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Simulation Studies of Methods to Delay Corrosion and Increase Service Life for Cracked Concrete Exposed to Chlorides

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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 µm or 500 µm 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.

Keywords: Chloride ingress; corrosion; crack filler; reinforced concrete; service life; transverse cracking.

1.0 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 50 µm or 500 µm 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.

2.0 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]. Figure 1 shows a schematic representation of the model. Based on symmetry considerations, only one half of the geometry is modelled, with an adiabatic boundary condition being enforced at the central axis and at the edges of the domain. A fixed concentration, C_{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_{rebar}/C_{ext}) [3]. For the value of C_{ext}=872.3 mol/m^3 (a 5 % NaCl solution) used in this study, the initiation of corrosion is assumed to take place at C_{rebar}/C_{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.

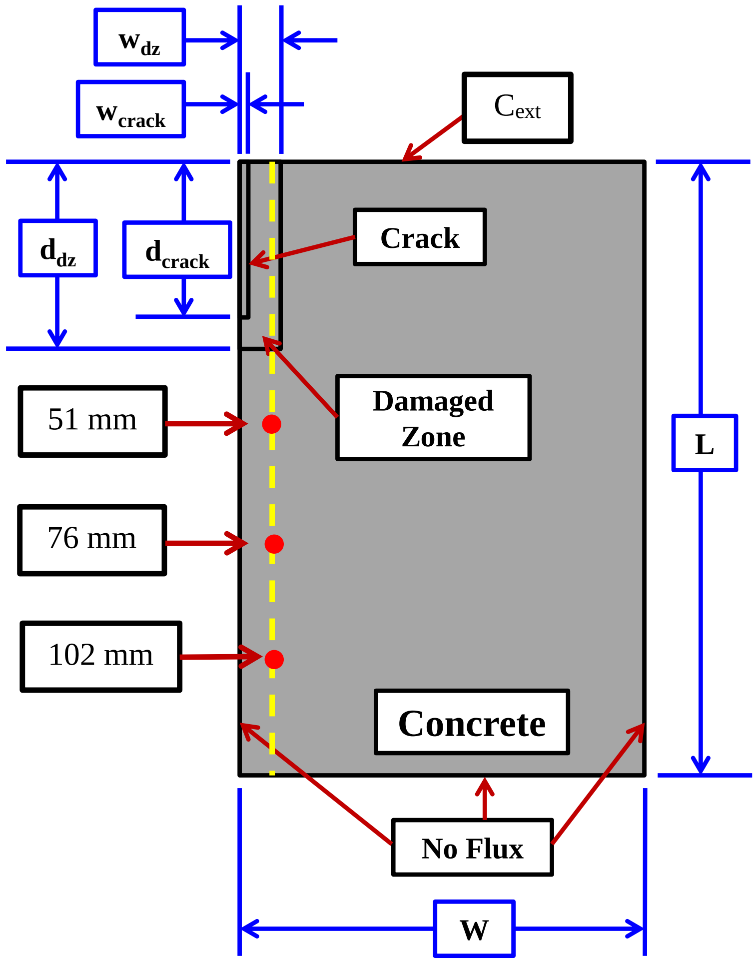

Figure 1: Schematic diagram of two-dimensional domain used to model chloride transport into (cracked) concrete. The domain is divided up into three regions representing the crack, the DZ, and the bulk concrete. Each region is defined by a rectangle, and the transport properties of each are as defined in table 1. The red dots represent points where the chloride concentration was recorded for service life calculations.

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 µm wide crack and a small 50 µm 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 ($D_{DZ} = D_{concrete}$), remained at 20 times the bulk concrete diffusivity ($D_{DZ} = 20*D_{concrete}$), or was repaired by the crack filler ($D_{DZ} = D_{crackfiller}$). Results are presented (table 2) as the predicted service life of the structure and the free chloride concentrations at cover depths of 51 mm, 76 mm, and 102 mm, as a function of time. Two types of crack fillers where 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.

Table 1: List of material properties and dimensions used for this study.

Variable	Value	Description
$D_{concrete}$	1.5×10^{-12} m^2/s	Diffusivity of concrete
	0.5×10^{-12} m^2/s	Diffusivity of concrete with 5% silica fume
	0.3×10^{-12} m^2/s	Diffusivity of concrete with 7% silica fume
D_{damage}	$20*D_{concrete}$	Diffusivity of damaged zone
D_{crack}	2.0×10^{-09} m^2/s	Diffusivity of 50 µm wide crack
	4.0×10^{-09} m^2/s	Diffusivity of 500 µm wide crack
$D_{methacrylate}$	2.0×10^{-12} m^2/s	Diffusivity of methacrylate
D_{epoxy}	1.0×10^{-13} m^2/s	Diffusivity of epoxy
d_{crack}	20.0 mm	Crack depth of 50 µm wide crack
	40.0 mm	Crack depth of 500 µm wide crack
w_{crack}	25.0 µm	Half width of crack with depth 20 mm
	250.0 µm	Half width of crack with depth 40 mm
d_{damage}[1]	21.0 mm	Depth of damage zone with crack depth 20 mm
	44.0 mm	Depth of damage zone with crack depth 40 mm
w_{damage}[1]	1.025 mm	Width of damage zone with crack width 50 µm
	4.25 mm	Width of damage zone with crack width 500 µm
C_{ext}	872.3 mol/m^3	Cl^- concentration at top surface (5 % NaCl solution)
L	204.0 mm	Concrete thickness
W	100.0 mm	Width of section
k	3.0×10^{-7} s^{-1}	Cl^- binding reaction rate
λ	2.4	Parameter in linear Cl^- binding isotherm

[1]Depth of damage zone includes full depth of crack; width of damage zone includes half width of crack (Figure 1).

2.2 Cracked Concrete Domain

In figure 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 µm (small) crack is set at 2.0x10^{-9} m^2/s, and a value of 4.0x10^{-9} m^2/s is used for the 500 µm (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.

It is common in the construction industry to repair concrete cracks, especially if these cracks are in a structure such as a bridge deck. Repair methods vary, but in general the cracks are filled with a crack-filling material [12]. The type of material used to fill the crack is typically either a methacrylate or an epoxy material [13]. In this work, the chloride ion diffusivity of the methacrylate and the epoxy was estimated from the diffusivity of water in these polymers, by assuming that the ratio of the crack filler's water diffusivity to chloride ion diffusivity is equal to the ratio of water's self-diffusivity to chloride ion diffusivity in water. The water diffusivities for methacrylate and epoxy were taken from [14] and [15], and the water self-diffusivity and chloride diffusivity values were taken from [16] and [17]. The diffusivity values are determined assuming isothermal conditions at 25 ^{o}C. When simulating an epoxy or methacrylate crack filler, it is assumed that the crack filler is present when the simulation begins, at t = 0, and that the chloride content in the concrete is zero. This allows for comparison of the service life between the cases with and without a crack filler and highlights the effect the crack filler has on the ingress of chloride ions.

The effect of the methacrylate or epoxy is modeled by setting the diffusivity of the crack equal to that of the chloride diffusivity of the crack filler. The effect that the crack filler has on the DZ is unknown, so each case is run with the diffusivity of the damage zone unchanged (20x concrete diffusivity), restored to that of the bulk concrete, and changed to be equal to the diffusivity of the crack filler material itself.

2.3 Description of Mathematical Model

For this study, we assume that the concrete is fully saturated, such that the ingress of chlorides into concrete is driven strictly by diffusion. Previous models have assumed a Fick's second law behavior and modeled the chloride ingress using an apparent diffusion coefficient that accounts for not only diffusion, but capillary suction and binding. The apparent diffusion coefficient is often estimated by determining the total chloride concentration as a function of depth into a concrete or mortar specimen and fitting equation 1 to the results through a nonlinear regression. Equation 1 is the solution to Fick's second law for one-dimensional semi-infinite spatial domain and time [18].

$$\frac{C(x,t)}{C_s} = erfc\left(\frac{x}{2\sqrt{D_{app}t}}\right) \tag{1}$$

where *erfc(x)* represents the complementary *erf* (error) function (=1-*erf(x)*). In our approach, chloride ion transport due to convection is not considered, but we do include the chloride binding process explicitly by separately adding a reaction term to Fick's second law. Chloride ions in the pore solution of concrete interact with the cementitious phases in a process known as chloride binding. Binding is a result of the formation of Friedel's salt and other reaction products and the physical absorption of chloride ions by calcium silicate hydrate gel and other hydration products [19]. To model chloride binding, Freundlich, Langmuir, and linear isotherms are commonly used. These isotherms relate the concentration of chlorides bound to concrete to the concentration of chlorides in the pore solution. The Freundlich, Langmuir, and linear isotherms are given in equations 2 to 4.

Freundlich: $$C_b = \mu C_f^{\gamma} \tag{2}$$

Langmuir: $$C_b = \frac{\alpha C_f}{1 + \beta C_f} \tag{3}$$

Linear: $$C_b = \lambda C_f \tag{4}$$

In equations 2 to 4, C_b and C_f are the bound and free chloride concentrations, μ and γ are the Frendulich parameters, α and β are the Langmuir parameters, and λ is the ratio of the bound to free chlorides in the linear isotherm. In this work, to increase numerical stability, a simple linear isotherm, via equation 4, was implemented [3].

In this paper, the mass transport of free chloride ions into a saturated concrete is modeled using Fick's second law with the addition of a binding term, shown in equation 5, which is solved over the domain in figure 1. In equation 5, D_{eff} is the effective diffusivity that describes chloride ion transport resulting from diffusion. The sink due to chloride binding is represented by the reaction term on the right-hand side of equation 5.

$$\frac{\partial C_f}{\partial t} = \nabla \cdot \left(D_{eff} \nabla C_f\right) + k\left(C_b - \lambda C_f\right) \tag{5}$$

The chloride binding process is modeled as a first-order reaction described by equation 6.

$$\frac{dC_b}{dt} = k\left(\lambda C_f - C_b\right) \tag{6}$$

In equations 5 and 6, C_f is the free chloride concentration, C_b is the bound chloride concentration, and k is the reaction rate of the binding process. The solution to equation 6, $C_b(t)$, is used in equation 5. In the software package utilized in this research, both equations are solved at each time step, and the product λC_f is not allowed to exceed C_b. The total chloride concentration at a given location for a given time step is the sum of the free and bound chlorides.

In the cases where the crack contains an epoxy or methacrylate, equation 5 describes the transport of chloride ions through the crack filler. Here, the binding between the chlorides and the epoxy is negligible and $k = 0$. The effective diffusivity becomes the diffusivity of chloride ions in the crack filler.

2.4 Solution to Mathematical Model

To solve equations 5 and 6 over the domain in figure 1, a commercial finite element software package was used (Comsol Multiphysics®[1]). This package allows one to define a set of domains and the equations and boundary conditions that are applicable. For each study, the domain was discretized using triangular elements. The software automatically determines the appropriate element size and number of nodes, with the user having the ability to further refine the element density. Figure 2 shows a typical mesh used in this study. The mesh density was increased around the crack and DZ to improve solution conversion and precision of results. The simulation was carried out over 250 years to ensure that the end of service life was reached for each concrete mixture at a depth of 102 mm. The results were reported and stored every 5 years. The software automatically determines the appropriate time step to use at each iteration.

The output of the simulation is the free (equation 5) and bound (equation 6) chloride concentrations at each time interval. These concentrations corresponding to depths of 51 mm, 76 mm, and 102 mm were exported to represent three typical cover depths. These points were located on a line positioned 50 µm to the right of the crack geometry, as shown in figure 1, or directly down the left side of the (half) specimen when no crack was present.

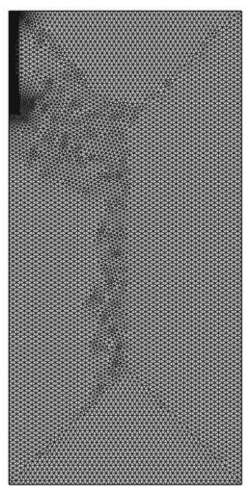

Figure 2: Triangular mesh used to solve equations 5 and 6. Mesh density is increased around the crack and DZ (upper left of mesh) to improve precision of results.

3.0 Results/Discussion

The results presented here are the service life for reinforced concrete structures as predicted by the solution to equations 5 and 6. All results presented here are for OPC concrete except where the addition of silica fume is noted. To test the performance of the finite element method, one-dimensional and two-dimensional solutions of Fick's law were computed. The average error between the solution in equation 1 and the finite element solution was 7.2 % at 75 years. The majority of the difference between the finite element solution and equation 1 is a result of the fact that the latter assumes the medium is semi-infinite, while the finite element solution contains a no

[1] Certain commercial products are identified in this paper to specify the materials used and procedures employed. In no case does such identification imply endorsement or recommendation by the National Institute of Standards and Technology, nor does it indicate that the products are necessarily the best available for the purpose.

flux boundary condition at the bottom surface. This result demonstrates a good agreement between the finite element solution and the analytical solution to Fick's law. In this study, results are reported at a time of 75 years to show the chloride concentration in a reinforced concrete structure designed for a 75 year service life.

3.1 Base case: No cracks in cover

The base-case configuration represents the control, where the cover concrete is pristine and contains no cracks. Service lives calculated from the free chloride ion concentration are given in table 2. The service lives for cover depths of 51 mm, 76 mm, and 102 mm were determined to be 34 years, 76 years, and 137 years, respectively. As expected, increasing the cover depth increased the service life, as a larger cover depth increases the distance the free chloride ions have to travel to reach the rebar and diffusion times (service life) scale as the square of the cover depth (doubling the cover depth should increase the service life by a factor of 4, as observed). The addition of silica fume to concrete was assumed to reduce its diffusivity (table 1); because of this, the results in table 2 show an increase in service life as the silica fume percentage increases. For the 51 mm cover depth, adding 5 % and 7 % silica fume increased the service life to 103 years and 172 years, respectively. However, silica fume may increase early-age cracking due to an increase in plastic and autogenous shrinkage that is particularly high when the concrete is improperly cured or exposed to elevated temperatures [20-22].

Table 2: Service lives calculated from the free chloride ion concentration determined by solving equations 5 and 6. These results serve as the base-case service lives for comparison with service lives calculated for cracks and crack fillers.

Variable		Service life (years)	Increase
$C_{rebar}/C_{ext} = 0.1$	51 mm cover	34	--
	76 mm cover	76	120 %
	102 mm cover	137	300 %
	5% silica fume (51 mm)	103	200 %
	7% silica fume (51 mm)	172	410 %
$C_{rebar}/C_{ext} = 0.3$	Corrosion inhibitor (51 mm)	86	150 %
$C_{rebar}/C_{ext} = 0.5$	Epoxy-coated rebar (51 mm)	203	500 %

With the assumptions used in the study, the use of a corrosion inhibitor increased the service life from 34 years to 86 years in the case of a 51 mm cover. Corrosion inhibitors interact with the chloride ions in the pore solution, reducing the free chloride concentration and the $[Cl^-]/[OH^-]$ ratio [4,5,23]. This corresponds to an increase in the threshold chloride concentration required to initiate corrosion and thus in the service life, as reflected in the results in table 2. For this study, it was assumed that corrosion began to occur when $C_{rebar}/C_{ext} = 0.3$, based on experimental results given in [23]. Higher dosages of corrosion inhibitor generally produce further increases in the value of C_{rebar}/C_{ext} required to initiate corrosion.

Using an epoxy-coated rebar increased the service life to 203 years. Again, this approach is modelled by increasing the threshold chloride level needed to initiate corrosion at the depth of the reinforcement from 0.1 to 0.5 [24].

3.2 Small cracks in cover

In this section, the results are reported in three groups to show the effect of the crack in the cover, the effect of filling the crack with a crack filler, and the effect of changing the DZ diffusivity when a crack filler is used. Figure 3 shows the free chloride ion concentration after 75 years in OPC concrete containing a small crack. Figure 3a presents results for the case where the crack is saturated with a chloride ion solution, and figures 3b and 3c present results for when the crack is filled with either methacrylate or epoxy, respectively.

Table 3 shows the service life for the case of a 50 µm wide crack in the cover. The last column is the change in service life relative to the base-case results reported in table 2. Values in parentheses represent a projected decrease in service life. The service life for the case with a 51 mm cover and a small crack is reduced to 23 years, a 32 % reduction from the base case. As might be expected, with a thicker 102 mm cover, the reduction in service life is only 8 %. When 5 % or 7 % silica fume is used in the concrete mixture, the small crack reduced the service life to 69 years and 113 years, respectively, corresponding to 33 % and 34 % reductions in service life over the base cases with the same levels of silica fume. This can be explained by the difference between the crack diffusivity and the concrete diffusivity, which is larger for silica fume concrete

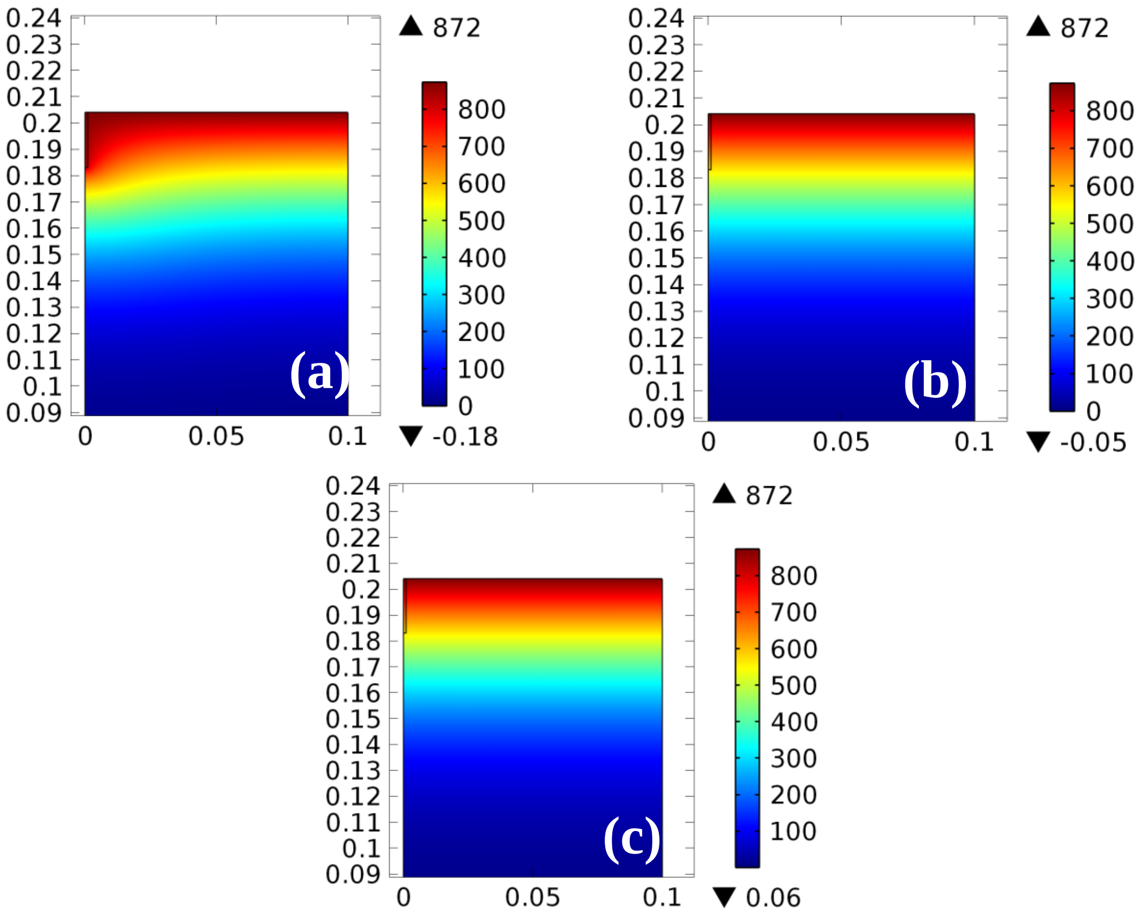

Figure 3: Free chloride concentration at 75 years in OPC concrete cover with a small crack when the crack is (a) saturated with a chloride solution, (b) filled with methacrylate, and (c) filled with epoxy. The DZ diffusivity is assumed to be the concrete diffusivity when the crack is filled with methacrylate or epoxy. Units of concentration are mol/m^3.

Table 3: Calculated service life at various depths with a small crack in the concrete cover showing the effect the crack has on the service life of the structure, along with the change from the un-cracked case (parentheses denote a negative change). Bulk concrete diffusivity is 1.5×10^{-12} m^2/s, except in the cases of the 5 % and 7 % silica fume mixtures (see Table 1).

Variable		Service life (years)	Change from uncracked case
$C_{rebar}/C_{ext} = 0.1$	51 mm cover	23	(32 %)
	76 mm cover	65	(14 %)
	102 mm cover	126	(8 %)
	5% silica fume (51 mm)	69	(33 %)
	7% silica fume (51 mm)	113	(34 %)
$C_{rebar}/C_{ext} = 0.3$	Corrosion inhibitor (51 mm)	67	(22 %)
$C_{rebar}/C_{ext} = 0.5$	Epoxy-coated rebar (51 mm)	167	(18 %)

than it is for OPC concrete. The larger difference in diffusivities magnifies the effect of the crack, as the ions travel much faster through the crack than through the silica fume concrete. While the change in service life is much greater for silica fume concrete, the service life of silica fume concrete with a small crack is still greater than that of OPC concrete with a small crack, assuming the cracks to be the same in the two concretes. For the case of a small 50 µm wide crack and a cover depth of 51 mm, the silica fume increased the service life from 23 years to 69 years with 5 % silica fume and to 113 years with 7 % silica fume.

The corrosion inhibitor increased the service life from 23 years to 67 years when a crack is present. In this model, it is assumed that the corrosion inhibitor does not affect the diffusivity of the concrete or the chloride binding reaction rate; it only acts to increase the percentage of free chloride ions necessary to initiate corrosion at the reinforcement depth. The time it takes for the free chlorides to reach the rebar remains the same. The increase in service life is a result of the requirement that the concentration of free chlorides present must be three times higher to initiate corrosion with a corrosion inhibitor than without one. When a corrosion inhibitor is used in the base case, the service life is 86 years. Therefore, the effect of the small crack is to reduce the service life to 67 years, a 22 % reduction.

A similar result is seen with the epoxy-coated rebar. It increased the service life from 23 years to 167 years when the crack is present, but its service life was reduced by 18 % over the base epoxy-coated rebar (no crack) case. The use of epoxy-coated rebar does not affect the diffusivity of the concrete; it requires a higher concentration of free chloride ions to be present to initiate corrosion compared to the use of black rebar.

Table 4 shows the corresponding service life when the crack is filled with methacrylate or epoxy crack filler and the DZ diffusivity is restored to the value of the bulk concrete. The change column represents the percent change in service life over the base case in table 2. The predicted service lives in table 4 are approximately equal to the base case with a 1 % increase in service life for some cases, as the diffusivity of the epoxy filler is significantly lower than that of the control bulk concrete. The lower epoxy diffusivity means chloride ions travel slower through the (crack) matrix. This is the reason why the service life is restored to the un-cracked case and suggests that effective crack filling means selecting a crack filler with a diffusivity comparable to that of the surrounding concrete.

Table 5 presents the service life when the DZ diffusivity is varied, for those cases where the crack is filled with a crack filler. When the DZ is assumed to be 20 times the concrete diffusivity, the service lives associated with use of methacrylate or epoxy crack filler were computed to be 18 % lower than the case where the DZ is assumed to be the concrete diffusivity when the crack filler is present. As the cover increases, so does the service life, while the influence of the crack decreases. The change in service life from the base case decreases to 4 % for both methacrylate and epoxy when the cover is 102 mm and the DZ diffusivity is 20 times the concrete diffusivity. Assuming that the DZ diffusivity is the same as the crack filler diffusivity effectively restores the service life to the base case for the methacrylate and produces a 3 % increase for the epoxy, once again due to its lower assumed chloride ion diffusivity.

To further demonstrate the effect of the DZ diffusivity on the service life, the free chloride concentration is plotted in figures 4 and 5 as a function of time for the case of the 51 mm cover containing a small crack. Figure 4 shows the free chloride concentration for the cases where the crack-filling material is methacrylate, and figure 5 shows results for the cases where the crack-filling material is epoxy. The horizontal lines in figures 4 and 5 represent the threshold chloride levels where corrosion initiation begins for black rebar, black rebar with corrosion inhibitors, and epoxy-coated rebars. In both figures 4 and 5, for the cases where the DZ diffusivity is 20 times the bulk concrete diffusivity, the chloride concentration is significantly higher than for the other two DZ diffusivity cases, but not as high as the case without the crack filler. These results indicate that, if the crack filler does not positively influence the surrounding damage zone, the DZ may become the new preferred pathway for the ingress of chloride ions.

Table 4: Calculated service life with methacrylate or epoxy crack filler in a small crack showing the effect the crack filler has on service life. These results were calculated with the DZ diffusivity equal to the bulk concrete diffusivity, when the crack is filled with methacrylate or epoxy.

<table>
<tr><th colspan="3">Variable</th><th>Service life (years)</th><th>Change from uncracked case</th></tr>
<tr><td rowspan="7">Methacrylate</td><td rowspan="5">$C_{rebar}/C_{ext} = 0.1$</td><td>51 mm cover</td><td>34</td><td>0 %</td></tr>
<tr><td>76 mm cover</td><td>76</td><td>0 %</td></tr>
<tr><td>102 mm cover</td><td>138</td><td>1 %</td></tr>
<tr><td>5% silica fume (51 mm)</td><td>102</td><td>(1 %)</td></tr>
<tr><td>7% silica fume (51 mm)</td><td>171</td><td>(1 %)</td></tr>
<tr><td>$C_{rebar}/C_{ext} = 0.3$</td><td>Corrosion inhibitor (51 mm)</td><td>87</td><td>1 %</td></tr>
<tr><td>$C_{rebar}/C_{ext} = 0.5$</td><td>Epoxy-coated rebar (51 mm)</td><td>204</td><td>1 %</td></tr>
<tr><td rowspan="7">Epoxy</td><td rowspan="5">$C_{rebar}/C_{ext} = 0.1$</td><td>51 mm cover</td><td>34</td><td>0 %</td></tr>
<tr><td>76 mm cover</td><td>76</td><td>0 %</td></tr>
<tr><td>102 mm cover</td><td>138</td><td>1 %</td></tr>
<tr><td>5% silica fume (51 mm)</td><td>103</td><td>0 %</td></tr>
<tr><td>7% silica fume (51 mm)</td><td>172</td><td>0 %</td></tr>
<tr><td>$C_{rebar}/C_{ext} = 0.3$</td><td>Corrosion inhibitor (51 mm)</td><td>88</td><td>2 %</td></tr>
<tr><td>$C_{rebar}/C_{ext} = 0.5$</td><td>Epoxy-coated rebar (51 mm)</td><td>204</td><td>1 %</td></tr>
</table>

Table 5: Service life with methacrylate or epoxy crack filler in a small crack with different DZ diffusivities. Bulk concrete diffusivity is assumed to be 1.5×10^{-12} m^2/s, and end of service life is

assumed to be when $C_{rebar}/C_{ext} = 0.1$. Percent change is calculated from base case results in table 2.

Variable			Service life (years)	Change
Methacrylate	No DZ repair $D_{DZ} = 20*D_{concrete}$	51 mm cover	28	(18 %)
		76 mm cover	70	(8 %)
		102 mm cover	132	(4 %)
	Crack filler repair $D_{DZ} = D_{methacrylate}$	51 mm cover	34	0 %
		76 mm cover	76	0 %
		102 mm cover	138	1 %
Epoxy	No DZ repair $D_{DZ} = 20*D_{concrete}$	51 mm cover	28	(18 %)
		76 mm cover	70	(8 %)
		102 mm cover	132	(4 %)
	Crack filler repair $D_{DZ} = D_{epoxy}$	51 mm cover	35	3 %
		76 mm cover	77	1 %
		102 mm cover	139	1 %

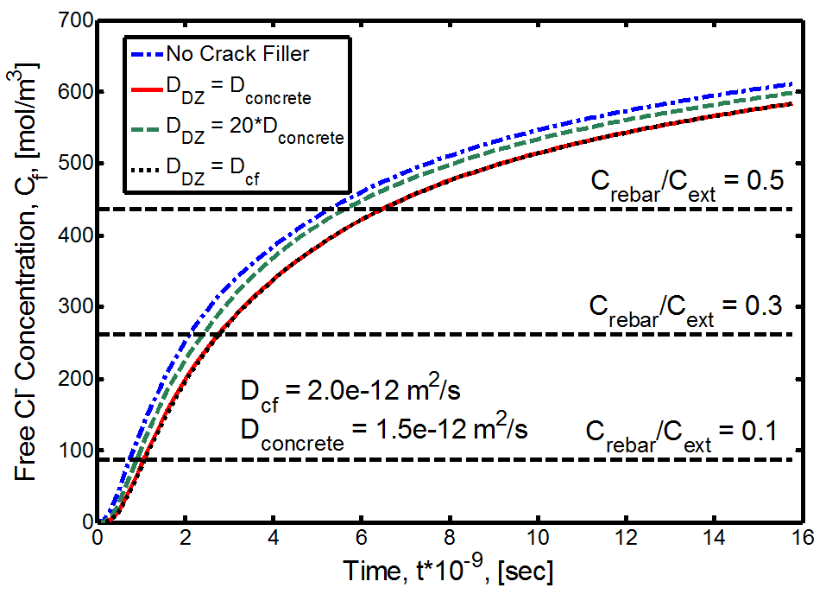

Figure 4: Free chloride concentration at a depth of 51 mm into the concrete cover as a function of time for different DZ diffusivities with methacrylate crack filler. These results are for the small (50 μm wide) crack.

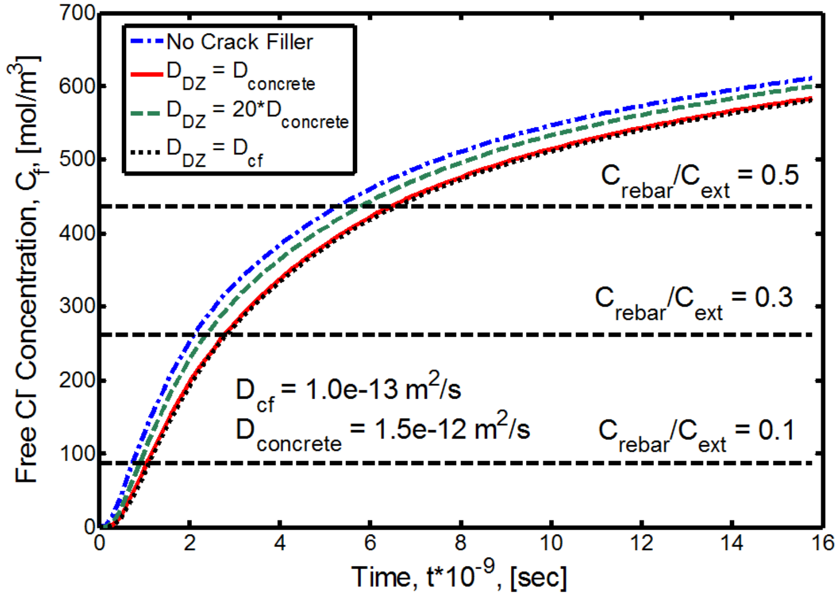

Figure 5: Free chloride concentration at a depth of 51 mm into the concrete cover as a function of time for different DZ diffusivities with epoxy crack filler. These results are for the small (50 µm wide) crack.

3.3 Large cracks in cover

To study the effects of the crack size, the simulation program was repeated for the large (500 µm wide) crack geometry. The results presented in table 6 show that the large crack reduced the service life to 1 year for the case of a 51 mm cover, a 98 % reduction over the base case. Such a large reduction may seem extreme but has also been noted in actual practice [2]. Increasing the cover increased the service life, but the effect of this is limited, as the service life is increased by 82 years for a cover depth of 102 mm, compared to an increase of 103 years for the small crack and the same cover depth. The depth of the large crack is 40 mm, placing the bottom of the crack only 11 mm above the rebar for the 51 mm cover (even closer when the damage zone is considered as well). Figure 6a shows the free chloride ion concentration as a function of position in the cover. The chloride concentration around the bottom of the crack is higher than that in the bulk concrete. This shows that the crack allows chloride ions to bypass the bulk concrete. The effectiveness of the cover is significantly reduced because the large crack allows the chloride ions to penetrate farther into the cover without having to travel through the concrete by diffusion.

Table 6: Calculated service life at various depths with a large crack in the concrete cover. Bulk concrete diffusivity is 1.5x10^{-12} m^2/s except in the case of the 5% and 7% silica fume concrete mixtures (ref. table 1).

Variable		Service life (years)	Change from uncracked case
$C_{rebar}/C_{ext} = 0.1$	51 mm cover	1	(97 %)
	76 mm cover	26	(66 %)
	102 mm cover	83	(39 %)
	5% silica fume (51 mm)	2	(98 %)
	7% silica fume (51 mm)	4	(98 %)
$C_{rebar}/C_{ext} = 0.3$	Corrosion inhibitor (51 mm)	4	(95 %)
$C_{rebar}/C_{ext} = 0.5$	Epoxy-coated rebar (51 mm)	16	(92 %)

Additional results are given in figure 6 and tables 7 and 8, with the change calculated with respect to the base case in table 2. Figure 6 shows the free chloride concentration in OPC concrete cover containing a large crack. Figure 6a presents the results for the case where the crack is saturated with a chloride ion solution, and figures 6b and 6c present the results for when the crack is filled with methacrylate or epoxy, respectively. Similar trends are seen for all cover depths and with the use of silica fume, corrosion inhibitor, and epoxy-coated rebar, emphasizing the critical importance of repairing wide, deep cracks in concrete bridge decks in a timely fashion.

Table 7 shows the calculated service life for the case when the crack is filled with methacrylate or epoxy and the DZ diffusivity is restored to that of the bulk concrete. When methacrylate crack filler is used with OPC concrete, the service life increased to 33 years but is still 3 % lower than the base case. With 102 mm of cover, methacrylate has restored the service life to the base case levels. When methacrylate crack filler is used in a concrete mixture containing silica fume, the service life is 99 years for 5 % silica fume concrete and 162 years for 7 % silica fume concrete. These service lives correspond to 4 % and 6 % reductions in service life over the base case, respectively, because of the lower diffusivity of the uncracked silica fume concrete. When epoxy is used as the crack filler, the service lives are basically restored to the respective base case levels (within 1 % to 3 %), as the assumed chloride ion diffusivity in epoxy is similar to that of the silica fume concretes.

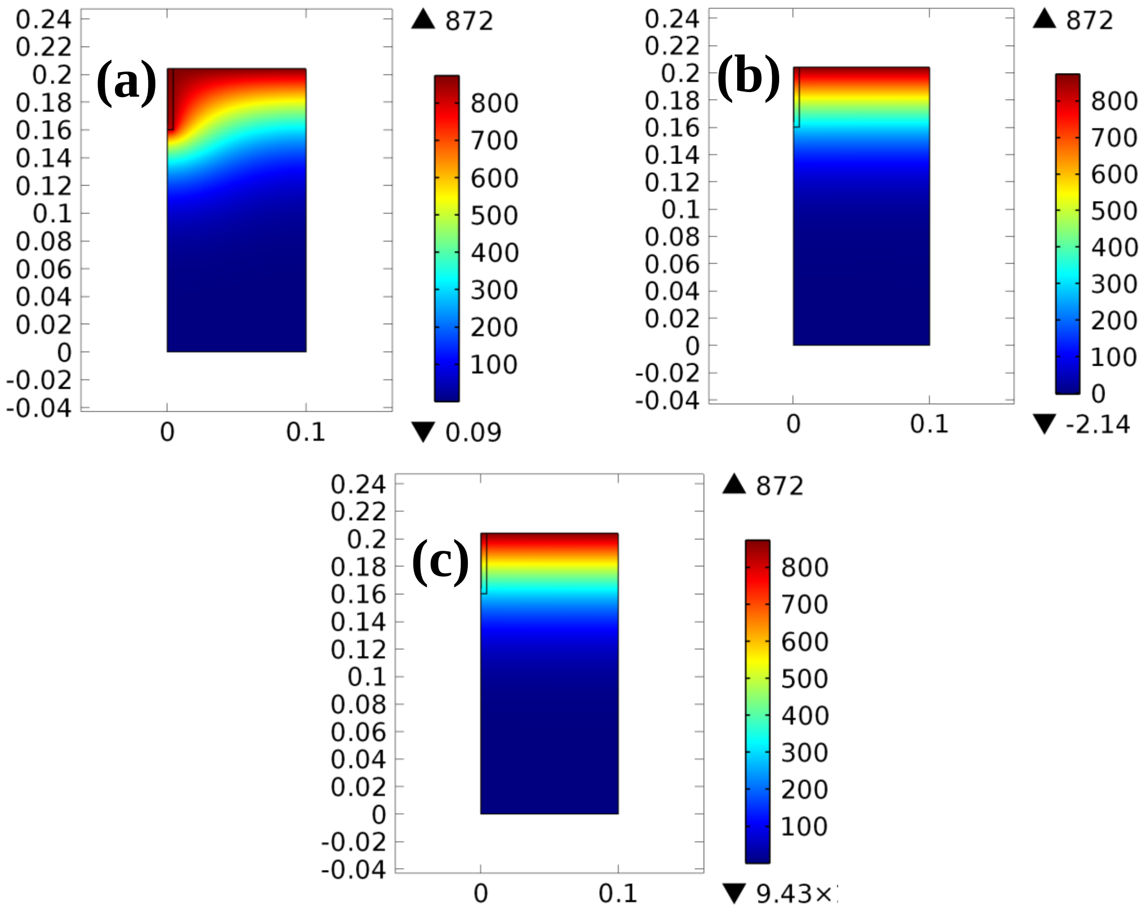

Figure 6: Free chloride concentration at 75 years in OPC concrete cover with a large crack when the crack is (a) saturated with a chloride solution, (b) filled with methacrylate, and (c) filled with epoxy. The DZ diffusivity is assumed to be the concrete diffusivity when the crack is filled with methacrylate or epoxy. Units of concentration are mol/m^3.

Table 8 shows the effect of the DZ diffusivity on service life calculations when the large crack is filled. For the case of a wide crack filled with methacrylate and a cover depth of 51 mm, the service life is 6 years when the DZ diffusivity is assumed to remain 20 times that of the bulk concrete diffusivity. The service life increases to 32 years when the DZ diffusivity is assumed to be the crack filler diffusivity. This trend is seen for all depths and also with the epoxy crack filler. Filling the DZ with methacrylate improved the results, but, because there is a larger area of the model occupied by the methacrylate with the large crack, there is a reduction in service life over the base case, as the diffusivity of chloride ions in methacrylate is slighter higher than that in the base concrete.

Once again, to further demonstrate the effect of the DZ diffusivity on the service life, the free chloride concentration is plotted in figures 7 and 8, as a function of time, for the case of a large crack and a cover depth of 51 mm. Figure 7 shows the results for a crack containing methacrylate. Figure 8 shows the corresponding results for an epoxy-filled crack. In both figures 7 and 8, for the cases where the DZ diffusivity is 20 times the bulk concrete diffusivity, the chloride concentration is higher than the other two DZ diffusivity cases, but not as high as the base case with no crack filler. Comparing figures 7 and 8 with figures 4 and 5 shows the critical effect of the crack size. The larger crack allows for higher concentrations of free chloride ions at earlier times, as noted previously [3].

Table 7: Service life with methacrylate or epoxy crack filler in a large crack in OPC concrete. The DZ diffusivity is assumed to be the bulk concrete diffusivity when the crack contains crack-filling material. Percent change is calculated from base case results in Table 2.

Variable			Service life (years)	Change
Methacrylate	$C_{rebar}/C_{ext} = 0.1$	51 mm cover	33	(3 %)
		76 mm cover	76	0 %
		102 mm cover	137	0 %
		5% silica fume (51 mm)	99	(4 %)
		7% silica fume (51 mm)	162	(6 %)
	$C_{rebar}/C_{ext} = 0.3$	Corrosion inhibitor (51 mm)	86	0 %
	$C_{rebar}/C_{ext} = 0.5$	Epoxy-coated rebar (51 mm)	204	1 %
Epoxy	$C_{rebar}/C_{ext} = 0.1$	51 mm cover	34	0 %
		76 mm cover	76	0 %
		102 mm cover	138	1 %
		5% silica fume (51 mm)	103	0 %
		7% silica fume (51 mm)	172	0 %
	$C_{rebar}/C_{ext} = 0.3$	Corrosion inhibitor (51 mm)	87	1 %
	$C_{rebar}/C_{ext} = 0.5$	Epoxy-coated rebar (51 mm)	205	1 %

Table 8: Service life with methacrylate or epoxy crack filler in a large crack with different DZ diffusivities. Bulk concrete diffusivity is assumed to be 1.5×10^{-12} m^2/s, and end of service life is assumed to be when $C_{rebar}/C_{ext} = 0.1$. Percent change is calculated from base case results in table 2.

Variable			Service life (years)	Change
Methacrylate	No DZ repair $D_{DZ} = 20*D_{concrete}$	51 mm cover	6	(82 %)
		76 mm cover	42	(45 %)
		102 mm cover	101	(26 %)
	Crack filler repair $D_{DZ} = D_{methacrylate}$	51 mm cover	32	(6 %)
		76 mm cover	75	(1 %)
		102 mm cover	137	0 %
Epoxy	No DZ repair $D_{DZ} = 20*D_{concrete}$	51 mm cover	6	(82 %)
		76 mm cover	42	(45 %)
		102 mm cover	101	(26 %)
	Crack filler repair $D_{DZ} = D_{epoxy}$	51 mm cover	42	24 %
		76 mm cover	83	9 %
		102 mm cover	144	5 %

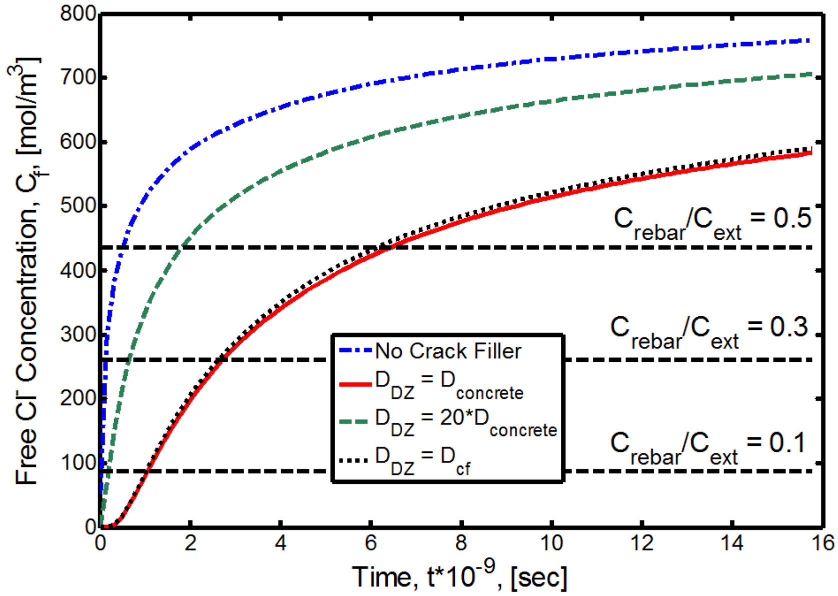

Figure 7: Free chloride concentration at a depth of 51 mm into the concrete cover as a function of time for different DZ diffusivities with methacrylate crack filler. These results are for the large (500 µm wide) crack.

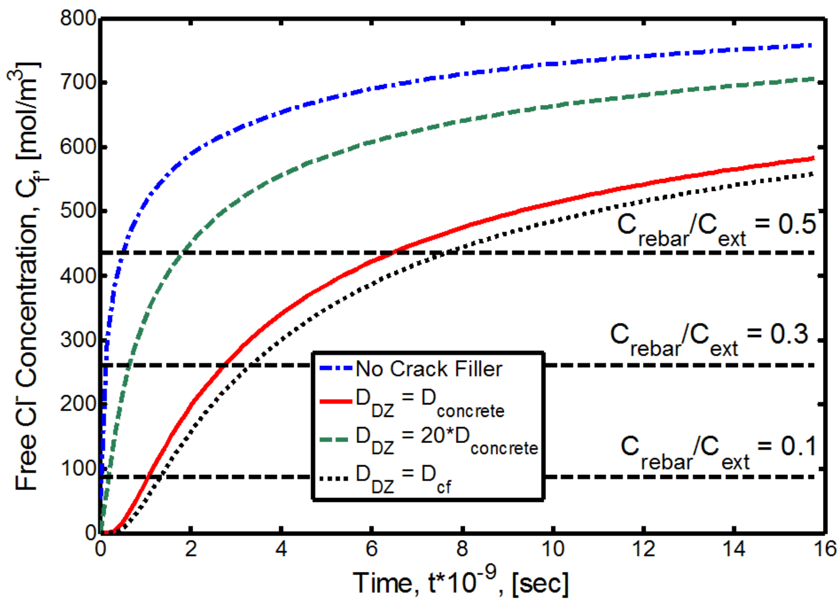

Figure 8: Free chloride concentration at a depth of 51 mm into the concrete cover as a function of time for different DZ diffusivities with epoxy crack filler. These results are for the large (500 µm wide) crack.

Figure 9 shows the free chloride concentration around a small crack and DZ at 75 years in OPC concrete for the three DZ values used in this study. Figure 10 shows the free chloride concentration around a large crack and DZ at 75 years in OPC concrete for the three DZ values used in this study. In Figures 9 and 10, the effect of the DZ diffusivity is apparent. Whether the crack is filled with epoxy or methacrylate, if the DZ diffusivity remains at 20 times the bulk concrete diffusivity, the chloride concentration is higher in the region around the crack, as the DZ effectively becomes the weak link in the system with respect to impeding chloride ingress. This result suggests that the preferred crack repair procedure might be to carefully remove the DZ concrete (e.g., routing the crack) before filling the crack with crack filler. As the effect of the crack filler on the DZ is unknown, further experimental investigation is necessary to determine which assumption best represents the true effects of these crack fillers.

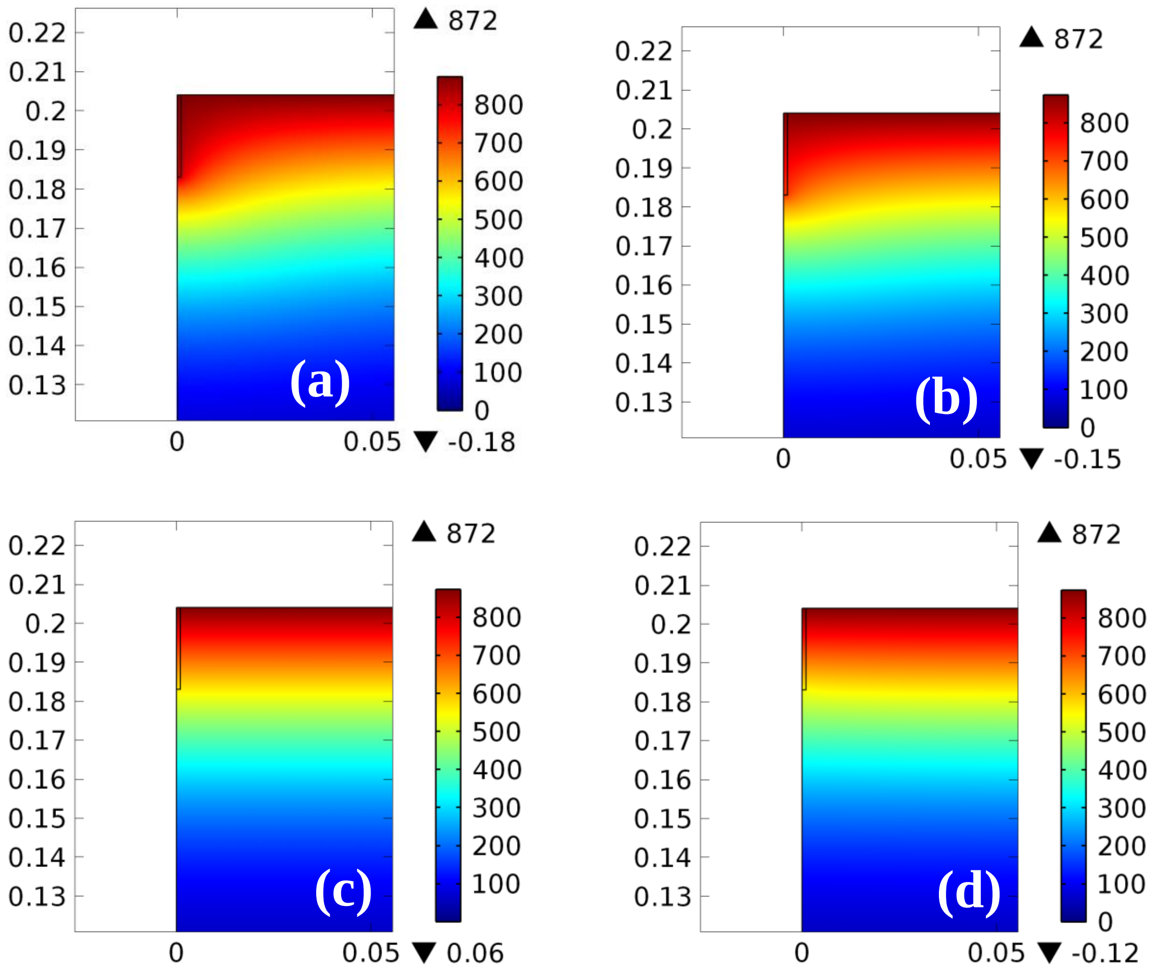

Figure 9: Free chloride concentration around a small crack and DZ at 75 years in OPC concrete showing the effect the DZ diffusivity has on the resulting chloride distribution. In (a), the crack is saturated with a chloride solution. In (b), the crack is filled with epoxy and the DZ remains at $20D_{concrete}$. In (c), the DZ is assumed to be restored to the bulk concrete diffusivity, and in (d) the DZ diffusivity is assumed to be equal to the epoxy diffusivity.

The results reported in table 4 indicate that the methacrylate crack filler can restore the structure to the base-case service life for all cases. The assumed methacrylate diffusivity is 2.0x10^{-12} m^2/s, close to the assumed bulk concrete diffusivity value of 1.5x10^{-12} m^2/s; this difference is reflected in the negligible change in service life over the base case. Because the diffusivities are approximately equal, the base case and the cases involving methacrylate-filled cracks are mathematically similar. This is also seen in the results for the silica fume concrete as the difference in diffusivity between the concrete and crack filler is small compared to the difference in diffusivity between the crack and the concrete. A similar behavior is observed with the epoxy crack filler except the results show a 1 % increase in service life. The difference between the epoxy and concrete diffusivities is larger than that for the methacrylate and accounts for this minor increase.

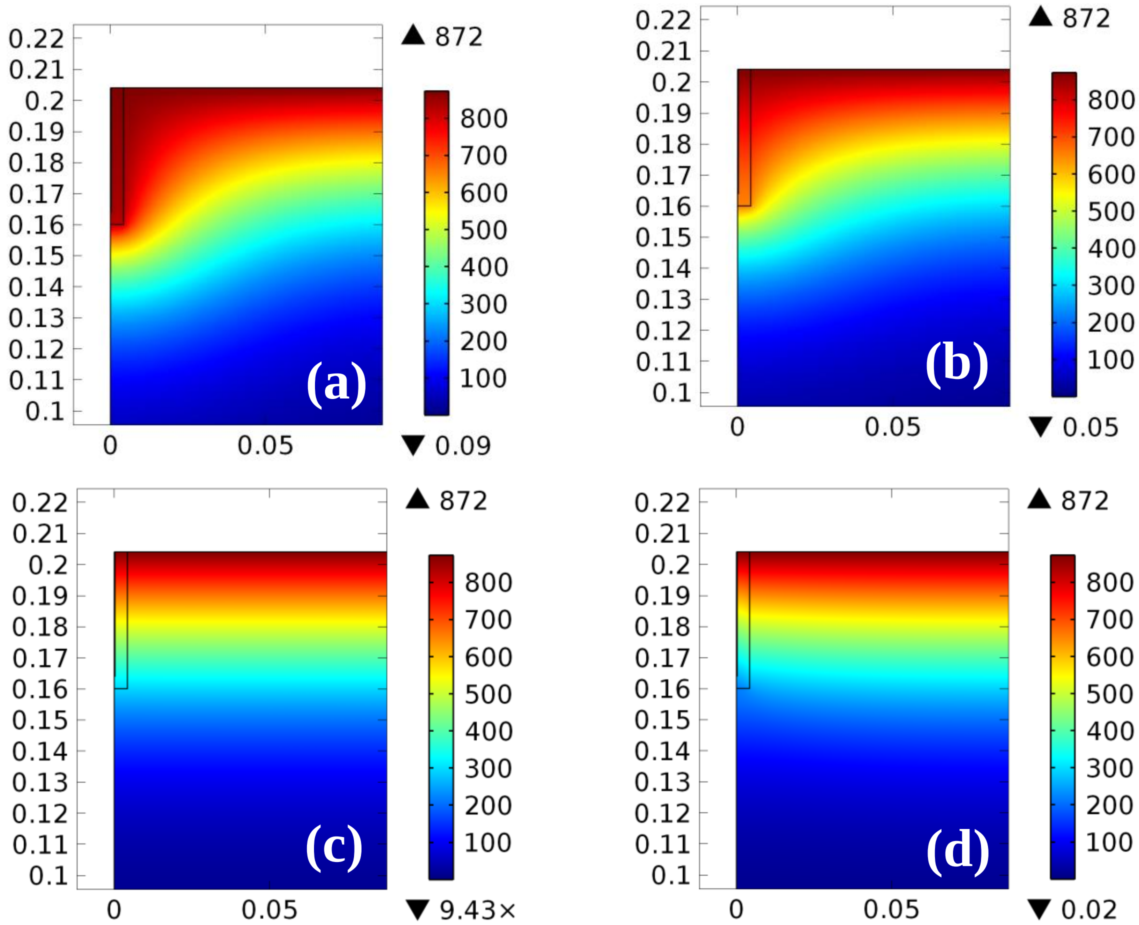

Figure 10: Free chloride concentration around a large crack and DZ at 75 years in OPC concrete showing the effect the DZ diffusivity has on the resulting chloride distribution. In (a), the crack is saturated with a chloride solution. In (b), the crack is filled with epoxy and the DZ remains at $20D_{concrete}$. In (c), the DZ is assumed to be restored to the bulk concrete diffusivity, and in (d) the DZ diffusivity is assumed to be equal to the epoxy diffusivity.

3.4 Effect of Physical Presence of Rebar on Chloride Concentration

Finally, the influence of the rebar's physical presence on chloride concentration and, in turn, its service life is examined [25]. The effects of different cover depths, inclusion of silica fume, and use of epoxy-coated rebar were considered. Figures 11 and 12 show the simulation set up and resulting chloride concentration profiles. Since the rebar acts as an impenetrable barrier, the ingressing chloride ions must move around the rebar in order to progress deeper into the concrete. As a result, it is observed that the chloride concentration can increase near the rebar surface and consequently shorten its service life. Table 9 shows the change in service life when rebar is included in the simulation. Surprisingly, the service life was typically shortened by close to 20 %

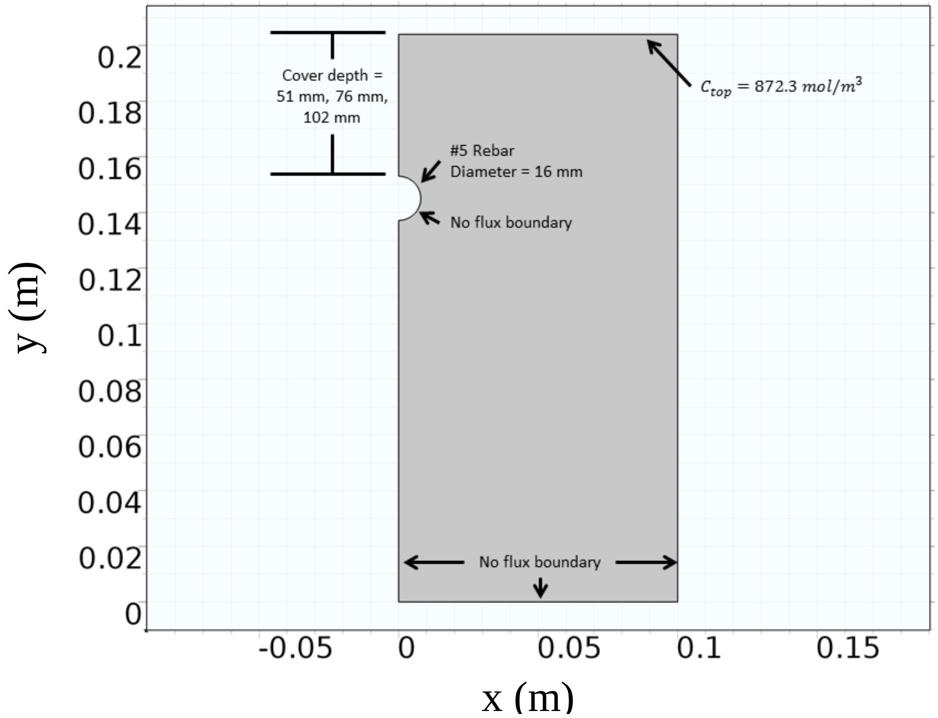

Figure 11: Geometry of base-case model with rebar. A #5 rebar with 16 mm diameter is used with cover depths of 51 mm, 76 mm, and 102 mm.

or more, consistent with the projections of Kranc et al. [25]. While a possible approach for mitigating this effect could be to introduce a more permeable layer around the rebar, there is then the risk of decreasing the strength of the bond between the concrete and the rebar. Regardless, service life predictions obtained from modeling that does not inherently include the effects of this geometrical barrier may need to be adjusted to account for this feature.

Table 9: Service lives for cases with rebar and without rebar. Results are calculated with the rebar located at the specified cover depth for OPC concrete except where noted.

		Service life (years)				Change with rebar	Change with rebar DZ
		Fick's 2nd law	Without rebar	With rebar	With rebar DZ		
$\frac{C_{rebar}}{C_{ext}} = 0.1$	51 mm cover	14	34	27	28	(21 %)	(18 %)
	76 mm cover	31	76	64	66	(16 %)	(13 %)
	102 mm cover	56	137	120	122	(12 %)	(11 %)
	5 % SF (51 mm)	42	103	84	86	(18 %)	(17 %)
	7 % SF (51 mm)	70	172	140	143	(19 %)	(17 %)
$\frac{C_{rebar}}{C_{ext}} = 0.3$	Corrosion inhibitor (51 mm)	35	86	65	68	(24 %)	(21%)
$\frac{C_{rebar}}{C_{ext}} = 0.5$	Epoxy-coated rebar (51 mm)	84	203	148	156	(27 %)	(23 %)

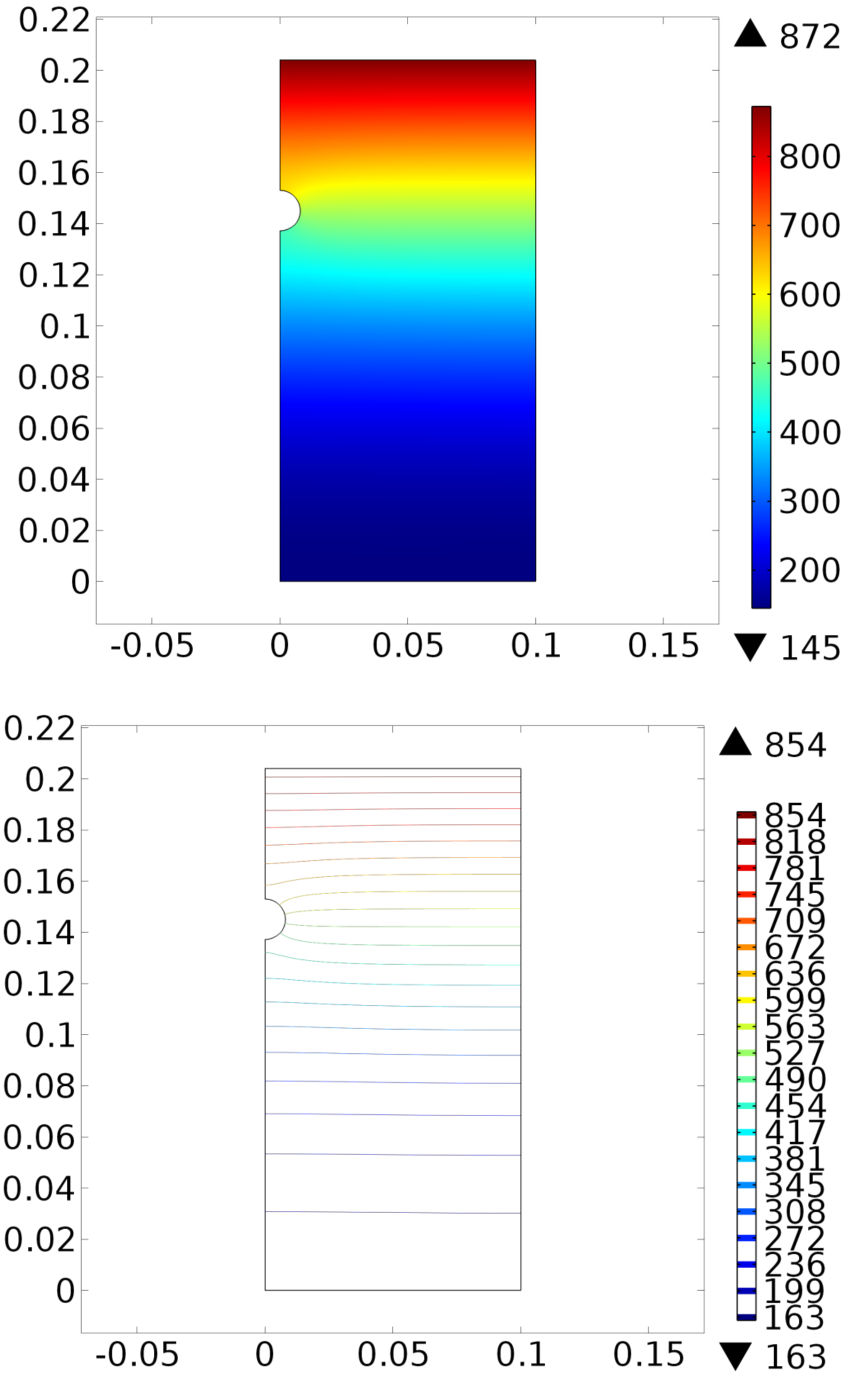

Figure 12: Free chloride ion concentration with reinforcement bar in model at 500 years. Plots show an accumulation of chloride ions on the top surface of the rebar. The chloride concentration at 500 years is shown to clearly demonstrate the effect of the reinforcement.

4.0 Conclusions

The following conclusions are made based on the results presented here:

1) When the cover does not contain a crack, the service life can be increased by methods such as increasing the cover depth, using a corrosion inhibitor, using silica fume, or employing epoxy-coated rebar.
2) The presence of a crack in the concrete cover, specifically a crack that was located over the steel reinforcement, reduced the service life in all cases. The reduction in service life depended on the size of the crack. Wider, deeper cracks reduced the service life more than narrower, shallower cracks.
3) Filling a crack with a crack-filling material can increase the service life of the structure. The effectiveness of the crack-filling material depends on the size of the crack and its chloride ion diffusivity relative to the bulk concrete. For large cracks, the difference in performance is more pronounced because the crack-filling material occupies a large percentage of the cover immediately over the rebar.
4) When crack filler is used, the diffusivity of the DZ will significantly affect the service life predicted by the model. When the crack filler has no effect on the DZ, the remaining service life is less than for the case where the crack filler restores the DZ to the bulk concrete diffusivity.
5) Experimental investigation is required to more precisely quantify the effect the crack-filling material has on the DZ diffusivity. This is required for an improved prediction of the service life of cracked reinforced concrete structures.
6) The actual presence of the steel reinforcement can inhibit chloride transport, leading to higher chloride concentrations above the rebar and consequently a significantly shorter service life.

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