

Sensitivity analysis of simplified diffusion-based corrosion initiation model of concrete structures exposed to chlorides

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Received 29 June 2005; accepted 10 January 2006

Abstract

This paper presents the results of a sensitivity analysis of the diffusion-based corrosion initiation model for reinforced concrete structures built in chloride-laden environments. Analytical differentiation techniques are used to determine the sensitivity of the time to corrosion initiation to the four governing parameters of the model, which include chloride diffusivity in concrete, chloride threshold level of steel reinforcement, concrete cover depth, and surface chloride concentration. For conventional carbon steel, the time to corrosion initiation is found to be most sensitive to concrete cover depth, followed by chloride diffusion coefficient, with normalized sensitivity coefficients of about 2 and -1 . For corrosion resistant steels, the time to corrosion initiation is most sensitive to the surface chloride concentration and chloride threshold level followed by the concrete cover depth and chloride diffusion coefficient. The results of this sensitivity analysis are discussed in detail, including the variations in predicted time to corrosion initiation induced by variations of the four model parameters and their implications for the design and maintenance of concrete structures built in corrosive environments.

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Keywords: Chloride diffusion; Corrosion initiation; Sensitivity analysis

1. Introduction

The chloride-induced corrosion of the steel reinforcement is identified as the main cause of deterioration of different types of concrete structures (e.g. bridges, parking garages, off-shore platforms, etc.). The sources of chlorides are the seawater and deicing salts used during winter. The corrosion of the steel reinforcement leads to concrete fracture through cracking, delamination and spalling of the concrete cover, reduction of concrete and reinforcement cross sections, loss of bond between the reinforcement and concrete, and reduction in strength and ductility. As a result, the safety and serviceability of concrete structures are reduced. One of the earliest studies on corrosion of reinforcing steel embedded in concrete structures was reported by Stratfull [22], in which chlorides and moisture were identified as the main causes for extensive corrosion in reinforced concrete bridge piers built in a marine environment after only seven years from initial construction. In the last three

decades, the chloride-induced corrosion of reinforced concrete structures has been extensively studied [8,19,15,6], particularly, as a result of the high costs of highway bridge repair in North America and Europe from the effects of deicing salts used during winter or from seawater for coastal structures.

A reliable prediction of the time to corrosion initiation of concrete structures exposed to chlorides is critical for the selection of a durable and cost-efficient design and for the optimization of the inspection and maintenance of built structures, which is essential to minimize the life cycle costs. Existing models are mostly based on the assumption of a Fickian process of diffusion for predicting the time and space variations of chloride content in concrete and on the concept of chloride threshold to define the corrosion resistance of reinforcing steel to chloride attack. Therefore, the governing parameters of this diffusion-based corrosion initiation time include the concrete cover depth, chloride diffusion coefficient in concrete, surface chloride concentration, and chloride threshold level assuming the presence of moisture and oxygen for the corrosion to proceed. In practice, the design of durable concrete structures is mainly based on specifying a minimum

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concrete cover depth (depending on the environmental exposure), a maximum water-to-cement ratio (to achieve low chloride diffusivity), and as well the use of more corrosion resistant reinforcing steels (e.g. stainless steel).

However, a considerable level of uncertainty may be associated with one or more of the above identified parameters. This is due to: (i) heterogeneity and aging of concrete with temporal and spatial variability of its chloride diffusivity; (ii) variability of concrete cover depth, which depends on quality control, workmanship and size of structure; (iii) variability of surface chloride concentration, which depends on the severity of the environmental exposure; and (iv) uncertainty in chloride threshold level that depends on the type of reinforcing steel, type of cementing materials, test methods, etc. [1]. It is clear that the combination of these uncertainties leads to a considerable uncertainty in the model output, i.e. the time to corrosion initiation. This uncertainty in the model output could have serious consequences in terms of reduced service life, inadequate planning of inspection and maintenance and increased life cycle costs.

Therefore, undertaking a sensitivity analysis becomes imperative to assess the impact of uncertainties from the input parameters on the uncertainty of the model output. In the literature, several methods and techniques have been used for the sensitivity analysis of different types of models in different fields of applications, including Monte Carlo simulations, response surface methods, differential analysis techniques, nominal range sensitivity analysis, etc. [21]. Fewer sensitivity studies are found in the literature that deal with the performance of concrete structures that incorporate or evaluate the impact of the uncertainties in the model parameters on the model output, such as service life [5,11,12,13,14].

In this paper, a sensitivity analysis of the diffusion-based model for time to corrosion initiation using the differential analysis technique is undertaken to identify the most significant parameters and quantify their impacts on the time to corrosion initiation. This consists of evaluating the variations in the time to corrosion initiation caused by variations in the input data of the model, which include concrete cover depth, chloride diffusion coefficient, surface chloride concentration, and chloride threshold level. The results of a sensitivity analysis can provide valuable insights and a better understanding of the chloride diffusion-induced corrosion of reinforcing steel in concrete and its governing parameters. A sensitivity analysis can be used to identify the importance of uncertainties in the model input for the purpose of prioritizing additional data collection or research on the parameters that are found significant. Furthermore, the results of a sensitivity analysis can provide effective decision support in the design of durable new structures, as well as in the optimization of inspection and maintenance of existing structures.

2. Diffusion-based corrosion initiation model

2.1. Chloride ingress into concrete structures

The corrosion of concrete structures can be described as a two-stage process: (i) corrosion initiation stage; and (ii)

corrosion propagation stage [19] as illustrated in Fig. 1. For chloride-induced corrosion, the initiation stage corresponds to the period of time during which chlorides penetrate the concrete but no damage is observed. The corrosion initiation time is defined as the time at which the concentration of chlorides at the steel surface reaches a critical or threshold value. The propagation stage corresponds to the period of time during which corrosion products accumulate and initiate fracture of concrete and ultimately failure. The service life of concrete structures in chloride-laden environments can be defined as the sum of the durations of the two stages. In general, the durability and serviceability of concrete structures depend greatly on the duration of the initiation stage. As a result, a reliable prediction model of chloride penetration into a reinforced concrete structure is of utmost importance in predicting the time to corrosion initiation, as well as the total service life.

Aggressive agents such as chlorides, water, and oxygen penetrate into concrete through the pore spaces in the cement paste matrix and micro-cracks. The rate of penetration is dependent primarily on the quality of concrete and more particularly on the water–cement ratio of the concrete mix and the presence of supplementary cementing materials (e.g. silica fume, fly ash, or slag) and/or protective systems that delay or slow down chloride ingress. In porous solids, such as concrete, moisture may flow via the diffusion of water vapor, and via non-saturated or even saturated capillary flow in finer pores [10]. Chloride ingress into concrete from external sources is therefore due to multiple transport mechanisms, such as diffusion and adsorption. However, adsorption occurs in concrete surface layers that are subjected to wetting and drying cycles, and it only affects the exposed concrete surface down to 10–20 mm [23,20]. Beyond this adsorption zone, the diffusion process will dominate [20].

Chloride diffusion is a transfer of mass by random motion of free chloride ions in the pore solution resulting in a net flow from regions of higher to regions of lower concentration [7]. The rate of chloride ingress is proportional to the concentration gradient and the diffusion coefficient of the concrete (Fick's first law of diffusion). Since in the field, chloride ingress occurs under transient conditions, Fick's second law of diffusion can

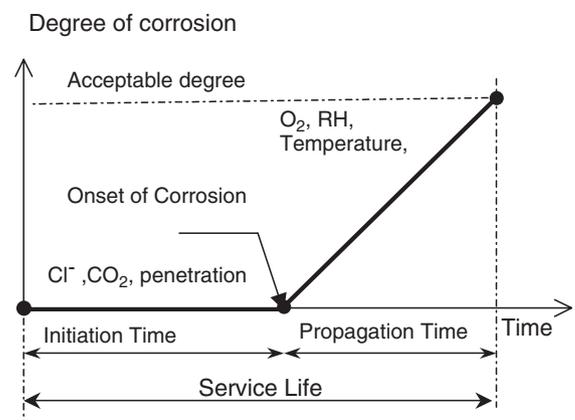


Fig. 1. Service life of concrete structures subjected to corrosion (adapted from Ref. [19]).

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