Cement and Concrete Research 108 (2018) 87–102

Contents lists available at ScienceDirect

Cement and Concrete Research

journal homepage: www.elsevier.com/locate/cemconres

A non-uniform corrosion model and meso-scale fracture modelling of concrete

Xun Xi[a,b], Shangtong Yang[b,*], Chun-Qing Li[c]

[a] School of Civil and Resource Engineering, University of Science and Technology Beijing, Beijing 100083, China
[b] Department of Civil and Environmental Engineering, University of Strathclyde, Glasgow G1 1XJ, United Kingdom
[c] School of Engineering, RMIT University, Melbourne, Vic 3001, Australia

ARTICLE INFO

Keywords:
Non-uniform corrosion
Cohesive crack model
Meso-scale
Reinforced concrete structures
Finite element method

ABSTRACT

Corrosion-induced concrete cracking is a significant durability problem for reinforced concrete structures. Considerable research has been carried out in the last few decades to understand and model the expansion mechanism of the corrosion products around the reinforcing bar and simulate the cracking behaviour of the concrete cover. In this paper, a new corrosion model based on non-uniform corrosion expansion is formulated and validated against experimental data. A meso-scale fracture model, consisting of aggregates, cement paste/mortar and ITZ, is established for the cases of both middle and side reinforcing bars. Under the developed corrosion and concrete fracture model, the cracking phenomena of the concrete cover are accurately simulated. It has been found that the non-uniform corrosion model can be used to express the realistic corrosion rust progression around the reinforcing bar, with the best accuracy. It has also been found that some microcracks occur before they are connected to form the dominating discrete crack which usually appears on the concrete surface. Moreover, the effects of the corrosion variables, as well as other key material and geometric parameters, on surface cracking of concrete are investigated.

1. Introduction

Reinforced concrete (RC) structures are widely used for civil structures and infrastructures, e.g., buildings, bridges, retaining walls and tunnels. Concrete are normally considered a durable material while corrosion of reinforcement has significant effects on the durability of RC structures. Cracks induced by corrosion destroy the integrity of concrete cover, reduce the reliability of concrete and lead to premature failure of RC structures and infrastructure. Worldwide, the maintenance and repair costs for corrosion-affected concrete infrastructure are estimated around $100 billion per annum [1]. With regard to serviceability and timely maintenance of the corrosion-affected RC structures and infrastructures, the engineers and/or asset managers need better informed decisions.

Over the past two decades, considerable research has been carried out in understanding and simulating the cracking mechanism of concrete cover induced by corrosion of reinforcement [2–8]. Andrade et al. [2] indicated that a negligible loss (e.g., 20 μm) of the cross-section of reinforcing bar could lead to a crack width of 0.05–0.1 mm, based on accelerated corrosion tests. Liu and Weyers [3] modelled the surface cracking time of concrete cover due to corrosion of reinforcement, taking the thickness of the "porous zone" around the steel/concrete interface into account. Bhargava et al. [5,6] proposed models for predicting the time to cracking by considering the residual strength of cracked concrete and the stiffness reduction. Li et al. [8] developed an analytical model to calculate the crack width of concrete cover by assuming the cracks smeared in concrete and considering concrete as a quasi-brittle material. Amongst these existing studies, most are focused on uniform or general corrosion of the reinforcement.

Chlorides, as well as moisture and oxygen, diffuse into concrete and reach a threshold value at the surface of steel bar, before the passive layer on steel surface is destroyed and corrosion is initiated [9]. However, it is rare to have a uniform corrosion around the reinforcing bar, due to different amount of chlorides, moisture and oxygen that are available on different sides of the reinforcement; for example, the side of a reinforcing bar facing concrete cover should have more sources to advance corrosion and hence more corrosion products accumulated on this side. Recently, many researchers have started to model the cracking of concrete cover induced by non-uniform corrosion of reinforcement. González et al. [10] perhaps first compared the depth of pitting corrosion penetration on steel bar with the depth of general corrosion and found that the maximum penetration of pitting corrosion on the steel

* Corresponding author.
E-mail address: shangtong.yang@strath.ac.uk (S. Yang).

https://doi.org/10.1016/j.cemconres.2018.03.009
Received 15 September 2017; Received in revised form 4 March 2018; Accepted 19 March 2018
0008-8846/

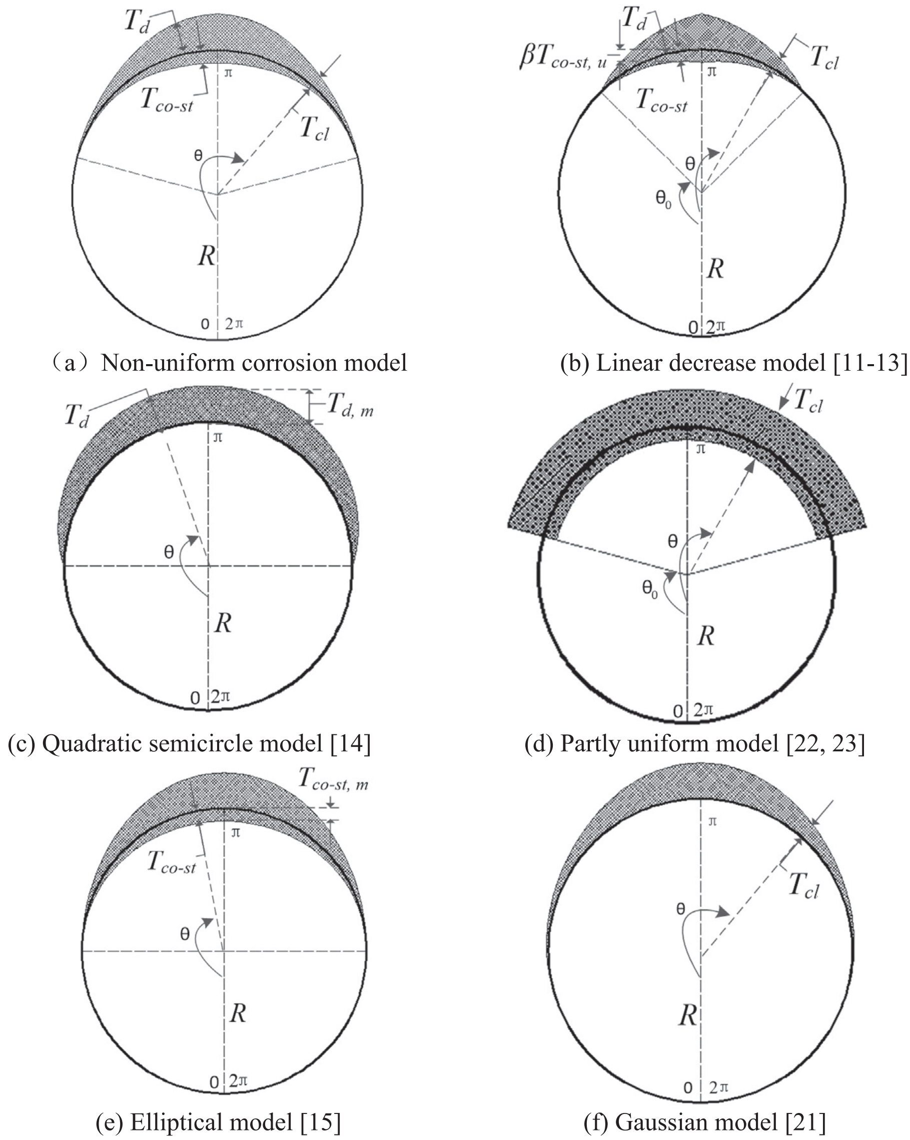

Fig. 1. Various models on corrosion rust progression around the reinforcement in concrete.

bar is equivalent to about three to sixteen times of the penetration of general corrosion. Jang and Oh [11] extended the experimental results in [10] and designed a factor for the ratio of the maximum thickness of non-uniform corrosion layer to the thickness of uniform corrosion layer to express the non-uniform corrosion. Moreover, some researchers postulated corrosion products followed a linear decrease distribution along the circle of steel bar [12,13]. Pan and Lu [14] proposed a non-linear corrosion model with a quadratic expansion function to model the cracking of concrete induced by non-uniform corrosion. Further, Yuan and Ji [15] conducted corrosion tests on RC samples by using artificial environmental chamber and found the corrosion products distribution around the reinforcement is in a semi-elliptical shape. Based on the semi-elliptical assumption, Yang et al. [16] proposed an analytical model to calculate the time to cracking of concrete cover and Xi and Yang [17] developed a numerical model to investigate cover cracking caused by corrosion of multiple reinforcing bars. In addition, Zhao et al. [18–21] carried out corrosion tests on RC samples and proposed a Gaussian non-uniform corrosion model to quantitatively define the corrosion products distribution. Tran et al. [22] and Qiao et al. [23] proposed a non-uniform corrosion model by considering uniform corrosion for part of rebar and no corrosion for the other part, according to their results of experiments.

Once corrosion boundary model is established, the cracking of concrete caused by corrosion of reinforcement can be simulated. Jang and Oh [11] simulated the stress to cracking of concrete based on the linear decrease non-uniform corrosion model and Mohr-Coulomb failure model. Zhao et al. [18] modelled the crack patterns of concrete based on Gaussian non-uniform corrosion model and smeared crack model for concrete. Zhang et al. [24] employed damage plasticity model to simulate the crack propagation of concrete based on elliptical non-uniform corrosion model. However, most studies considered concrete as a homogeneous material. The homogeneity assumption is only an approximation and, for more accurate prediction, concrete should be treated as a three-phase heterogeneous material at the mesoscale, consisting of cement paste/mortar, aggregate and interfacial transition zone (ITZ). It has been found that the mechanical behaviour of the ITZ between aggregate and cement paste has a significant effect on concrete strength and cracking prediction of concrete [25]. Du et al. [26] employed damage plasticity model to simulate the heterogeneous concrete cracking patterns under elliptical non-uniform corrosion model [15]. Branko et al. [13] and Chen et al. [12] built lattice models to simulate the time to cracking of heterogeneous concrete cover based on the linear decrease corrosion model proposed by Jang and Oh [11]. However, amongst these limited literatures on modelling heterogeneous