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Numerical determination of concrete crack width for corrosion-affected concrete structures

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ABSTRACT

Corrosion-induced deterioration of reinforced concrete (RC) structures results in premature failure of the RC structures. In practice concrete crack width is one of the most important criteria for the assessment of the serviceability of RC structures. It is therefore desirable to predict the growth of the crack width over time so that better informed decisions can be made concerning the repairs due to concrete cracking. Literature review shows that little research has been undertaken on numerical prediction of concrete crack width. The intention of this study was to develop a numerical method to predict concrete crack width for corrosion-affected concrete structures. A cohesive crack model for concrete is implemented in the numerical formulation to simulate crack initiation and propagation in concrete. Choices for evaluating the parameters of cohesive elements are extensively discussed which is a key for developing a plausible model employing cohesive elements. The surface crack width is obtained as a function of service time. Accurate prediction of crack width can allow timely maintenance which prolongs the service life of the reinforced concrete structures.

1. Introduction

Reinforced concrete (RC) structures have been the most common type of structures used in the civil engineering construction since middle nineteenth century. RC structures have been widely used for building, bridges, retaining walls, tunnels, and indeed any physical infrastructure built on and under the ground. Since 1970s, it has become an accepted knowledge that the concrete cover has its limitation on protecting the reinforcing steel from corrosion. As a result, a series of research has been initiated on improving the understanding of the corrosion of steel in concrete [1], such as the Concrete in the Oceans research programme in the UK in the 1970s. Furthermore, it appears to be inevitable that RC structures will suffer from reinforcement corrosion in chloride (Cl^-) and carbon dioxide (CO_2) laden environment. Practical experience and experimental observations [2–5] suggest that corrosion affected RC structures deteriorate faster in terms of serviceability (e.g., cracking or deflection) than safety (e.g., strength). Therefore, there is a well justified need for a thorough investigation of the cracking process and crack width of concrete, not least bearing in mind that crack width is one of the most important practical parameters for the design and assessment of RC structures.

To model cracking of concrete, some researchers have resorted to analytical approach, mainly due to the accuracy of the solution and the convenience of its practical application [6–8]. For example, Li and Yang [7] developed an analytical model for concrete crack width caused by reinforcement corrosion and applied load, by introducing a stiffness reduction factor to account for the post-cracking quasi-brittle behaviour of concrete. The stiffness reduction factor then modifies the differential equation for obtaining the cracked stress and strain components. Correlations between material corrosion and the structural effects can then be established, e.g., crack width [7], time to surface cracking [8], etc. However, the application of analytical modelling in crack propagation in concrete is limited to some special cases, e.g., particular boundary conditions, and the assumption that the crack is smeared and uniformly distributed in the damaged solid to satisfy the requirement on continuous displacement. Some studies have employed complex functions to formulate the stress development under arbitrary boundary conditions [9,10]; however, they have been limited to elastic problems only so far.

In light of the limitation of analytical modelling on crack propagation in concrete, numerical modelling has brought considerable advantages. Depending on the specific application and the scale of

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the problem, different numerical techniques may be used, e.g., finite element method (FEM) [11,12], discrete element method (DEM) [13], boundary element method (BEM) [14,15] and peridynamics [16,17]. Amongst these numerical methods, FEM has received the most research interest in solving corrosion-induced reinforced concrete cracking. Roesler et al. [11] developed a FE model with cohesive crack concept to predict the fracture performance of concrete beams. A number of geometrically similar beams were investigated and the global mechanical behaviour of the cracked beams was obtained. For corrosion induced concrete cracking, Guzmán et al. [18] developed a concrete cover cracking model based on embedded cohesive crack finite element. Time to surface cracking was then able to be predicted. Sánchez et al. [19] proposed a mesoscopic model simulating the mechanical performance of reinforced beams affected by corrosion. Both cross-sectional and out of cross-section mechanisms, affected by corrosion, were coupled for determination of corrosion effects on the concrete structures. Moreover, Bossio et al. [20] considered the effects of corrosion of four reinforcing rebars on the behaviour of a single structural element. According to the research literature, however, there are very few models on numerical modelling of concrete crack width due to internal pressure such as corrosion induced expansion. Crack width is an important parameter regarding the durability of concrete structures while it is still not quite clear how those underlying factors, e.g., corrosion rate, material/mechanical properties of concrete, may quantitatively affect the development of crack width of the concrete. Therefore, it is well justified that a numerical method be developed to predict corrosion induced concrete crack width over service time.

This paper is based upon Yang et al. [21], but the current paper includes additional research in model formulation, i.e., cracking criteria, choice of parameters of cohesive elements and calculation of corrosion-induced displacement, and a parametric study, i.e., effects of numerical parameters on concrete crack width results. This paper attempts to develop a numerical method to predict the cracking and crack width for corrosion affected concrete structures. Cohesive crack model is used and cohesive elements are embedded for simulating the crack propagation. The choices of parameters of cohesive elements have been extensively discussed which is the key for establishing a plausible model with cohesive elements. After formulation of the model, an example is worked out to demonstrate the application of the method and verification by comparing with analytical/experimental results is provided. Parametric study is finally carried out to investigate the effects of some numerical parameters on the concrete crack width. The crack width obtained from this model is the total crack width which can be used to estimate, with reasonable accuracy, the degradation of concrete cover. It can also be regarded as the maximum possible crack width for design or divided by the number of cracks. Further, this numerical model is highly complimentary to most analytical models, since the same hypothesis was assumed.

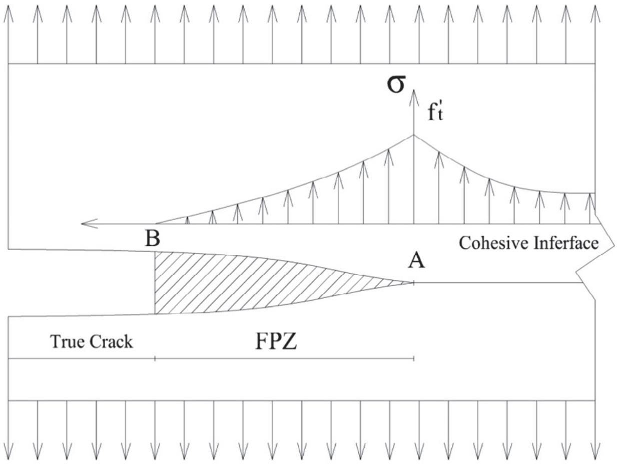
2. Constitutive model

The failure of structures is significantly influenced by the properties of the material used. In terms of tensile stress-elongation relationship, most of engineering materials can be classified into brittle, ductile and quasi-brittle [22]. Different materials used will result in different failure mechanisms of structures and hence different material models should be applied correspondingly. For example, Drucker-Prager Model and Von Mises Model are used for ductile materials. For brittle materials, Griffith model based on linear elastic fracture mechanics is usually applied. Cohesive Crack Model, one of few nonlinear fracture mechanics models, is developed and widely used for quasi-brittle materials.

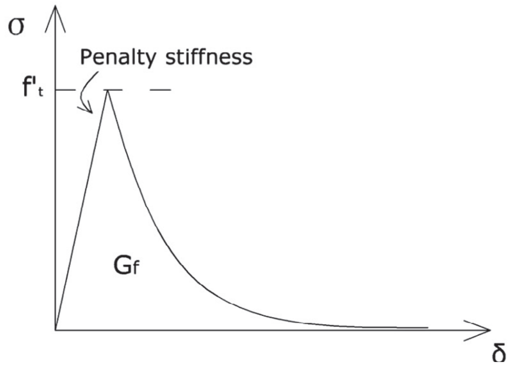
Concrete is considered as a quasi-brittle material, in which the tensile stress gradually decreases after it reaches the tensile strength while the tensile strain/displacement continues to increase. This behaviour of concrete is called strain softening. The concept of strain softening evolves from plasticity where the post-peak decline of the tensile stress is considered as a gradual decrease of the tensile strength, i.e., softening. Since the softening is related to all the strain components, it is normally called strain softening. The reason of strain softening is that there is an inelastic zone developed ahead of the crack tip which is also referred to as fracture process zone (FPZ) as shown in Fig. 1a. When a crack propagates in concrete, the cracked surfaces may be in contact and are tortuous in nature [23], due to various toughening mechanisms such as aggregate bridging, void formation or microcrack shielding [22]. Therefore, the cracked surfaces may still be able to sustain the tensile stress which is characterized by the softening degradation curve.

Cohesive Crack Model (CCM), originally developed by Hillerborg et al. [24], is generally accepted as a realistic simplification for FPZ [25]. CCM assumes that FPZ is long and narrow and is characterized by a stress-displacement curve as typically shown in Fig. 1b. In Fig. 1a, the shadowed zone from point A to B is FPZ and the area beyond Point B is the true crack where the cracked surfaces are completely separated. The CCM is normally incorporated into finite element analysis as an interface when the crack path is known in advance.

Since the FPZ is represented by the cohesive interface and the thickness of the cohesive interface should be very small or zero,



(a) Schematic of mechanism of FPZ



(b) Stress-displacement curve for cohesive material

Fig. 1. Cohesive crack model for the FPZ.

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