Numerical study of corrosion induced cracking in reinforced concrete structure

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Abstract. This research was conducted to study the initiation and propagation of surface crack width due to corrosion on reinforcement in reinforced concrete structures using finite element (FE) approach. Corrosion parameters, such as attack penetration and loss of steel section were used to define the relationship with the surface crack width. The objective of using numerical approach in the current study is to understand the effects of corrosion expansion on the behaviour of surface crack pattern and to validate the crack pattern with the available data. The output from the previous works was used to model specimens with different bar diameters and bar locations. The results from the finite element analyses were discussed subsequently.

1. Introduction

In the last few years, many researchers had adopted various approaches in modelling the initiation of surface cracks induced by reinforcement corrosion [1-3]. The first crack model was proposed previously by Bazant [4], who modelled the concrete cover as a thick-wall cylinder subjected to internal pressure from the volume expansion of corrosion products. This internal pressure was derived from plane-strain isotropic linear elastic assumptions, according to which cracking occurred when the peak stress reached the tensile strength of concrete. This model predicted mainly the time for the cover to crack; however, it was not validated on a real corroded structure. In this model, the time for corrosion crack initiation was based on the corrosion rate and the properties of concrete, such as the concrete cover thickness, diameter of steel reinforcing bars and their spacing, modulus of elasticity and tensile strength. Bazant’s model was subsequently upgraded by Liu and Weyers [5], Pantazopoulou and Papoulia [6], Bhargava et al. [7], and Allampallewar and Srividya [8] by assuming that a porous zone existed around the steel/concrete interface caused by air voids entrapped/entrained near the transition from cement paste to steel. As the corrosion takes place on the surface of the steel, the porous zone will gradually be filled with the corrosion products before corrosion begins to exert internal pressure [9]. The cracks will initiate at the rebar concrete interface where the maximum tensile stress of concrete first reaches. Then these initial cracks propagate to concrete surface as inner cracks which cannot be detected from outside of the concrete cover. The crack becomes visible on the concrete surface when the width reaches 0.05 mm.

In this study, a numerical model was used to determine the influence of corrosion penetration on the formation and propagation of cracks visible on the surface of a RC member. It concentrates on the estimation of the amount of corrosion products that produce pressure around the steel-concrete interface and initiate the crack and the subsequent growth of surface crack width. In this analysis, corrosion is assumed to be uniform along the main bar; therefore, a two-dimensional finite element model of the section perpendicular to the bar axis is adopted to describe the initiation and propagation
of concrete cracking. For a corner bar (Figure 1(a)), two continuous sides to the left and bottom were fixed in the X and Y directions, while for a centre bar [Figure 1(b)], half of the specimen was modelled. This model was adopted based on the experimental works done previously in order to show the influence of concrete cover on crack propagation where in first model (corner location), the concrete cover thickness was equal for the top and the side, while on the second model (centre location) the top cover was thinner that the side cover [10]. In modelling the crack, a two-stage process was adopted. First, a smeared crack approach is used to determine the crack location and direction because it offers an automatic generation of cracks without the redefinition of the finite element topology and complete generality in the possible crack direction. Second, after the crack location has been determined from the smeared crack analysis, discrete cracks are represented by delamination interface elements to analyse the crack width from its initiation to propagation.

![Figure 1. Idealisation of specimens.](image)

2.1. Loading condition

The modelling of the expansion of corrosion products by applying the thermal analogy was used previously by Val et al. [11] and Chernin and Val [12] in their works. Therefore, as no corrosion type of loading is provided in the LUSAS modelling procedure, the similar approach was applied in this work to study the propagation of surface cracks resulting from the expansion of corrosion products. The temperature load was used in the analysis and the thermal strain of the reinforcement bar was obtained using the temperature rise and the coefficient of thermal expansion. For the plane strain element, the thermal strain is defined as:

\[ \varepsilon_t = (1 + \nu)\Delta T \alpha_T \]

where \( \varepsilon_t \) = radial thermal strains, \( \nu \) = Poisson ratio, \( \Delta T \) = temperature rise (as given in Equation (2)) and \( \alpha_T \) = coefficient of thermal expansion.

\[ \Delta T = T - T_{ref} \]

where \( T \) and \( T_{ref} \) are the current temperature and reference temperature, respectively.

The conversion from the radial thermal strain (\( \varepsilon_t \)) to the radial thermal expansion (\( \Delta r \)) of the bar radius is done as follows:
\[ \Delta r = \varepsilon_r \cdot r \] (3)

The conversion of the expansion of the bar radius to corrosion penetration is made as follows. According to Lundgren [13], at a free increase in the bar radius caused by corrosion, \( \Delta r \), can be estimated by using Equation (4).

\[ \delta = \sqrt{r^2 + (\alpha - 1) \cdot (2rx - x^2)} - r \] (4)

where, \( r \) is a radius of steel bar; \( x \) is a corrosion penetration and \( \alpha \) is the volume of rust relative to uncorroded steel. \( \alpha \) was used as an input by assuming that the volume of the rust is \( \alpha \) times the volume of the steel that has corroded [13] and a value of 2 has been used by many researchers in their analysis [14,-15]. If corrosion penetration, \( P_{corr} \ll r \), \( \Delta r \) can be estimated as follows:

\[ \Delta r = (\alpha - 1) P_{corr} \] (5)

Equation (5) is used to calculate the corrosion expansion analytically.

2.2. Mesh configuration

For smeared and discrete crack model, eight-node quadrilateral mesh is used to describe the concrete, while six-node triangle mesh is used to describe the steel reinforcing bars (Figure 2). Once the location of the crack is determined from smeared crack analysis, the interface was placed at the crack location to determine the opening of crack due to the expansion of steel reinforcement during the corrosion process. In this stage, 2D interface element was used as shown in Figure 3. The properties of interface element was based on fracture energy and imitation stress where the linear softening was assumed once the threshold strength has been reached and the materials does not resist any further straining once the total fracture energy has been exceeded [16]. These elements have no geometric properties and are assumed to have no thickness. Based on pre-analysis model, six divisions were taken as the minimum division used in this study. The nonlinear properties of concrete are used as an input in the properties of the interface elements. Therefore, the tension behaviour of the interface elements is similar to that of concrete.

**Figure 2.** Mesh element for concrete and steel materials.

**Figure 3.** 2D interface elements.
3. Results and model validation

Based on smeared crack model analysis, the location of surface crack propagation due to the reinforcement bar expansion is shown in Figures 4 and 5 for 10 mm and 16 mm bar diameters respectively. As can be seen, the first crack was first observed on the side of the specimens for 10 mm bar and 16 mm bar with thin concrete cover. For high concrete cover, the crack was propagated on the both sides of the samples. Discrete crack analysis is used to obtain the actual crack width for the aforementioned phases. In modeling the propagation of surface cracks, the interface elements were placed at the crack location determined from the smeared crack analysis, and the analysis was conducted to determine the actual propagation of the surface cracks. The opening of these interface elements caused by the expansion of bar radius is considered as propagation of surface cracks.

Figure 4. Crack location for 10 mm diameter main reinforcing bars with different bar locations.

Figure 5. Crack location for 16mm diameter main reinforcing bars with different bar locations.

The propagation of surface crack width versus the increasing in bar radius due by thermal expansion is presented in Figure 6. The results were plotted for different cover to diameter ratios, where the dash lines represent the corner bar location while lines with a marker indicate the centre bar.
location. Both the corner and centre bar locations show a similar linear relationship between crack width and bar thermal expansion. Based on crack width, it can be seen that, for a similar radius expansion, higher crack width is observed at the corner bar location than the centre face bar due to the confinement condition of the bar. The surface crack on the 16 mm bar diameter is higher than the 10 mm bar diameter.

![Graph showing crack width vs. radius expansion](image1)

**Figure 6.** Propagation of surface crack width.

### 3.1 Model validation

To account for the validity of the crack pattern in this study, a similar modelling procedure is adopted for experimental specimens based on Cabrera’s [17] study on the corrosion of multiple reinforcing bars. Two selected specimens reinforced with 16 mm and 20 mm steel bars have a similar cross section, as shown in Figure 7. The comparison of experimental and numerical crack patterns was presented in Figure 8. The friction coefficient of 0.4 was applied between the reinforcing bar and the concrete. Based on these figures, the crack pattern from the model shows similarities with the experimental crack location in that it has moved vertically. The experimental corrosion penetrations that produced these patterns were 0.53 mm and 0.34 mm for 16 mm and 20 mm diameter bars, respectively. Based on the discrete crack model, the similar penetration had produced 1.0 mm and 1.6 mm crack widths, which are 50% and 71% higher than the experimental crack width.

![Diagram showing Cabrera’s study](image2)

**Figure 7.** Cabrera’s [17] specimen with multiple reinforcements.
4. Conclusion
The first section showed the locations of surface cracks using a nonlinear concrete analysis. The location of surface cracks is determined based on the strain softening of concrete element caused by the strains imposed by thermal expansion of the bar radius. Following this, interface elements were placed at the same location and an analysis was conducted to determine the actual width of the surface cracks. The experimental crack location in this study is expected to be as similar as observed previously in the experiment. Furthermore, as this numerical work has shown the propagation of surface crack width is controlled by several parameters such as the bar diameter, the thickness of the concrete cover, and the location of the bar (corner or centre). These parameters should be considered in the experimental work to understand clearly the influence of corrosion cracks on residual bond strength.

5. References
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