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Concrete cracking process induced by steel corrosion- A review

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ABSTRACT

The article reviews a number of empirical and analytical models to describe the cracking process of concrete induced by steel corrosion. The experimental study is a direct method to investigate the corrosion-induced concrete cracking. Based on the limited experimental data, generally the empirical models are the simple mathematical expressions and cannot be universally valid. Introducing the smear crack and considering the post-peak softening of concrete, the analytical models can describe the concrete cracking process of a thick-walled cylinder subjected to an internal uniform pressure due to steel corrosion. However, the current analytical is not yet able to handle the uneven corrosion situation and consider the influence of the external loading and stirrups. The further studied in this area are also identified.

Keywords: Concrete structures; Steel corrosion; Cracking

1. INTRODUCTION

The corrosion of steel in concrete is a major cause of durability problems in reinforced structures. After steel depassivation, corrosion products are formed at the steel/concrete interface. Because the volume of the corrosion products is greater than that of the original metal, the formation of the corrosion products will induce a pressure on the surrounding concrete and generate stresses in the concrete cover. As the volume of corrosion products increases, cracks initiate at the steel/concrete interface and propagate outwards and eventually spread to the surface of the concrete cover. These cracks in turn provide a path for more rapid ingress of aggressive agents to the reinforcement, which can accelerate the corrosion process, thus cause damage to concrete structures.

Because the investigation on the corrosion-induced cracking process is important for the prediction of the serviceability and durability of reinforced concrete structures, considerable research has been undertaken on corrosion-induced cracking process. The experimental and analytical researches are summarized in this article.

2. EXPERIMENTAL STUDY

A considerable number of experimental studies have been conducted on corrosion-induced concrete cracking, primarily focusing on two aspects of the cracking process: (1) predicting steel corrosion at surface cracking and (2) linking the crack width on the surface of the concrete cover with steel corrosion. The main work has been summarized in Table 1 and Table 2. Fig. 1 shows a comparison between steel corrosion on surface cracks calculated by empirical models [Alonso et al. 1998; Rodriguez et al. 1996; Vidal et al. 2004; Mullard and Stewart 2009; Zhang et al. 2010; Oh et al. 2009] and corrosion observed in accelerated corrosion tests [Andrade et al. 1993; Alonso et al. 1998; Rodriguez et al. 1996; Webster and Clark 2000; Zhang et al. 2010; Oh et al. 2009], whereas Fig. 2

shows a comparison of surface crack width propagation between model-predicted results [Vidal et al.2004; Rodriguez et al. 1996; Mullard and Stewart 2009; Zhang et al.2010] and experimental results [Vu et al.2005].

Table 1 Steel corrosion depth at concrete surface cracking

Reference	Empirical model
[Andrade et al. 1993]	$\delta = 11.6 \cdot i_{\text{corr}} \cdot t$
[Alonso et al. 1998]	$\delta^{\text{surface}} = 7.53 + 9.32C/d$
[Rodriguez et al. 1996]	$\delta^{\text{surface}} = 83.8 + 7.4 C/d - 22.6f_t$
[Webster and Clark 2000]	$\delta^{\text{surface}} = 1.25 C$
[Zhang et al.2010]	$\delta^{\text{surface}} = 8 C/d + 0.55 f_c - 7.5$
[Oh et al. 2009]	$\rho^{\text{surface}} = 0.0018C^{2.07}$

Table 2 Crack width at concrete cover surface

Reference	Empirical model
	15~50μm steel corrosion depth can produce 0.05~0.1mm crack width at cover surface; 0.2~0.3mm crack width needs 50~200μm steel corrosion depth.
[Alonso et al. 1998]	
[Rodriguez et al. 1996]	$W_s = 0.05 + \beta[\delta - (83.8 + 7.4c/d - 22.6 f_t)]$
[Vu et al.2005]	$t = A(C/wc)^B$
[Vidal et al.2004]	$W_s = 0.0575(\Delta A_s - \Delta A_{s0})$
[Zhang et al.2010]	$W_s = 0.1916\Delta A_s + 0.164$
[Wang et al.2008]	$\delta = 234.5 W_s + 17.5$
[Mullard and Stewart 2009]	$t_{(\text{exp})} = \frac{k_R (w - 0.05)}{0.0008k_c \exp[-1.7C/(d \cdot f_t)]} \left(\frac{0.0114}{i_{\text{corr}}} \right)$

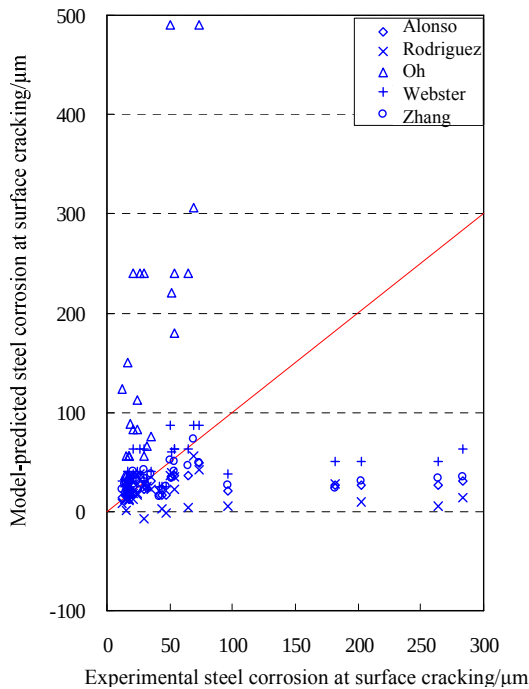


Figure 1 Comparison of steel corrosion at concrete surface cracking between the predicted results and the experimental data

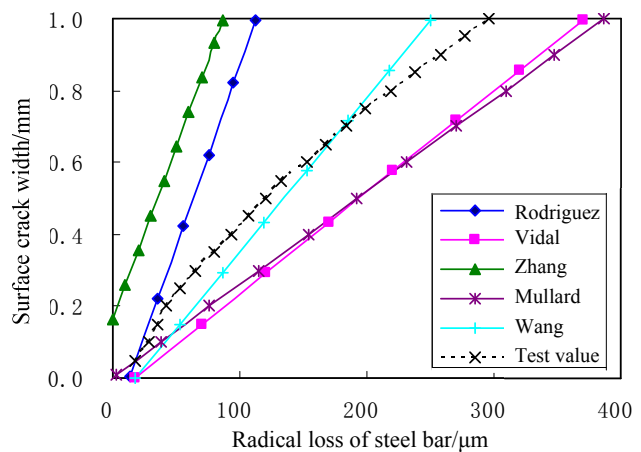


Figure 2 Comparison of concrete surface crack width propagation between the predicted results and the experimental data.

The empirical models normally are capable of adequately predicting the experimental values which they were fitted to. However, if the models are used to predict experimental data of other studies, the agreement between predicted and observed values is generally low. It can be clearly observed from Fig. 1 and Fig. 2 that none of the empirical models provide a good prediction of all of the experimental data, as empirical models usually cannot take into account all of the relative parameters. Therefore, analytical methods, which are able to consider more the relevant parameters, such as geometrical dimensions, concrete properties and corrosion etc, were undertaken to study corrosion-induced cracking process.

3 CORROSION-INDUCED CRACKING MODEL

3.1 Three-stage corrosion-induced cracking model

In general, a corrosion-cracking process involves three stages [Liu and Weyers 1998], namely, free expansion period, stress initiation period and concrete cover cracking period(as shown in Fig. 3). After steel depassivation, corrosion products are assumed to fill the porous voids around the steel/concrete interface. In this stage, the formation of the corrosion products will not create extra stresses in the surrounding concrete and the volume increase is compensated by the filling of voids. As the further increase of corrosion products, an expansive pressure in the surrounding concrete is generated. This pressure increases with the corrosion products and creates extra stresses and strains in the concrete cover surrounding the reinforcing steel. When the internal tensile stresses exceed the limited tensile strength of the concrete cover, cracks will be initiated in the concrete cover starting from the steel surface towards the dconcrete surface. During the process of the cracking propagation, the corrosion products are regard to fill the space within the cracks in this stage.

The total radial loss of the steel bar when the concrete cover has cracks can be approximately taken as the summation of three components [Zhao and Jin 2006]. The first is the radial loss of steel bar δ_{pore} produced at stage 1. The second is the radial loss of steel bar δ_{stress} produced between the stress initiation in the concrete cover and the surface cracking of the concrete cover. The third is the radial loss of steel bar δ_{crack} , in which the corrosion products will fill the space in the cracks in the concrete cover. Mathematically, this can be expressed as follows:

$$\delta = \delta_{\text{pore}} + \delta_{\text{stress}} + \delta_{\text{crack}} \quad (1)$$

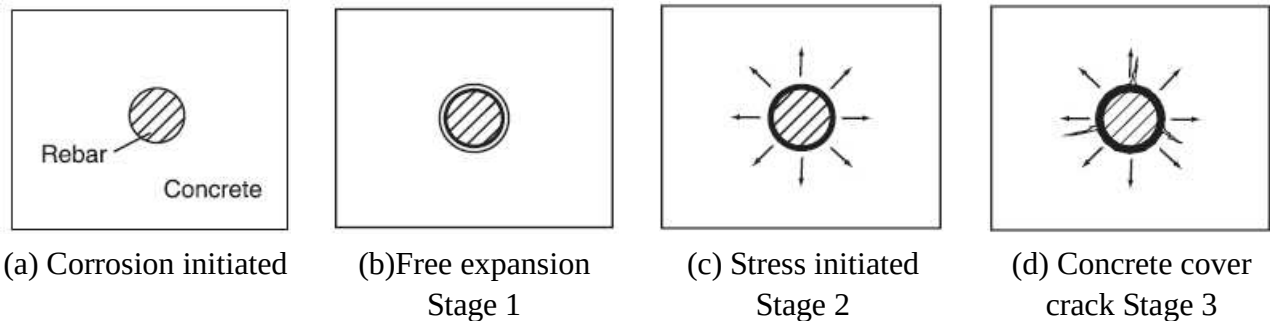


Figure 3 Three-stage corrosion-induced cracking process

The following sections review the research which has been done in these three stages separately.

3.2 Rust free expansion stage

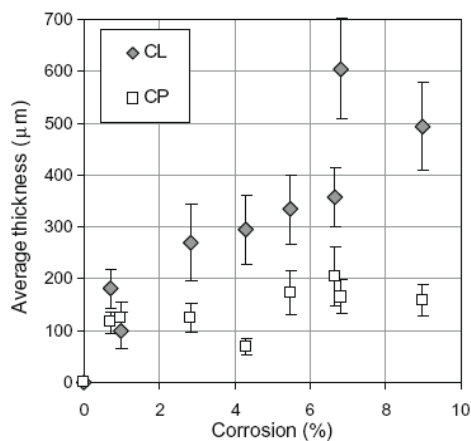
Previous studies [Asami and Kikuchi 2003; Duffó et al 2004; Chitty et al 2005; Care et al. 2008;

Jaffer and Hansson 2009; Wong et al 2010; Michel et al. 2011; Zhao et al. 2012a; Zhao et al. 2012b] have observed the area of concrete around the rebar penetrated by corrosion products, which was called “corrosion-filled paste (CP)” by a previous study [Wong et al 2010] or “corrosion accommodating region (CAR)” [Michel et al. 2011]. The existence of CP has been verified for reinforced concrete members that had deteriorated in a natural environment [Asami and Kikuchi 2003; Duffó et al 2004; Chitty et al 2005], in artificial cyclic wet-dry tests [Wong et al 2010; Jaffer and Hansson 2009] and under electro-chemical corrosion [Michel et al. 2011; Zhao et al. 2012a; Zhao et al. 2012b; Care et al. 2008].

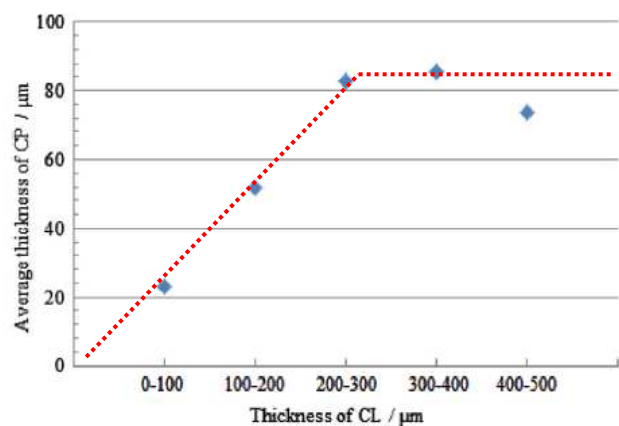
Table 3 gives the experimental studies which measure the corrosion-filled paste by researchers. The authors [Zhao et al. 2012b] have observed from the experiment of corroded reinforced concrete specimen under dry-wet cycle, and the results shows that the penetration of corrosion products into the porous zone of concrete and the formation of a corrosion layer (CL) at the steel/concrete interface may proceed simultaneously, as illustrated in Fig. 4b. This finding reveals that the assumption of “rust free expansion” is the Stage 1 might not be right. More experimental work needs to further the study on the porous zone at the interface of steel bar and concrete.

Table 3 Experimental study of CP

Reference	Corrosion method	Stage 1: corrosion-filled paste
[Michel et al 2011]	External current	CAR increases along with the corrosion-induced cracking process, its thickness reaches 0.09-0.18 mm when the first crack occurred, the maximum thickness of CAR can reach 0.6mm.
[Care et al. 2008]	External current	CP does not exist the whole area around rebar. When rust filled in the pores, it produces pressure on paste layer too.
[Wong et al 2010]	Dry-wet cycle	The average depth of CP with different corrosion degrees is about 100-200 μ m (Fig.4a).
[Zhao et al. 2012b]	Dry-wet cycle	The penetration of corrosion products into the porous zone of concrete and the formation of a corrosion layer at the steel/concrete interface proceed simultaneously (Fig.4b).



(a) [Wong et al 2010]



(b) [Zhao et al. 2012b]

Figure 4 Relation between CP thickness and CL thicknesses.

3.3 Expansive pressure stage

The previous corrosion-induced concrete cracking model normally considered the concrete around the steel as a one or two layer thick-walled cylinder subjected to an internal pressure due to the formation of corrosion products, as shown in Fig. 5. In the double-layer thick-walled cylinder, the concrete cylinder can be divided into two coaxial cylinders, one is the inner cracked cylinder and the other is the outer intact cylinder, as shown in Fig. 5(b).

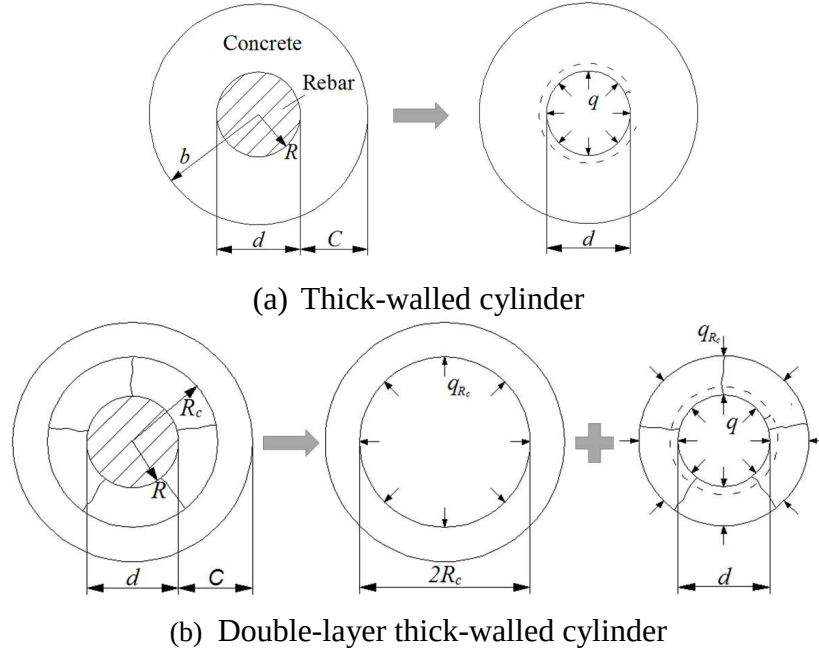


Figure 5 Corrosion-induced concrete cracking model

Table 2 gives the summary of all the models. For example, Bazant [Bazant 1979] proposed a model to predict the time of concrete cover cracking caused by the corrosion of embedded reinforcing steel. The model considers the concrete around the steel as a thick-walled cylinder subjected to an internal pressure due to the formation of corrosion products. Stresses in the cylinder are calculated using the solution provided by linear elasticity theory. Liu and Weyers [Liu and Weyers 1998] developed a corrosion cracking time model, which considered the critical amount of corrosion products needed to fill the interconnected void space around the reinforcing steel and needed to generate sufficient tensile stresses to crack the cover concrete. Bhargava [Bhargava et al. 2004] proposed an analytical model to predict the time required for cover cracking and the weight loss of reinforcing steel. The model considers the residual strength of cracked concrete and the stiffness contribution from the combination of reinforcement and expansive corrosion products. The mechanical properties of the combination were assumed to be the same as the reinforcement. Zhao [Zhao and Jin 2006] developed a concrete cracking model to estimate the total amount of steel corrosion at the cracking of the concrete cover with considering the elastic modulus and the Poisson's ratio of corrosion products. Li [Li et al. 2006] derived a theoretical model for corrosion-induced crack width in reinforced concrete structures, in which fracture mechanics was used for analyzing stresses and strains in the concrete surrounding the reinforcing steel. Corrosion-induced cracks in concrete were assumed to be smeared and the concrete was assumed to be quasi-brittle material. Yu [Yu 2011] used the damage mechanics to study the concrete cracking process. The damage process of the concrete cover can be divided into two distinct stages: the non-cracking stage and the partial cracking stage. An analytical model based on damage mechanics and elastic mechanics is developed to predict the concrete cracking due to steel corrosion. It can be seen that most of existing models neglected the behavior of the rust layer between the steel bar. Steel corrosion directly induces the

cracking of the concrete cover; it also participates in the mechanical interactions that are induced by the volume expansion between the concrete cover and the steel. Therefore, the rust volume expansion coefficient and the mechanical behaviour of the rust should be considered in the concrete cracking model. What's more, the current analytical is not yet able to handle the uneven corrosion situation and consider the influence of the external loading and the stirrups. These work need to be further.

Table 2 Corrosion-induced cracking model

Reference	Method	Model	Residual stiffness of Cracking concrete	Rust performance
[Bazant 1979]	Elastic mechanics	Thick-walled cylinder	Not consider	Not consider
[Liu and Weyers 1998]	Elastic mechanics	Thick-walled cylinder	Not consider	Not Consider
[Bhargava et al. 2004]	Elastic mechanics	Double-layer thick-walled cylinder	Different elastic modulus in cracking and uncracking concrete	Consider
[Zhao and Jin 2006]	Elastic mechanics	Thick-walled cylinder	Not consider	Consider
[Li et al. 2006]	Fracture mechanics, Elastic mechanics	Double-layer thick-walled cylinder	Smeared crack, considering the softening of cracking concrete	Not consider
[Yu 2011]	Damage mechanics, Elastic mechanics	Double-layer thick-walled cylinder	Smeared crack, considering the softening of cracking concrete	Consider
[Zhen et al. 2004]	Elastic mechanics	Double-layer thick-walled cylinder	Smeared crack, considering the softening of cracking concrete	Not consider
[Pantazopoulou et al. 2001]	Elastic mechanics	Double-layer thick-walled cylinder	Cracking concrete Performance is determined by the stress-strain curve	Not consider
[Chernin et al. 2010]	Elastic mechanics	Double-layer thick-walled cylinder	Circumferential elastic modulus changes with radius	Not consider
[Maaddawy and Soudki 2007]	Elastic mechanics	Thick-walled cylinder	Not consider	Not consider

[Lu et al. 2011]	Elastic mechanics	Thick-walled cylinder	Not consider	Consider
[Kim et al. 2010]	Elastic mechanics	Thick-walled cylinder	Not consider	Not consider
[Malumbela et al 2011]	Elastic mechanics	Thick-walled cylinder	Not consider	Not consider
[Li et al. 2008]	Muskhelishvili complex function	Infinite plane	Not consider	Not consider

3.4 Rust filling in corrosion-induced cracks

The rust filling in corrosion-induced cracks has been studied by several researchers, as shown in Table 3. The authors [Zhao et al. 2012a] observed that the rust cannot fill the corrosion-induced cracks under the condition that the external current accelerated steel corrosion. In the later observations from the experiment of corroded reinforced concrete specimen under dry-wet cycle [Zhao et al. 2012b], it was found that before concrete surface cracking during the corrosion process, the rust does not fill in the cracks either. But there will be some corrosion products flowing out with the solution, and attached to the edges of cracks after concrete surface cracking. The researches about the rust filling in corrosion-induced cracks with are listed in Table 3. From the research results, it is known that, to predict the concrete surface cracking, the rust filling in the crack does not need to be considered. Based on these researches, the two-stage concrete cracking model, instead of the three-stage model, is proposed by the authors as the following section.

Table 3 Rust filling in corrosion-induced cracks

Reference	Corrosion method	Stage 3: rust filling in corrosion-induced cracks
[Michel et al 2011]	DC current accelerate corrosion	No rust filling in the cracks in the process of electrifying corrosion
[Wong et al 2010]	Dry-wet cycle accelerate corrosion	Observed the cracks, but no qualitative conclusion
[Zhao et al. 2012a]	DC current accelerate corrosion	no rust filling in the cracks
[Zhao et al. 2012b]	Dry-wet cycle accelerate corrosion	no rust filling in the cracks before concrete surface cracking

3.5 Two-stage corrosion-induced cracking model

The cracking process of reinforced concrete caused by corrosion is divided into two stages, as described below:

Stagel: After steel depassivation, the cracking process enters the first stage, as shown in Fig. 9(a-c).

In this stage, several corrosion products accumulate in the steel/concrete interface to form the corrosion layer (CL). The thickness of the CL is T_{CL} . The remainder of the corrosion products fill the voids in the concrete around the steel to form the CP. The thickness of the CP is T_{CP} , as shown

in Fig. 6(b). With the development of the steel corrosion, T_{CP} increases until it reaches the maximum $T_{CP}^{\max}$, and stage 1 is complete, as shown in Fig. 9(c). The radial loss of steel in this stage is denoted as δ_I .

Stagell: In this stage, the CP layer growth stops, and all of the corrosion products accumulate in the steel/concrete interface. T_{CL} increases until the surface of the concrete cracks, as shown in Fig. 9(d). The radial loss of steel in this stage is δ_{II} .

Therefore, the total radial loss of steel when the surface of the concrete cracks can be expressed as follows:

$$\delta = \delta_I + \delta_{II} \quad (2)$$

where δ is the total radial loss of steel bar in μm , δ_I is the radial loss of steel bar in stagelin μm , and δ_{II} is the radial loss of steel bar in stagellin μm .

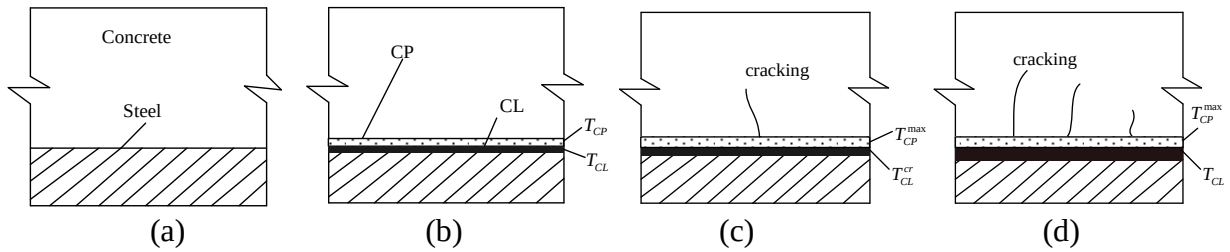


Figure 6 The two-stage corrosion-induced cracking model. (a) Steel depassivation. (b) Simultaneous formation of CP and CL. (c) CP thickness reaches the maximum, and stage I is complete. (d) CP thickness remains unchanged and CL thickness increases.

4 CONCLUSIONS

The article reviews a number of empirical and analytical models to describe the cracking process of concrete induced by steel corrosion, the following conclusions are drawn:

- (1) The experimental study is a direct method to investigate the corrosion-induced concrete cracking. However, the empirical models normally are only capable of adequately predicting the experimental values which they were fitted to, but not the experimental data of other studies. The existing empirical models are not universally valid.
- (2) Introducing the smear crack and considering the post-peak softening of concrete, the analytical models can describe the concrete cracking process of a thick-walled cylinder subjected to an internal uniform pressure due to steel corrosion. However, the current analytical model cannot yet be able to handle the uneven corrosion situation and consider the influence of the external loading.
- (3) The penetration of corrosion products into the porous zone of the concrete and the formation of a corrosion layer at the steel/concrete interface occur simultaneously with the initiation of steel corrosion. Hence, these phenomena should be included in the corrosion-induced concrete

cracking model.

- (4) The corrosion products cannot fill the cracks before the initiation of concrete surface cracking. Therefore, instead of the three-stage corrosion-induced concrete cracking model, a two-stage model for predicting concrete surface cracking is proposed that can consider the corrosion filling in concrete pores and accumulating at the steel/concrete interface synchronously.

A number of areas needs to be further to improve the research of concrete cracking induced by steel corrosion, including the quantitative description of porous zone at the interface of steel bar and concrete, the model of uneven steel corrosion distribution, concrete components subject to both loading and steel corrosion, influence of stirrups on corrosion-induced concrete cracking.

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