



# Simulation studies of methods to delay corrosion and increase service life for cracked concrete exposed to chlorides



Scott Jones<sup>\*</sup>, Nicos Martys, Yang Lu, Dale Bentz

Engineering Laboratory, National Institute of Standards and Technology, 100 Bureau Drive, Stop 8615, Gaithersburg, MD 20899, USA

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## ABSTRACT

The ingress of chlorides in reinforced concrete leads to the onset of steel reinforcement corrosion and eventually compromises a structure's integrity. To extend its service life and improve safety, it is crucial to develop sound repair strategies for our nation's infrastructure. In this paper, results are presented for numerical simulations to study the effectiveness of fillers for repair of cracks in concrete, so as to delay the onset of corrosion in reinforcing steel. Concretes without cracks and with either a 50  $\mu\text{m}$  or 500  $\mu\text{m}$  wide crack located directly above the steel reinforcement are simulated, with the addition of silica fume, a corrosion inhibitor, or epoxy-coated reinforcement being considered as additional scenarios. The effectiveness of the crack filler depends not only on its inherent diffusivity with respect to chloride ions, but also on its ability to penetrate and fill the damaged zone or interface between the open crack region and the bulk concrete. Additional simulations indicate that using continuum models instead of models that include details of the rebar placement can lead to underestimating the chloride concentration and overestimating the service life. Experiments are needed to study the ingress of chlorides in damaged (interfacial) regions adjacent to the crack or at the reinforcement surface, as the local transport properties of these regions can significantly influence service life predictions.

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## 1. Introduction

With the recent emphasis on sustainable building practices, it has become critically important to increase the service life of reinforced concrete. Besides its strength and insulating capabilities, an important function of the concrete in a reinforced concrete structure is to serve as a cover/barrier to protect steel reinforcement from the onset of corrosion, most often due to chloride ingress. Here, transport properties, thickness of cover, chemical interactions (binding), resistance to cracks, and repairability of the concrete cover play a crucial role in determining its ability to limit chloride ingress over the service life of the structure. While the transport properties of concrete can be controlled such as to produce very low diffusivities in the bulk regions, in practice, it is the presence and growth of cracks that often provide the main pathways for chloride ingress [1,2]. There are many mechanisms that produce cracks in concrete: plastic, autogenous, and drying shrinkage; thermal and mechanical loading; design issues such as unanticipated loadings; and expansive degradation reactions.

In addition, the crack networks can take on a variety of geometric forms and have a tendency to localize in certain regions of the concrete, due to the underlying mechanisms producing the cracks. One of the simplest types of cracking of practical importance in civil infrastructure is the transverse crack. Here, the crack is most often situated directly above the top layer of transverse reinforcement and extends from the outer surface inward, hence serving as a conduit for water and chlorides [1–3]. For example, when the crack penetrates through the concrete cover thickness and the cracked concrete surface is exposed to de-icing salts, significant chlorides can reach the reinforcement in less than a year, so as to initiate the corrosion process and thus dramatically shorten the service life of the reinforced concrete [2]. Clearly, accurate estimates of service life for infrastructure elements are needed for robust life-cycle cost analysis of structures. Due to the complexity of such systems, let alone accounting for different scenarios of environmental exposure, computational modeling in tandem with experimental investigation can play a crucial role in providing such information.

In this paper, results of a numerical study are presented to determine the effectiveness of fillers (epoxy or methacrylate-based) for repair of cracks in concrete, so as to mitigate the onset of corrosion in steel reinforcement. Following up on a previous study [3], concretes without cracks and those with either a

<sup>\*</sup> Corresponding author.

E-mail addresses: [scott.jones@nist.gov](mailto:scott.jones@nist.gov) (S. Jones), [nicos.martys@nist.gov](mailto:nicos.martys@nist.gov) (N. Martys), [yangluf@boisestate.edu](mailto:yangluf@boisestate.edu) (Y. Lu), [dale.bentz@nist.gov](mailto:dale.bentz@nist.gov) (D. Bentz).

50  $\mu\text{m}$  or 500  $\mu\text{m}$  wide transverse crack are simulated. Concrete mixture modifications, such as the addition of silica fume or a corrosion inhibitor, as well as the incorporation of epoxy-coated reinforcement, are considered in additional parametric studies.

## 2. Model/methods/approach

In this work, a two-dimensional model is used to represent the concrete, a length of rebar, a vertical crack, and a damaged zone (DZ) near the crack surface. The crack and the DZ are modeled as a rectangle to simplify the geometry and represent a worst-case scenario – the width of the rectangle is assumed to be the crack mouth opening [3]. Fig. 1 shows a schematic representation of the model. Based on symmetry considerations, only one half of the geometry is modeled, with an adiabatic boundary condition being enforced at the central axis and at the edges of the domain. A fixed concentration,  $C_{\text{ext}}$ , of chlorides is introduced at the exposed surface to simulate exposure due to application of de-icing salts at the surface. The concentration profile throughout the concrete, as a function of time, is subsequently determined.

The service life of the model reinforced concrete was determined by calculating the time required for the concentration of free chloride ions to reach a certain threshold level to initiate corrosion at the design depth of the reinforcement. In this study, we write the threshold level as the ratio of the chloride concentration at the rebar to the chloride concentration at the surface of the concrete ( $C_{\text{rebar}}/C_{\text{ext}}$ ) [3]. For the value of  $C_{\text{ext}} = 872.3 \text{ mol/m}^3$  (a 5% NaCl solution) used in this study, the initiation of corrosion is assumed to take place at  $C_{\text{rebar}}/C_{\text{ext}}$  equal to 0.1, 0.3, and 0.5 for the cases of black (uncoated) rebar, black rebar with the addition of a typical corrosion inhibitor admixture, and epoxy-coated rebar, respectively [4–7]. The corrosion threshold values used in this study are derived from laboratory specimens using the half-cell potential method [5,8]. It is recognized that these values are dependent on the testing method, the condition of the reinforcing bars, and the environment surrounding the reinforcement. The values used in this study represent a worst-case scenario, i.e., the lowest threshold level found in the literature. The effect of adding silica fume as a supplementary cementitious material at two concentrations was also modeled by adjusting the effective diffusivity of the concrete [9].

### 2.1. Simulation approach

To assess the effectiveness of the crack filler on the service life, several model parameters were varied according to Table 1. A base-case model was first run, where the concrete did not contain a crack.

This model served as a reference for comparison to simulations containing cracks and using crack fillers. Two crack geometries were modeled, including a large 500  $\mu\text{m}$  wide crack and a small 50  $\mu\text{m}$  wide crack. For each crack geometry, the crack was saturated with a solution of chloride ions (at the same concentration as the external solution) or filled with either a methacrylate or an epoxy crack filler. This was done for three different concrete diffusivities intended to represent an ordinary Portland cement (OPC) concrete and concrete with either 5% or 7% silica fume, added on a mass basis, with water-to-cementitious materials ratio (w/cm) of approximately 0.40 [9]. The effect of the diffusivity of the DZ surrounding the crack on the chloride concentration profile was studied by assuming that the DZ diffusivity was restored to the bulk concrete value ( $D_{\text{DZ}} = D_{\text{concrete}}$ ), remained at 20 times the bulk concrete diffusivity ( $D_{\text{DZ}} = 20 * D_{\text{concrete}}$ ), or was repaired by the crack filler ( $D_{\text{DZ}} = D_{\text{crackfiller}}$ ). Results are presented (Table 2) as the predicted service life of the structure and the free chloride

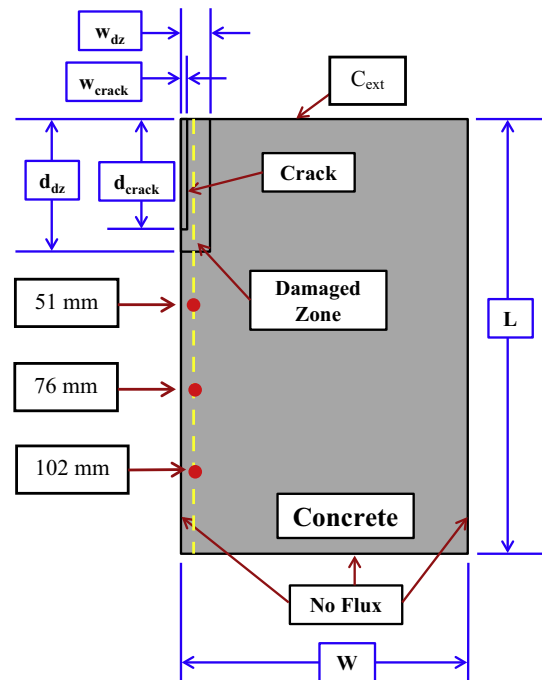


Fig. 1. Schematic diagram of two-dimensional domain used to model chloride transport into (cracked) concrete. The domain is divided up into three regions representing the crack, the DZ, and the bulk concrete. Each region is defined by a rectangle, and the transport properties of each are as defined in Table 1. The red dots represent points where the chloride concentration was recorded for service life calculations. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

concentrations at cover depths of 51 mm, 76 mm, and 102 mm, as a function of time. Two types of crack fillers were examined. One had a diffusivity greater than the bulk concrete, while the other had a diffusivity lower than the bulk concrete. In the analysis of the results, the change in service life over the base case and when the crack is filled with a crack filler is explored.

### 2.2. Cracked concrete domain

In Fig. 1, three regions of the concrete domain are defined to represent the crack, its surrounding DZ, and the concrete cover. The crack is modeled as a rectangle with the width being the crack mouth opening and the length representing the crack depth. This geometry is idealized, as real cracks narrow as their depth increases and their path may be tortuous. The diffusion coefficient of the solution in the crack is given in Table 1. The diffusivity of the crack listed in Table 1 is an effective diffusivity that includes the influences of molecular diffusion, permeability, and water and vapor transport in the concrete cover [3]. In this work, two (bounding) crack geometries are used. The effective diffusivity of the 50  $\mu\text{m}$  (small) crack is set at  $2.0 \times 10^{-9} \text{ m}^2/\text{s}$ , and a value of  $4.0 \times 10^{-9} \text{ m}^2/\text{s}$  is used for the 500  $\mu\text{m}$  (large) crack to account for an increase in ionic transport in the larger crack [3]. Around the crack is the DZ. In the DZ, the concrete diffusivity is greater than that in the bulk concrete as a result of the surface characteristics of the crack and micro-cracking/damage adjacent to the crack [10]. The size of the DZ is assumed to depend on the crack width and is set at 1.0 mm for the small crack and 4.0 mm for the large crack, calibrated to match data from laboratory studies [11]. The nominal diffusivity of the DZ is assumed to be 20 times that of the bulk concrete for all cases [3]. Chloride binding is assumed to be unaffected by the DZ; thus, the chloride binding parameters are the same in the DZ as in the bulk concrete.

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