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Laboratory studies on influence of transverse cracking on chloride-induced corrosion rate in concrete

Yongsheng Ji [a], [b], [*], Yijie Hu [b], Linglei Zhang [b], Zhongzheng Bao [b]

[a] State Key Laboratory for Geomechanics and Deep Underground Engineering, China University of Mining and Technology, Xuzhou, 221116 China
[b] Jiangsu Key Laboratory of Environmental Impact and Structural Safety in Engineering, China University of Mining and Technology, Xuzhou, Jiangsu, 221008 China

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ABSTRACT

To clarify the corrosion mechanism of steel induced by transverse crack, a study on the influence of crack widths and epoxy coating on corrosion of steel bars in cracked concrete is presented here. Microcell and macrocell corrosions of bars were investigated on single crack specimens with crack widths of 0.08, 0.26, 0.38 and 0.94 mm. The entire study was carried out in an artificially created chloride ion-induced corrosion environment. The results show that the steel in cracks was activated once the transverse crack occurred on concrete element, and the macrocell corrosion must co-exist with microcell corrosion of reinforcements in test specimens with transverse crack. The macrocell current of steel elements were separated from the crack width, and the wider the transverse crack is, the higher corroded area and the greater microcell current of the rebar is. Oxygen and water go into concrete through crack instead of through concrete cover. The epoxy coating cannot prevent the occurrence and propagation of crack, so it was not effective to prevent corrosion of steel bars in cracked concrete.

1. Introduction

Presence of damage and cracks in concrete structures is a major concern for the owners and operators of the concrete infrastructures [1,2]. Once a crack is formed, it provides an easy access for ingress of water, chloride ions and oxygen to the steel surface, resulting in accelerating corrosion of steel reinforcement [3–6]. The service life of concrete infrastructure is drastically affected by presence of cracks. Therefore, to accurately predict the service life of the structures the influence of cracks should be accounted for in service life prediction models.

Cracks in concrete regarding steel corrosion may include longitudinal cracks (cracks parallel to rebar)and transverse cracks (cracks perpendicular to rebar). Longitudinal cracks are usually generated as a result of rust expansion induced by corrosion [7–9]. On the other hand, transverse cracks are usually caused by loading, which may produce localized corrosion at the tip of the intersecting crack.

A debate among the researchers on relationships between transverse crack width and corrosion rate has been continuing since long ago [10–14]. Several researchers [10–12] suggested that transverse cracks allow aggressive species to penetrate faster into the reinforced concrete thereby accelerating corrosion of the steel and reducing the service life of structures. However, others [13,14] supported that, even though transverse cracks accelerate the initiation of corrosion and induce localized damage to the reinforcing steel, there are little correlations between crack width and corrosion rates. It is expected that with any size of cracks, the corrosion rate of steel bars in concrete will depend much more on the surrounding concrete (i.e., concrete resistance, oxygen permeability, and chloride ion content) rather than crack widths. Based on these studies, several design codes [15–17]limit transverse crack widths to avoid the attack of chloride salt to the reinforcement. However, European design code [18] suggested that limiting transverse crack widths is no means to control the rate of rebar corrosion.

The significant characteristic of localized corrosion is that the macrocell corrosion must co-exist with microcell corrosion of reinforcements in concrete [19]. The corrosion of rebar at transverse crack is a typical local corrosion for reinforced concrete structure [20,21]. The first viewpoint mentioned above comes from the

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[*] Corresponding author. State Key Laboratory for Geomechanics and Deep Underground Engineering, China University of Mining and Technology, Xuzhou, 221116 China..

E-mail address: jiyongsheng@cumt.edu.cn (Y. Ji).

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research results that there are little relationships between transverse crack width and macrocell current. Not only the microcell corrosion of active rebar itself at crack zone was not considered, but also the hypothesis is lack of experimental verification that oxygen and water for cathode reaction of macrocell corrosion go into concrete through concrete cover instead of through crack. However, the reason for the above second viewpoints is that some researchers equate the corrosion mechanism of steel in cracked concrete to that of steel exposed to atmosphere, ignoring macrocell corrosion between active steel at transverse crack and passive steel in sound concrete.

Against the above background, this study was conducted to evaluate the relative contributions of the macro and micro cell components to the total corrosion of steel which was induced by chloride in a reinforced concrete member with bending crack. Microcell and macrocell corrosions of bars were investigated on single crack specimens with crack widths of 0.08, 0.26, 0.38 and 0.94 mm and a study on the influence of epoxy coating on corrosion of steel bars in cracked concrete is presented here to determine the supply path of oxygen and water for macrocell corrosion.

2. Theoretical

2.1. Corrosion mechanism of steel induced by transverse crack

Once the transverse crack appears on concrete element due to the existence of load, the brittle concrete cover is not able to prevent the vertical extension of crack. As a result, the crack will extend to the steel surface rapidly. External corrosive media, such as chloride salt, can reach the steel surface regardless of the dimension of crack, which causes the steel corrosion due to its conversion from being passive to being active. The existence of crack has more significant influence on steel corrosion in concrete than crack width when the structure life time is taken into consideration.

The corrosion of rebar at transverse crack is a typical local corrosion for reinforced concrete structure (Fig. 1). There is the electrochemical potential difference between active area (passivity broken) at crack as an macroanode and passive area (intact passivity) in sound concrete as a macrocathode, which is the driving force for the macrocell corrosion. The macrocell corrosion current between the active and passive steel surfaces further expedite the corrosion process on the surface of the active steel. On this corroded surface at crack there are incalculable dense and tiny corrosion pits. A galvanic corrosion coupling comes into being between the steel in each corrosion pit and weeny area arounding the pit, the sizes of these galvanic corrosion cells are very small, so that the morphology of pitting will be less evident. Therefore, on a macroscale, the corrosion on the external surface of the reinforced steel is general. The countless dense and tiny galvanic corrosion macrocells can be viewed as microcell corrosion.

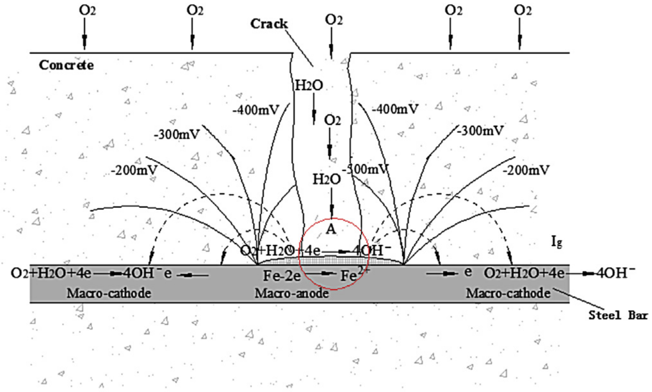
The most simple and most probable reactions that could occur are:

2.2. Anodic reaction at transverse crack

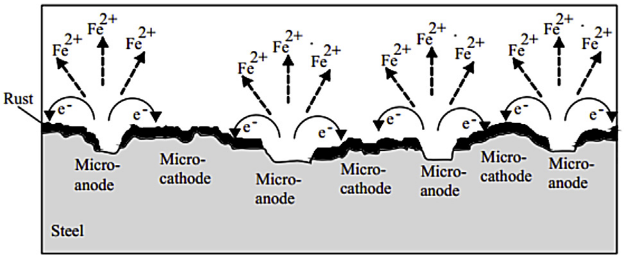
$$2Fe \rightarrow 2Fe^{2+} + 4e \tag{1}$$

Cathodic reaction in both transverse crack for microcell and sound concrete for macrocell:

$$4e + O_2 + 2H_2O \rightarrow 4OH^- \tag{2}$$



(a) Corrosion of steel bar at flexural crack



(b) Amplified area A

Fig. 1. Schematic illustration of microcell and macrocell corrosion of galvanized steel at crack.

Both macrocell and microcell corrosion mechanisms could play significant roles, and the total corrosion could be underestimated if each of two is overlooked.

Macrocell corrosion current is determined by the corrosion potential difference between the activated zone and surrounding passive zone on steel bar, and it is irrelevant to the crack width. The increase of crack width does not only enlarge the area of active zone on steel bar, but also introduces oxygen and water into crack directly through its opening to atmosphere environment. Consequently, microcell current is increased significantly and rapidly for steel bar in crack, and the microcell corrosion current is much greater than that of macrocell.

2.3. The electrochemistry of corrosion of steel bar in cracked concrete

The corrosion current and the corrosion potential of steel immersed in any given electrolyte can be theoretically determined by Evans diagrams, i.e., the graphic representation of anodic and cathodic polarization curves, based on electrochemical principles [22]. These diagrams are used in this work to illustrate and to discuss the mechanisms of a macrocell formation resulting from transverse crack of concrete structures and their effects on the rate of corrosion of reinforcements. A simple two-electrode macrocell corrosion system consists of one passive steel (electrode 1) and one active steel (electrode 2) as illustrated in Fig. 2. Curve C_1, C_2 in diagram are the cathodic polarization curves of active and passive reinforcing steel, and Curve A_1, A_2 are the anodic polarization curves of active and passive reinforcing steel. When these two electrodes are insulated from each other, the corrosion current of the passive steel (electrode 1) is I_{corr1} and the corrosion current of the active steel (electrode 2) is I_{corr2}, thus the total corrosion current