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Analytical assessment of the bearing capacity of RC beams with corroded steel bars beyond concrete cover cracking

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ABSTRACT

Corrosion of steel reinforcement is one of the major causes that limit durability and serviceability performance of reinforced concrete (RC) structures. This paper reviews thoroughly available experiments and analytical approaches in the relevant international literature and introduces a calculation model for assessing steel bar mass loss and contributes to further utilization of common in-situ inspections from a structural point of view. The model is based on the width of longitudinal crack of concrete cover, as a function of cover depth, bar diameter and mechanical properties of concrete. The model includes the well-known relationships for the steel mass loss during the first phase of rust formulation, filling the porous zone as well as during the phase that the radial pressure exceeds the concrete strength and causes cover cracking. The assumption followed herein for the flexibility of cracked concrete allows for the estimation of steel bar corrosion rate even beyond concrete cover cracking, by visual mapping of the width of longitudinal cracks. Then, the corresponding flexural capacity of the beams at yield and at maximum may be assessed. The predictions of the model are validated against 51 non-strengthened corroded beams and 24 strengthened corroded beams with Fiber Reinforced Polymer (FRP) materials published in the international literature.

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1. Introduction

Reinforcement corrosion is considered one of the main causes of premature damage in reinforced concrete structures. The prediction of the loss of rebars cross-section in corroded reinforced structure to reassess the residual bearing capacity involves the estimation of the loss of rebar section which initiates first corrosion induced cracks. In literature very few research works have been carried out on the prediction of corrosion induced crack width during propagation of related phenomena. Corrosion induced widths of cracks have been measured in several works. The aim is to correlate them with the level of steel reinforcement corrosion in RC specimens and subsequent structural capacity degradation.

1.1. Existing analytical models

Expansive corrosion products occupy several times the volume of the original steel consumed. Liu and Weyers [1] modeled the time from initiation to corrosion cracking, based on the amount of corrosion products required to cause cracking of concrete cover by taking into account the time required to fill the porous zone around the steel bar, before creating an internal pressure on the surrounding concrete.

The corrosion process is usually accelerated in experimental research on corrosion induced cracking on concrete so that the concrete cracking can be achieved in a relatively short time [2,3]. It is difficult to determine the relationship between the current induced corrosion and the natural corrosion. Most of the current research on the corrosion-induced cracking process focuses on corrosion induced surface cracking. Li et al. [4] proposed an analytical model for corrosion induced crack width as a function of time after a parametric study on four parameters. It was found that corrosion rate, as represented by corrosion current density i_{corr}, is the single most important factor that affects both the time to surface cracking and the growth of crack width. It has also been found that the geometry and properties of the reinforced concrete affect the time to surface cracking while to a less extent the crack width growth. Alonso et al. [2] and Torres-Acosta and Sagues [5] mentioned the ratio of concrete cover to bar diameterc/D as the

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factor with the greatest impact on initiation of concrete cracking. Yet, no correlation with the development of cracking was found. Similarly, Vidal et al. [6] associated the surface cracking with the ratioc/D, the diameter of bar steel and the quality of the steel-concrete interface. They also concluded that these factors do not interfere at all with the crack propagation, in terms of the crack width evolution, as a function of steel cross-sectional loss. Cabrera [7] found that when cover depths on side faces and on tensile face were varied, cracks were only observed on the face nearest to the corroding bar. When covers were equal, exterior bars either exhibited a crack on the side face or on the bottom tensile face but not on both faces. Similar crack patterns however on beams that were corroded under load were also observed [8–10].

The tensile strength and creep of concrete have a great influence on concrete cracking [11]. Weyers [12] mentioned that not all corrosion products contribute to the expansive pressure on the concrete, but some of them fill the voids and pores around the steel reinforcing bar and some migrate away from the steel reinforcing interface through concrete pores. Khan et al. [13] investigated the influence of steel stirrups. They concluded that no linear relationship exists between the crack width and the stirrup cross-sectional loss. The main reason is that the width of longitudinal corrosion cracks does not allow the cross-sectional loss of the stirrups to be predicted. They also stated that as corrosion develops new corrosion cracks form and lead to further degradation of steel-concrete interface. The process of evolution of this stage of crack propagation is slower for a concrete beam with thicker concrete cover because larger concrete cover offers more resistance to the formation of new corrosion cracks. The cover to diameter ratio has an effect on the evolution of crack width versus steel cross-section during the second stage of propagation of corrosion. Corronelli & Gambarova [14] combined the corrosion induced pressure with the pressure produced by bond action in determining the stress in concrete.

Hariche et al. [15] found that different steel arrangement seems to have a great influence on the nature and extent of damage to concrete cover when the steel corrodes. It seems to have an impact on the cracking pattern as well as on the increase of the corrosion-caused deflection.

It has been established from previously published experiments that cracking of the cover occurs later for corroded bars of smaller diameter, for increased concrete cover and for concrete with higher tensile strength (higher splitting resistance of cover and lower bursting forces from the bar, [16,17]. Du et al. [18] mentioned that failure patterns of cover concrete with different rebar diameters are very similar as the cover thickness remains the same. With an increase of rebar diameter, the maximum corrosion radial pressure generated by the corrosion products increases. The larger the rebar diameter is, the more easily the concrete cover cracks. Furthermore, larger bar diameters may require higher concrete cover thickness to ensure bonding with surrounding concrete and avoid concrete splitting failure. The thicker the concrete cover is, the later the cracks will occur on concrete surfaces. In the cases the distance between successive steel reinforcing bar is not large enough, the concrete cracking occurs firstly between the bars. Therefore, it can be concluded that the cover to diameter ratio has an effect on the evolution, path and width of cracking and therefore on the steel mass loss of corroded reinforcement.

The experimental approach and the loading conditions also have an effect on the corrosion induced cracks. Specimens corroded while not being loaded or corroded while sustaining load during the corrosion phase or specimens initially corroded and then subjected to loading, present variable cracking. Thus, beams are expected to show varying corrosion crack widths and different corrosion crack patterns when subjected to simultaneous sustained load. El Maaddawy and Soudki [19] proposed a model for the prediction of the time required for corrosion products to fill a porous zone (corrosion initiation) before they start inducing expansive pressure on the concrete surrounding the bar (corrosion cracking). Malumbela et al. [20] investigated the corrosion amount to fill the porous zone and proposed a relation for the maximum expansion of concrete near the corroded area, necessary to accommodate the corrosion products. Malumbela et al. [21] found similarly to El Maaddawy and Soudki [19] that as corrosion progresses, the crack patterns change. In many cases, multiple cracks were formed on tensile faces of beams that propagated along positions of each bar because of the larger spacing between the bars. Long drying cycles caused larger losses of steel because they allowed more drying of the corrosion region, while patterns of corrosion cracks as well as the rate of widening of the cracks, in each pattern, were independent of the duration of drying cycles [21].

Zhang et al. [10] divided the corrosion cracking process into three phases in terms of corrosion pattern evolution and the relationship linking reinforcement corrosion with crack width. At the initiation of cracking, the local pitting is the only pattern. At the first stage of cracking propagation, the pits of corrosion are discontinuous along the steel bars and not symmetric. The crack width is related to the maximum localized corrosion of reinforcement. At the second phase of propagation, the presence of wide cracks converts the corrosion pattern much closer to homogeneous corrosion along steel bars. Thus, the crack width is related to the average cross section loss. They concluded that predictions of Vidal's model were significantly over-conservative, as the corrosion pattern changed from localized to generalized. The location of the maximum crack width does not necessarily correspond to the location of the maximum pit depth [22,23]. Furthermore, crack widths significantly vary along the corrosion region and their rate of widening is dependent on the pattern of the cracks [21].

Wu et al. [24] proposed a model which excludes the time parameter and is established as geometric model to relate the rust, the pores and the cracks. A linear relationship between crack width and corrosion rate was found, with the slope based on the particular test. Xia and Jin [25] established an analytical prediction model of crack width after considering concrete cover depth and corrosion penetration depth according to their experimental results. Balafas & Burgoyne [26] proposed a new formula for the rate of rust production, based on fracture mechanics and strain energies.

1.2. Corroded RC beams strengthened with FRPs

1.2.1. Externally bonded reinforcement without patch repair

Much research has been conducted on the durability of FRP-repaired concrete beams and different techniques have been applied. Externally bonded reinforcements (EBR) in the form of fabrics and FRP laminates for flexure, shear strengthening and confining of RC members is the most popular technique for the retrofit of concrete structures. Some researchers corroded the beams by directly simulating field conditions (natural corrosion process), while to accelerate the aging process several researchers used an accelerated technique by the application of an induced electrical current. It is also important to evaluate the effectiveness of repairs to extend the service life of corroded structures based on their ability to control further steel corrosion. Preceding experimental work on strengthening corroded RC structures with FRPs has often excluded the patch repair process. El-Maaddawy and Soudki [27] studied the viability of using CFRP sheets to repair RC beams at different levels of corrosion damage and found that the ultimate strength of a severely corroded beam (approximately 31% steel mass loss) was increased to a level higher than that of an uncorroded beam after the application of CFRPs. Hu et al. [28]

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