Dehestani[2*]

[1]Graduate Student, Faculty of Civil Engineering, Babol Noshirvani University of Technology, Babol, Iran
[2]Associte Professor, Faculty of Civil Engineering, Babol Noshirvani University of Technology, Babol, Iran

ABSTRACT

Corrosion of rebar is one of the major problems in reinforced concrete structures under a corrosive environment which causes serious damage to the structures. Corrosion of rebar is a complex process and one of the important factors of failure of reinforced concrete structures which reduces the strength and serviceability of the structures thus avoiding these adverse effects requiring a high cost. For this reason, this process needs to be modeled using probabilistic analysis and reliability analysis with uncertainties in the corrosion phase. Considering the different maintenance strategies and life cycle analysis methods, the cost of maintenance and repair can be delayed. One of the corrosion effects on structure performance is crack on the concrete surface due to the expansion of the corrosion product. The crack width is an important parameter for designing and evaluating the performance of concrete structures. Therefore, this paper presents an analytical model to calculate the crack width due to corrosion. Crack evolution in the concrete cover due to expansive corrosion products is investigated at different stages during crack propagation across the cover, from the reinforcing bar-concrete interface to the concrete. A merit of this model is that it is directly related to the factors that affect the corrosion-induced cracking process. Then, the predicted crack width is chosen as a stochastic variable and the probability of failure in concrete structures is calculated by using a stochastic deterioration model and the gamma process. The calculated probability is then used to calculate the life cycle cost and determine the optimal repair time by using the renewal process. The effect of structural parameters on the probability of failure is also investigated. The results show that the corrosion rate is one of the most important factors affecting the crack width, the probability of failure and life cycle cost.

KEYWORDS

Corrosion of reinforcement, reliability, life cycle, probability of failure, corrosion rate

[*] Corresponding Author: Email: dehestani@nit.ac.ir

1-Introduction

The major reason for reinforced concrete structures to collapse is corroding the rebar buried in concrete especially for marine environments. By penetrating chloride ions and corrosion initiation, the corrosion products begin to appear on the surface of rebar which exerts pressure on the neighboring concrete[1]. If the amount of this stress exceeds the concrete tensile strength, crack creates in the concrete cover and therefore reduces the structure strength.

Many investigations have been carried out in recent decades on the effect of rebar corrosion and concrete crack on the concrete structure's performance[1-3]. This study investigates the cracking process through an analytical procedure. Then the width of the predicted crack is chosen as a random variable for modeling the collapse process. The probability of fracture and life cycle costs are obtained based on the Gamma process and renewal process respectively. Besides, the effect of corrosion rate and rebar diameter on the failure probability is investigated.

2-Methodology

Concrete cracking can be modeled as a process of tensile softening[4] in which the crack is considered integrated. For this purpose, the thick-walled cylinder model is used. By assuming the corrosion rate to be steady, the equivalent crack width [5]is defined as equation 1.

$$w(t)=\begin{cases} 0 & 0\le t\le T_c \\ a^c t^{1/2} - b^c & T_c < t \le T_{cr} \\ a^d t^{1/2} - b^d & t > T_{cr} \end{cases} \qquad (1)$$

the Gamma process has been used to model the collapse process. The distribution function of a lifetime [6] proportional to random variable S=W(t) is obtained according to equation 2,

$$F(t)=Pr\left\{t\ge T_l\right\}=\Pr\left\{S(t)\ge S_l\right\}=\int_{S=S_l}^{\infty} f_{s(t)}(S)dS=\frac{\Gamma^u(\eta(t),S_l\lambda)}{\Gamma(\eta(t))} \qquad (2)$$

By considering two maintenance strategy, preventive maintenance, and corrective maintenance strategy, The expected costs of damage using renewal theory[7] are calculated according to equation 3,

$$C_d(k)=\frac{(\sum_{i=1}^{k}\alpha^i p_i)C_F+\alpha^k(1-(\sum_{i=1}^{k}p_i))C_p}{1-\left[(\sum_{i=1}^{k}\alpha^i p_i)+\alpha^k(1-(\sum_{i=1}^{k}p_i))\right]} \qquad (3)$$

The optimal maintenance time interval is obtained by minimizing the expected costs.

3-Discussion and Result

To investigate structural parameters, a structure with a service life of 60 years is studied. Rebar with diameter 12 is immersed into concrete with a clear cover of 35 mm. the corrosion is assumed to be uniform and the corrosion rate is considered 1 μA/cm^2. The characteristics of concrete materials are given in Table 1.

Table 1. Characteristics of concrete materials

parameter	Value
Compressive strength f_c	36 (MPa)
Tensile strength f_t	4.14 (MPa)
Concrete elasticity modulus E	28 (GPa)
Poisson coefficient ϑ	0.18
Failure energy G_f	97.32 N/m
Critical crack width W_{cr}	0.14 mm
Normalized critical crack width	5.9
Number of cracks n_c	4
Cover radius R_c	41 mm

The results in figure 1 are for the equivalent crack width over time that is compared with previous experimental investigations[8, 9].

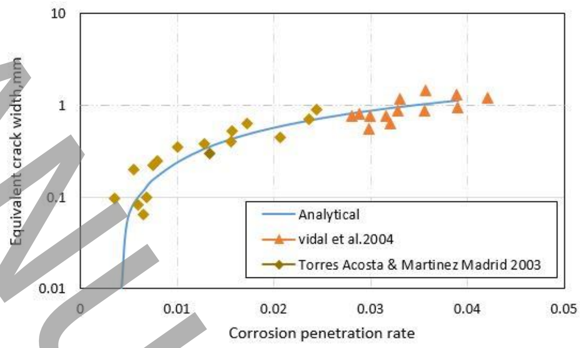

Figure 1. Equivalent crack width as a function of corrosion penetration rate

To investigate the effect of rebar diameter on crack evolution, various values of rebar diameter ranging from 8 mm to 20 mm are adopted. The results are shown in figure 2.

Various values of corrosion current rate i_{corr}, ranging from 0.3 μA/cm^2 to 5 μA/cm^2 corresponding to low-to-high corrosion intensities are adopted to predict of cost of failure. Different acceptable limits for example 0.3, 0.4 and 0.5 mm [5]are used to model the collapse process. The results are shown in Figures 3 to 5.

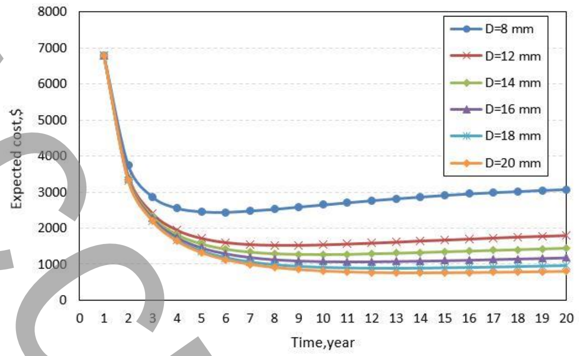

Figure 2. Expected cost during repair time for different diameter values

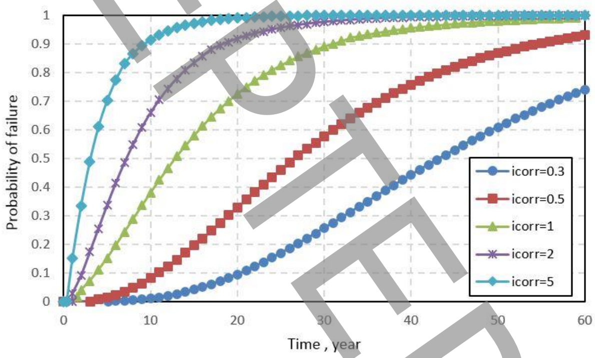

Figure 3. Probability of failure in structure service life for various corrosion rates

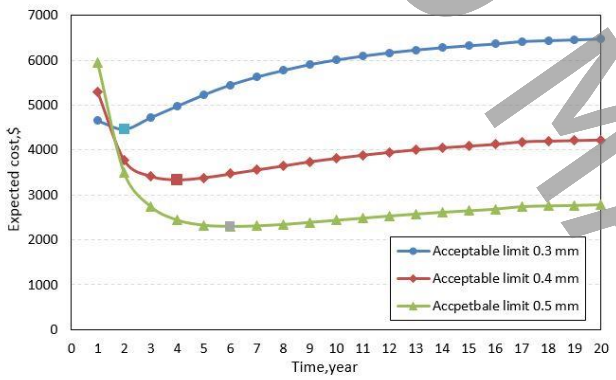

Figure 4. Failure cost diagram during maintenance time for icorr= 2 μA/cm2 in different allowable crack width

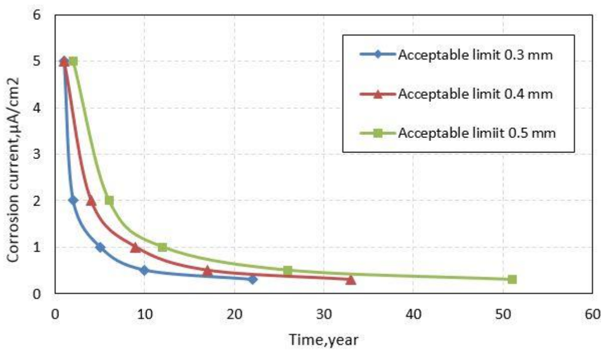

Figure 5. Optimal repair time as a function of corrosion current i_{corr}

4- Conclusions

The performance of concrete structures due to corrosion was studied in this paper. Concrete crack width is a key index in the concrete performance that can be selected as a random variable in probabilistic evaluation of structure fracture. The results obtained from the probabilistic analysis of crack reveal that the corrosion rate is the most effective factor in the probability of failure. The rebar diameter influences the time of cracking more i.e. increasing the rebar diameter by 2 times leads to rising the cracking time to nearly 2 years. Results from the life cycle analysis indicate that by optimizing the balance between failure probability and maintenance costs, optimum maintenance procedure can be determined. the optimum maintenance time depends on the maintenance corrosion rate. By increasing the corrosion rate from 0.3 to 5 μA/cm^2, the optimum maintenance time is decreased by 30 years therefore, it is important to keep the structure at an acceptable level by using proper maintenance procedures in the first years of construction.

5-References

[1] R. Weyers, Modelling the time-to-cracking in chloride contaminated reinforced concrete structure, ACI Materials Journal, 95(6) (1998).

[2] P.G. Gambarova, G. Rosati, C. Schumm, Bond and splitting: a vexing question, Special Publication, 180 (1998) 23-44.

[3] H. Narasimhan, M. Chew, Integration of durability with structural design: An optimal life cycle cost based design procedure for reinforced concrete structures, Construction and Building Materials, 23(2) (2009) 918-929.

[4] H.-P. Chen, Residual Flexural Capacity and Performance Assessment of Corroded Reinforced Concrete Beams, Journal of Structural Engineering, 144(12) (2018) 04018213.

[5] R. Zhang, A. Castel, R. François, Serviceability limit state criteria based on steel–concrete bond loss for corroded reinforced concrete in chloride environment, Materials and structures, 42(10) (2009) 1407.

[6] J.M. van Noortwijk, A survey of the application of gamma processes in maintenance, Reliability Engineering & System Safety, 94(1) (2009) 2-21.

[7] H.-P. Chen, A.M. Alani, Optimized maintenance strategy for concrete structures affected by cracking due to reinforcement corrosion, ACI Structural Journal, 110(2) (2013) 229.

[8] A.A. Torres-Acosta, M. Mart ı´ nez-Madrid, Residual life of corroding reinforced concrete structures in marine environment, Journal of Materials in Civil Engineering, 15(4) (2003) 344-353.

[9] T. Vidal, A. Castel, R. Francois, Analyzing crack width to predict corrosion in reinforced concrete, Cement and concrete research, 34(1) (2004) 165-174