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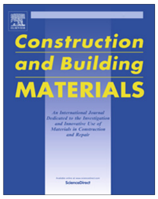

A comparative study on factors affecting time to cover cracking as a service life indicator

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HIGHLIGHTS

- A full review on time to cover cracking models has been conducted.
- Sensitivity analysis to identify the most influential factors on time to cover cracking is presented.
- The porous zone and the properties of rust are the most influential factors for time to cover cracking.
- There is high uncertainty in prediction of time to cover cracking as a service life indicator.

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ABSTRACT

Corrosion of steel in reinforced concrete structures has been a major worldwide problem. The time to cover cracking plays a key role in assessment of serviceability of reinforced concrete structures subjected to corrosion. A large number of analytical, numerical, and empirical models have been developed to predict the time to time to cover cracking. In addition, extensive experiments have been conducted in order to verify the developed models. In this paper, an overview of the existing models is presented. A large experimental database of reported data on time to cover cracking is collated. Performance of four analytical models taken from the available literature is then examined using the established experimental database. Sensitivity analysis followed by a probabilistic study is carried out to identify the factors affecting time to cover cracking as a service life indicator by means of the selected models. The results from sensitivity analysis show that the porous zone and the properties of rust are the most influential factors for time to cover cracking. It is also shown that there is high uncertainty in predicting service life of reinforced concrete structures based on time to cover cracking.

1. Introduction

Steel corrosion is one of the most predominant deterioration mechanisms in reinforced concrete (RC) structures worldwide, which influences the safety and serviceability of the structures. It has been reported that more than 55% of structural repairs carried out in Europe were caused by the steel corrosion [54]. In the US, the cost of damage to RC structures, such as bridges and car parks alone, due to de-icing salts caused by steel corrosion is between $325 and $1000 million per year [13]. It is well understood that the corrosion of steel in RC structures leads to concrete cover damage in the form of cracking, rust staining, spalling and delamination. However, it is suggested that concrete cover cracking, which is of most concern for asset managers, is the most useful indicator for assessment of structural deterioration [2,4,14,34,35]. This indicator has been used for predicting service life of corrosion-affected RC structures and also in optimal maintenance of these structures [2,11,26,59]. Therefore, development of reliable models for assessments of corrosion-induced cracking process is of paramount importance in studying durability and service life prediction of RC structures. In this regard, end of service life for a corrosion-affected RC structure can be defined as either the time at which corrosion is initiated [7] or the time at which surface concrete cover crack appears [39]. Furthermore, the time required for crack width to exceed a certain threshold (acceptable crack width limit) is also used to define the end of service life [37].

Extensive research on corrosion of steel in concrete has already been undertaken for decades [8,16,27,34,51,56]. Due to the slow nature of corrosion process, usually accelerated corrosion pro-

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Nomenclature

Symbol	Description
A, B	Calibration constants
a	Outer radius of thick-wall cylinder
b	Inner radius of thick-wall cylinder
C	Clear cover to rebar
C_c	Radius of the cover surface
D	Reinforcement diameter
d_0	Thickness of porous zone between steel and concrete
d_s	Radial displacement on the concrete-rust interface
E_c	Modulus of elasticity of concrete
E_{ef}	Effective modulus of elasticity of concrete
E_r	Material modulus of elasticity in radial direction
E_{rust}	Modulus of elasticity of corrosion product
E_s	Modulus of elasticity of iron
E_θ	Material modulus of elasticity in tangential direction
f'_c	Concrete compressive strength
f_t	Concrete tensile strength
i_{corr}	Corrosion current density
I_{corr}	Impressed current intensity
k	Coefficient accounts for ingress of corrosion products inside cracks
k_p	Coefficient of rust production
M_r	Mass of generated rust
M_s	Mass of lost steel
p_r	Pressure resulted from rust displacement
p_{rmax}	Maximum pressure resulted from rust displacement
r	Radial coordinate
R_b	Radius of rust front
R_c	Radius of crack front
R_r	Radius of the rust product
R_{rb}	Radius of corroded rebar
t	Time
t_{cr}	Time to cover cracking
u	Radial deformation on concrete-rust interface
wc	Water cement ratio
X_n	Independent parameters in the sensitivity analysis
Y	Dependent parameter in the sensitivity analysis
α	Molecular weight ratio of iron to corrosion products
α_v	Relative volume ratio of corrosion products to iron
ε_r	Strain in the radial direction
ε_θ	Strain in the tangential direction
γ	Density ratio of iron to corrosion products
δ	Model error
ΔV	The volume increase imposed by expansion of corrosion products
θ	Tangential coordinate
ρ_s	Mass density of iron
ρ_r	Mass density of corrosion products
σ_r	Stress in the radial direction
σ_θ	Stress in the tangential direction
υ_c	Poisson's ratio of concrete
υ_s	Poisson's ratio of iron
υ_{rust}	Poisson's ratio of corrosion products

cesses by various means, such as impressed Direct Current (DC) approach [5,6,25,40,41,44,49,60,61,65], salt spraying and wet and dry cycling in chloride-laden condition [33,62,66] are used. Based on the experimental results, some empirical models for predicting concrete cover cracking have been proposed [5,58]. Useful analytical models based on the fracture mechanics have also been proposed [10,37,48,65]. Furthermore, many numerical models for simulation of corrosion-induced crack process can be found in the available literature [22,36,42,44,57]. These models have been used to identify the influential factors affecting the time to cover cracking. There is a general agreement that the corrosion rate, the concrete cover thickness and the concrete cover-to-bar diameter ratio are the most critical factors in prediction of time to cover cracking [5,6,25,39,44,49,60]. Nonetheless, despite all these comprehensive efforts, due to the complicated nature of the corrosion and cracking processes, which depends on various mechanical and environmental factors, considerable discrepancies between the results of predictive models and those obtained from laboratory or field data have been reported. In some cases, the disparity amongst the available predictive models may lead to contradicting conclusions.

This paper attempts to investigate the influential factors that affect the time to cover cracking with the aid of some of the available analytical models. In order to assess the reliability of the considered analytical models, a large experimental database of tests on time to cover cracking of corrosion-affected concrete specimens from different sources is analysed. Then, using different sensitivity analysis methods, the most influential factors affecting the time to corrosion-induced crack initiation are identified. Finally, using a probabilistic approach, effect of variability of the influential factors on service life prediction of RC structures is investigated. Accurate prediction of time to cover cracking can help engineers and asset managers in better management of corrosion affected RC structures.

2. Corrosion-induced cracking mechanism

In an early research by Tuutti [56], corrosion of steel in reinforced concrete was divided in two stages consisting of corrosion initiation and corrosion propagation. Extending this concept to a further stage, the corrosion of steel in reinforced concrete can be described as a three-stage process: (i) corrosion initiation; (ii) rust propagation; and (iii) corrosion acceleration as is conceptually illustrated in Fig. 1.

The total service life of RC structures can be defined as the end of either stage II or stage III, since it includes time to corrosion initiation and corrosion propagation, which leads to structures that are no more serviceable. Therefore, depending on the failure criterion, the service life of RC structures can be considered as the end of stages II to III. In the current study, end of stage II is considered as the service life of RC structures, i.e., the time at which concrete cover cracks. To be complete, aspects of different stages of corrosion process are discussed.

2.1. Stage I

The corrosion initiation stage corresponds to a period during which aggressive ions, such as chloride ions or carbon dioxide, ingress to the steel surface disrupting or destroying the protective passive film. This stage is also referred to as the diffusion stage. Once the passive layer breaks down, the electrochemical reactions start to happen. The reactions, shown in Eqs. (1a) and (1b) are the same irrespective of corrosion being caused by either chloride attack or carbonation [12].

$$Fe \rightarrow Fe^{2+} + 2e^- \tag{1a}$$

$$2e^- + H_2O \rightarrow \frac{1}{2}O_2 + 2OH^- \tag{1b}$$