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► **To cite this version:**

Quynh Chau Truong, Charbel-Pierre El Soueidy, Emilio Bastidas-Arteaga, Yue Li. Optimizing Cover Rebuilding Maintenance for Reinforced Concrete Structures Exposed to Chloride Attack. Proceedings of the 1st Conference of the European Association on Quality Control of Bridges and Structures, Aug 2021, Padova, Italy. pp.148-156, 10.1007/978-3-030-91877-4_18 . hal-04642642

HAL Id: hal-04642642

<https://hal.science/hal-04642642v1>

Submitted on 10 Jul 2024

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Optimizing cover rebuilding maintenance for reinforced concrete structures exposed to chloride attack

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Abstract. Chloride-induced corrosion of steel reinforcement is one of the most critical deterioration that causes durability problems on reinforced concrete (RC) structures. Therefore, extending service life through repairing becomes an important mission in maintenance strategies of RC structures. However, the ability to prolong service life by concrete repair is affected by several factors, such as quality of construction, properties of repairing materials, concrete cover depths, etc. In this paper, different patch repair strategies for RC components exposed to chloride attack are considered. Numerical simulations of chloride penetration in new/repared materials are developed in FreeFEM++ software, which can then be used to model the maintenance measure by cover rebuilding. By adapting a deterministic analysis, this model allows us to study the influence of some main parameters on increasing the effectiveness of patch repair. Based on the results of this study, a proper repair strategy could be developed to optimize the serviceability and safety of RC structures subjected to chloride penetration.

Keywords: maintenance; corrosion; chloride ingress; reinforced concrete; cover rebuilding; modeling

1 Introduction

Generally, the service life of RC structures is assumed between 50 and 100 years. However, in chloride-contaminated environments, the deterioration of infrastructure may occur after 20 to 30 years [1]. Hence, the inspection and maintenance are essential to ensure an optimal level of serviceability and safety during its lifespan. In this context, the method of “cover rebuilding”, or the application of cement-based repair mortars or concretes for the chloride polluted areas is widely used in practice.

Some recent research [2, 3, 4] provide models for simulating chloride transport in new/repair materials. These studies have some limitations since they neglect the influence of temperature, humidity and the decrease of chloride diffusivity with concrete age. Consequently, it is necessary to establish a comprehensive model that can bridge those gaps. Therefore, a maintenance measure for chloride-induced corrosion in RC structures needs be proposed properly.

It is known that maintaining safety requirements may increase costs, hence proper repair strategies can save a considerable amount of expenses for the owner. The main objective of this paper is to propose a comprehensive model for optimizing cover rebuilding maintenance for RC structures, which considers several main parameters impacting the effectiveness of patch repair. Three groups of parameters are studied: (1) Number of repairs, (2) concrete cover depth, and (3) repair interval. A computational approach with a deterministic analysis for chloride transport in concrete with multiple repairs is proposed.

2 Cover rebuilding technique and chloride transport in RC before and after repair

2.1 Cover rebuilding

Repair for corrosion-damaged RC is a process of fixing the contaminated concrete areas that over time has lost its ability to protect the rebar due to damage or environmental exposure. In the strategy of maintenance considered herein, “cover rebuilding” repair could be undertaken by rebuilding the chloride-polluted concrete cover by several techniques (wet shotcrete, dry shotcrete, formed concrete and manual repair). Cover rebuilding is applicable to large-scale repair projects nowadays

2.2 Mechanisms of chloride transport in RC before and after repair

To predict the service life of repaired RC, there are two main mechanism of interest: chloride penetration in concrete before and after repair. These two mechanisms were previously studied by several authors [3, 5].

Regarding the first mechanism, the penetration process is occurred by a complex interaction between physical and chemical mechanisms, which can be considered as a diffusion phenomenon in saturated environment based on the Fick’s second law [6]. A proper model proposed by Bastidas-Arteaga et al. [7, 8] is used in this study, which takes into account the interaction between chloride ingress, moisture diffusion and heat transfer. The description of the formulation of the model can be found in reference [6]. A one-dimensional model combining finite element and finite difference methods to solve a set of partial differential equations (PDE) is used in our study.

In comparison, chloride penetration in concrete after repair is more complicated with the interaction of two main sources of chloride ions:

(1) Chloride penetration from the concrete surface exposed to the environment into the repaired concrete and the original concrete.

(2) The distribution of chloride ions that has not been taken-off in the original (old) concrete. It means that after repair, the chloride content near the common area between the two layers moves into two directions inside the original structure and towards the new layer (Fig. 1).

At a certain time, the chloride ingress from concrete surface will merge with the chloride redistribution inside the structure that causes the interaction between chloride ions in the original and repaired concretes. It will be even more complicated if the repairs are implemented multiple times.

Based on those two mechanisms, the chloride penetration without and with repair will be investigated numerically in Section 3 using a Finite Element modeling.

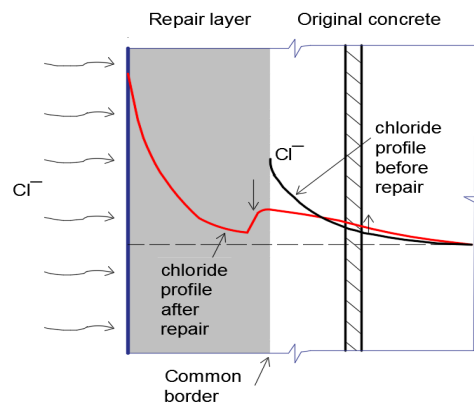


Fig. 1. Chloride ingress (Cl) and redistribution in a repaired concrete with residual chlorides.

3 Computational approach for modelling chloride penetration

As mentioned in section 2.2, the comprehensive model proposed by Bastidas-Arteaga et al. [6] can simulate the chloride penetration into concrete that is mainly governed by the diffusion phenomenon, with the consideration of temperature, humidity, and time effect. Other transport mechanisms could be involved in chloride ingress process, in particular capillary absorption or convection. However, in RC with cover thickness greater than 30mm, diffusion becomes the most effective and important mechanism for the corrosion initiation in concrete structures [4]. Therefore, a set of main equations used for this study are presented below:

Table 1. Chloride penetration considering temperature, humidity, and concrete aging

Governing equation	$\frac{\partial C_{fc}}{\partial t} = D_c^* * \left(\frac{\partial^2 C_{fc}}{\partial x^2} \right)$	(1)
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Chloride diffusion coefficient	$D_c = D_{c,ref} \cdot f_1(T) \cdot f_2(t) \cdot f_3(h)$	(2)
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Temperature effect	$f_1 = \exp \left[\frac{U_c}{R} \left(\frac{1}{T_{ref}} - \frac{1}{T} \right) \right]$	(3)
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Time effect	$f_2(t) = \left(\frac{t_{ref}}{t} \right)^{m_c}$	(4)
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Humidity effect	$f_3 = \left[1 + \frac{(1-h)^4}{(1-hc)^4} \right]^{-1}$	(5)
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The FreeFEM++ software with a simplified one-dimensional model is used, with some assumptions as follows:

- The chloride surface concentration is constant: $C_s = 6 \text{ kg/m}^3$
- The temperature is constant: $T = 15^\circ\text{C}$; the humidity is constant: $h = 0.7$. It means that the chloride diffusion coefficient is calculated at a certain temperature and humidity, but not neglecting the effect of concrete aging (time effect).
- The service life is 100 years. Time determination of multiple repairs (time of corrosion initiation) is when chloride content reaches the critical chloride value $C_{crit} = 2 \text{ kg/m}^3$ (0.5% of cement mass) at the concrete cover depth $X_c = 50\text{mm}$.
- The quality of repair material is the same as original concrete.
- Values selected for the model parameters are presented in Table 2:

Table 2. Values selected for the model parameters of the chloride penetration model.

Parameter	Symbol	Units	Value
Reference chloride diffusion coefficient	$D_{c,ref}$	m^2/s	3×10^{-11}
Activation energy of the chloride diffusion process (U_c) and Gas constant (R)	U_c/R	$^\circ\text{K}$	4600
Aging factor	m_c		0.15
Humidity at which D_c drops halfway	h_c		0.75
Reference temperature in $^\circ\text{K}$ at which $D_{c,ref}$ evaluated	T_{ref}	$^\circ\text{K}$	296
Time of exposure at which $D_{c,ref}$ evaluated	t_{ref}	day	28

In the meantime, the complicated mechanism of chloride ingress and redistribution in a 2-layer concrete system after repair has been investigated by the FreeFEM++ software. By setting the different initial conditions in two domains after repair and establishing the connection at common border between them, the multiple repairs during structure service life are efficiently calculated. (Fig. 2a, 2b)

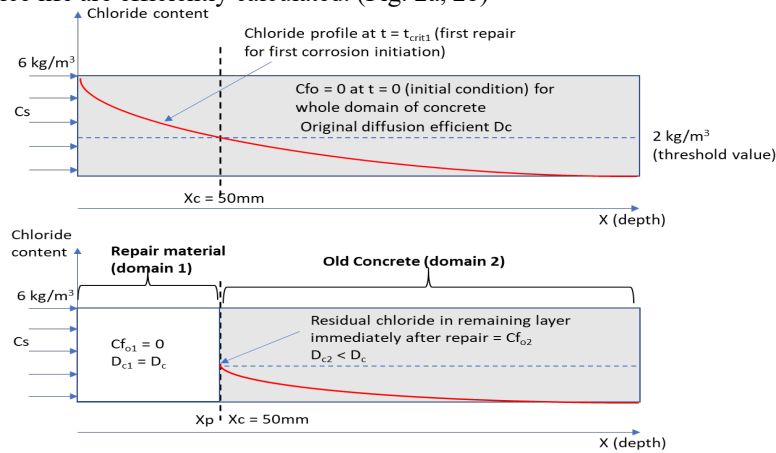


Fig. 2a, 2b. Chloride profile before and immediately after repair

4 Maintenance model and results

A maintenance model has been developed to simulate different repair strategies of cover rebuilding method. For example, a set of strategies related to quality of repair material, concrete repair depth (X_p), or repair interval are studied to evaluate and optimize the maintenance plan for RC structures. In this study, several repair strategies have been chosen and their results will be described in this section. Three factors are considered to study the effectiveness of the maintenance plan:

- The number of expected repairs
- Depth of repaired concrete, X_p ; and
- Repair interval (time between two repairs)

The maintenance model provides the evolution of the total chloride concentration (in kg/m³ of concrete) at several depths for each studied case.

4.1 Factor of expected number of repairs

The deterministic chloride profiles without and with repair is illustrated in Fig. 3. It concerns a maintenance policy that repair is carried out by removing for example 50 or 60 mm of chloride-contaminated concrete whenever the chloride concentration at the cover thickness of $X_c = 50\text{mm}$ reach a critical value of 2kg/m^3 . The number of expected repairs is presented in Table 3. It is observed that a deeper repair depth leads to fewer number of repairs, and the removing of 6 cm is optimal from economical aspect and environmental point of view. However, it is noticed that deeper depth of repairs is not always better, because it has the limitation on reducing the amount of chloride content, also the maintenance cost for deeper patch concrete is higher than a thinner one.

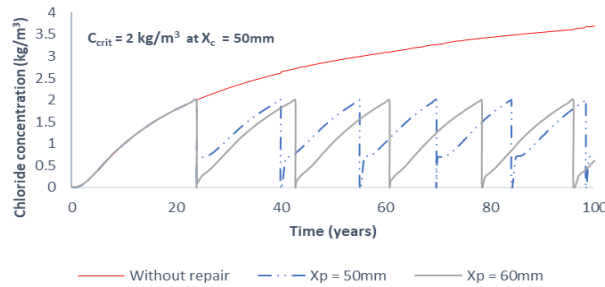


Fig. 3. Time-dependent chloride profiles without and with repair

Table 3. Number of repairs for each strategy of repair depth

Repair depth	Repair application time (year)							Number of repairs
	First	Second	Third	Fourth	Fifth	Sixth	Seventh	
50mm	23.9	40	55.2	69.8	84.2	98.4	>100	6
60mm	23.9	42.8	60.8	78.5	96	>100		5

4.2 Effects of repair depth

Considering the effect of two repair depths: $X_p = 50$ and 60mm and a repair interval of 15 years and 18 years (t_r). Fig. 4 and 5 present the effect of depth of patch concrete on the evolution of the chloride content at $x = 3, 5,$ and 7cm . It is shown in all the cases that the chloride content at 7cm decreases immediately after repair, and increases when the chloride ions ingress into the repaired concrete. It means that the chloride content at this position moves into two directions inside the structure and towards the concrete surface. When considering the critical chloride content of 2kg/m^3 at 5cm and a service life of 100 years, for $t_r = 15$ years (Fig. 4), the removing of 50mm is the best strategy with the lowest maintenance cost. However, in the case $t_r = 18$ years (Fig. 5), the repair depth of 60mm seems to be optimal from an economical aspect. Thus, depending on the repair interval chosen, an optimization strategy should be calculated and evaluated in each case. Hence, a comprehensive comparative review considering two above factors is necessary to make the best decision.

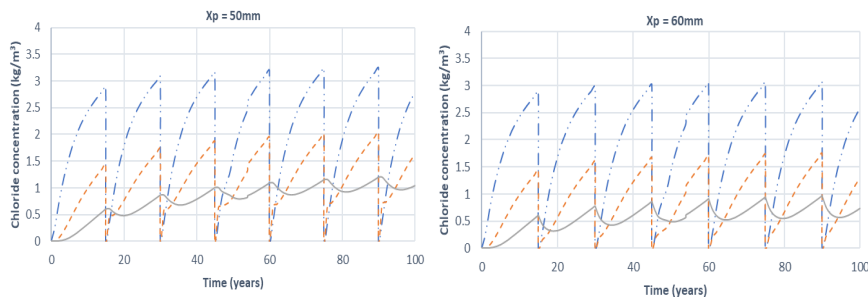


Fig. 4. Effect of cover depth on the chloride content ($t_r = 15$ years)

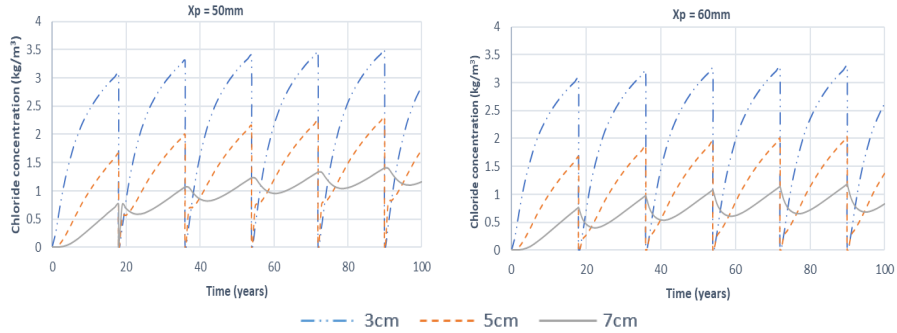


Fig. 5. Effect of cover depth on the chloride content ($t_r = 18$ years)

4.3 Effects of repair interval

To study the effects of the length of the repair interval, t_r , we consider the same quality material for original and repair concrete, and the patch repair of $X_p = 60$ mm. Fig. 6 illustrates the evolution of chloride content at 3, 5, and 7 cm for three repair intervals, 12, 18 and 24 years. The overall behavior indicates that the chloride concentrations at three surveyed depth decrease for lower t_r . Considering that the corrosion initiation starts when the chloride content reaches the critical chloride value $C_{crit} = 2\text{kg/m}^3$ at $x = 5\text{cm}$, it is observed that a repair interval of about 18 years seems to be optimal for the patch repair of 60mm concrete depth. However, a comprehensive maintenance strategy should evaluate different choices of repair interval to optimize the management of resources and minimize the probability of corrosion initiation.

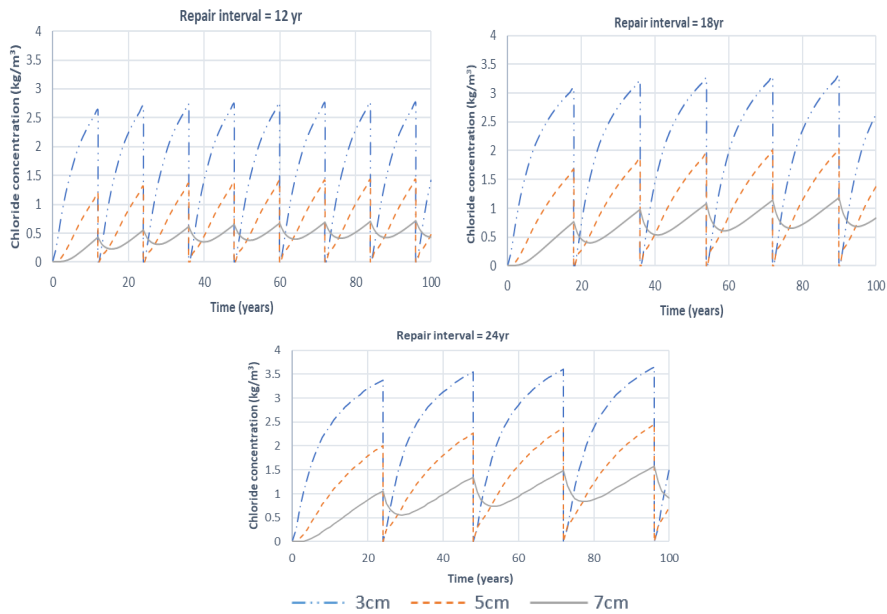


Fig. 6. Impact of repair interval on the chloride content

5 Conclusions

In this paper, a computational deterministic analysis of the service life of chloride-attacked concrete structures with multiple repairs is carried out. Three factors that affect the effectiveness of patch repair method are considered: (1) number of expected repairs, (2) depth of repair concrete and (3) repair interval. It is found that deeper repair depth leads to fewer number of repairs, while shorter repair interval decreases the probability of corrosion initiation but increases the maintenance cost. Therefore, a comprehensive maintenance policy should consider these main parameters for an optimum strategy that minimizes both material costs and environmental impact, as well as prevent the corrosion initiation. Other control factors, such as repair costs, should be taken-into account, because they play an important role for decision makers to compare different repair strategies.

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