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Modeling of time to corrosion-induced cover cracking in reinforced concrete structures

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Abstract

Service life of the concrete structures depends on the protective action provided by the cover concrete against the susceptibility of the reinforcement to the corrosive environment. Depending on the level of the oxidation of metallic iron, corrosion products may have much greater volume than the original iron that gets consumed by the process of corrosion. This volume expansion is mainly responsible for exerting the expansive radial pressure at the steel–concrete interface and development of hoop tensile stresses in the surrounding concrete resulting ultimately in the through cracking of the cover concrete. This cover cracking would indicate the loss of the service life for the corrosion-affected structures. In the present paper, an attempt has been made to develop analytical models for predicting the time to cover cracking by considering the residual strength of the cracked concrete and the stiffness provided by the combination of the reinforcement and expansive corrosion products. The problem is modeled as a boundary value problem wherein the governing equations are expressed in terms of the radial displacement and the analytical solutions are presented considering a simple 2-zone model for the cover concrete viz. cracked or uncracked. The analytical models are then evaluated through their ability to reproduce available experimental trends and subsequently a sensitivity analysis has also been carried out to show the influence of the various variable parameters of the proposed models with reference to the experimental trends.

Keywords: Reinforcement corrosion; Modeling; Time to cover cracking; Radial pressure

1. Introduction

One of the most predominant factors responsible for the structural deterioration in concrete structures is identified as corrosion of reinforcement, which may result in damage to the structures in the form of expansion, cracking and eventually spalling of the cover concrete. In addition to this, the structural damage may be due to loss of bond between reinforcement and concrete and loss of reinforcement cross-sectional area; sometimes to the extent that the structural failure becomes inevitable [1]. Therefore, monitoring and control of reinforcement corrosion assume a significant practical importance, if one has to prevent the premature failure of the reinforced concrete structures. Decisions regarding inspection, repair, strengthening, replacement and demolition of the age-degraded reinforced concrete structures are normally affected by the performance of such structures to withstand the extreme events during their service life. The end of service life for the reinforced concrete structures is generally associated with the loss of protective action to be provided by the cover concrete to the reinforcement against the contact with the corrosion inducing agents. Therefore, it would be worthwhile that analytical models be developed to assess the effect of reinforcement corrosion in the reinforced concrete structures, on the structural performance/deterioration for the reasonable prediction of safe residual service life of such structures. The prediction of structural deterioration

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would in turn be very useful to arrive at a cost-effective strategy in handling of the corrosion-affected concrete structures.

In the context of the aforementioned discussion, the prediction of time to cover cracking of reinforced concrete structures may be considered as a useful indicator towards the intensity of the corrosive environment to which the structures are subjected. This would be further useful in estimating the structural capacity to withstand the possible extreme events during the remaining service life of the structures. Prediction of safe residual service life and the time to cover cracking of corroded reinforced concrete structures have been studied by many researchers [2–11]. However, despite these efforts and due to the complexity of the corrosion process itself, some differences between the predicted values and the observed data from the field and laboratory have been reported. This may be attributed to a number of factors viz. the mathematical model for the rate of corrosion process, the residual strength of the concrete once its tensile strength is exceeded and/or the proper estimation of the material properties of the concrete itself besides the mathematical model to describe the structural response.

It is well known that corrosion of reinforcement results in the transformation of metallic iron to the corrosion products due to the process of oxidation resulting in an increase in volume which, depending on the level of oxidation, may be up to about 6.5 times the original iron volume [1,7]. In general the composition of the expansive corrosion products may be expressed as $\{a\cdot Fe(OH)_2 + b\cdot Fe(OH)_3 + c\cdot H_2O\}$ [7], where a, b and c are the variables that depend on the alkalinity of the pore water solution of concrete, the oxygen supply and the moisture content. The different corrosion products will have different volume expansions as presented in Table 1 [1]. This volume increase is believed to be the principal cause of the concrete expansion and ultimately the cover cracking.

In the present paper an attempt is made to formulate a mathematical model for the prediction of time to cracking of the cover concrete in the corroded reinforced concrete structures considering the stiffness offered by reinforcement plus corrosion products combine in addition to the stiffness contribution of concrete. A sensitivity analysis has also been carried out by considering variation of the various parameters of the mathematical model. The model is evaluated through its ability to reproduce the available experimental trends.

Table 1
Correlation between α and α_1 for various corrosion products [1]

Name of corrosion products	FeO	Fe_3O_4	Fe_2O_3	$Fe(OH)_2$	$Fe(OH)_3$	$Fe(OH)_3\cdot 3H_2O$
α	0.777	0.724	0.699	0.622	0.523	0.347
α_1	1.80	2.00	2.20	3.75	4.20	6.40

α=ratio of molecular weight of iron to the molecular weight of the corrosion products.

α_1=ratio of volume of expansive corrosion products to the volume of iron consumed in the corrosion process.

2. Problem definition for corrosion cracking model

The problem has been modeled as a boundary value problem, wherein to accommodate the expansive corrosion products the internal circular boundary at the steel–concrete interface is displaced resulting in the evolution of the expansive radial pressure at the boundary. Fig. 1(a) shows the initial unrestrained condition for concrete block and reinforcement wherein the reinforcing bar of initial diameter D_i is embedded in the concrete with a clear cover to the reinforcement being C.

A porous zone is assumed to exist around the steel–concrete interface [7] and its thickness is indicated by d_o in Fig. 1(a). The porous zone is assumed to take care of the unevenly distributed voids at the steel–concrete interface which are caused by the various reasons viz. transition from cement paste to steel, entrapped/entrained air voids and corrosion products diffusing into the cement paste capillary voids, etc. The thickness of the porous zone is the function of the total volume of the voids and in the present paper the same is taken from the reference literature [7] for the purpose of numerical predictions.

Fig. 1(b) shows the free expansion of the corrosion products at the surface of the reinforcement depending on the level of oxidation. Same figure also shows the combined diameter of reinforcement plus corrosion products combine being indicated by D_2 and the reduction in the initial diameter of reinforcement due to corrosion being indicated by $2d_1$.

The surrounding concrete is not subjected to any internal radial pressure during the initial filling of porous zone with rust products; however any further free expansion of corrosion products beyond the porous zone is restrained by the surrounding concrete. At this stage, the surrounding concrete is subjected to an expansive uniform radial pressure p_r and due to which it gets displaced by an amount d_c, i.e. the thickness of the expansive rust products deposited around the reinforcement at the internal boundary as shown in Fig. 1(c). It is noted that in actual practice, since the voids are unevenly distributed at the steel–concrete interface, the filling of voids and the pressure application over the surrounding concrete will be simultaneous and in that case the surrounding concrete will not be subjected to the uniform pressure and this scenario is very difficult to model analytically. Therefore, for the sake of simplicity, the voids around the bar are assumed to be uniform (represented by porous zone) and the pressure application over the surrounding concrete is also assumed to be uniform.

To maintain the equilibrium, the reinforcement plus corrosion products combine would be subjected to an equivalent external pressure p_r as shown in Fig. 1(d). Further increase in the corrosion products results in an