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Pull-out behavior of an imperfectly bonded anchor system

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ABSTRACT

A theoretical model of imperfectly bonded anchorage system was analyzed and validated using the ABAQUS code. Based on the proposed model, the axial stress in the anchor and shear stress at the anchor–epoxy interface along the embedded direction have been obtained. Then the slope of the axial stress in anchor along the embedded direction was analyzed and showed a steep drop at the location of imperfect bonding part. This behavior is useful in many engineering projects and can be used to obtain the debonded locations of adhesive layer or fracture zones in surrounding concrete (rocks) during anchor service period. Subsequently, a parametric study is adopted to analyze the distinct effect of composition factors on the behavior of the imperfectly epoxy bonded anchor system (IEBAS). Finally, a field application of the technique was conducted and correlated with the drill hole detector.

1. Introduction

Anchorage system has been applied in many engineering projects, such as slope strengthening, tunnel supporting and mining. The strengthening mechanism of perfect bonded anchorage system has been studied by many researchers in the past several decades. Different mechanical models of anchorage system have been built. However, there is little research about IEBAS, with debondings along the interface of epoxy and steel rebar or concrete.

Extensive experimental, analytical, and field investigations on the behavior of anchorage system have been reported in literature. Yang et al. [1] and Wu et al. [2] suggested a pull-out model of anchorage system with two different boundaries using a shear-lag model. In their paper, tensile stress of anchor, interfacial shear stresses along the embedment length and the pull-out load capacity have been derived and discussed. James [3] derived an approximate expression to predict the ultimate tensile strength of the anchorage system based on the linear and nonlinear finite element simulation results. Benmokrane and Chekired [4] estimated the pull-out resistance of an anchor system for a given embedment length and proposed a simple tri-linear constitutive model for the interface shear stress–slip relationship. Nak-Kyung Kim et al. [5] predicted the load transfer mechanism on ground anchors using a series of finite element and beam-column model and compared the prediction with observed measurements in a field load test. Delhomme and Debicki [6] studied the behavior of long and smooth anchor rod with enlarged head considering the visco-elastic behavior of epoxy described by the creep laws given in Euro-code 2 [7]. Serrano and Olalla [8] obtained the tensile resistance of rock anchors using the Euler's variation method [9] assuming the Hoek–Brown rock mass failure criterion [10,11]. Allowing the nonlinear force–displacement response of a tensile bar embedded in a massive soil by means of an elasto-plastic bonding agent, Froli [12] analyzed the main influence parameters on the optimal anchorage condition when plasticity initiated in the bar. Bažant and Desmorat [13] analyzed the size effect in fiber or anchor pull-out and pointed out that the distribution of interface shear stress shows higher non-uniformity with the increase of fiber or anchor sizes. However, no researchers have worked on IEBAS.

In fact, IEBAS are commonly found in practical engineering, due to various reasons such as water ingress and corrosion, joints or fractures existed in the surrounding concrete/rock, and poor grouting construction. IEBAS seriously affects the reinforcement quality and may lead to disastrous consequences. It is necessary to conduct comprehensive research on the IEBAS system. In this paper, based on the proposed theoretical model, the axial stress in anchor and the shear stress at the anchor–epoxy interface along the embedded direction were determined, and validated by ABAQUS model. Subsequently, a parametric study is adopted to analyze the distinct effect of composition factors, such as imperfectly bonded location, epoxy layer thickness, and anchor diameter, etc., on the behavior of IEBAS. Finally, the results were applied to analyze the field test data and used to interpret the working status of an anchor system in field.

2. Mechanics model of IEBAS

2.1. Geometry and boundary conditions of the proposed model

Assume that the model has geometry as shown in Fig. 1. An anchor with diameter D is embedded at the center of a coaxial

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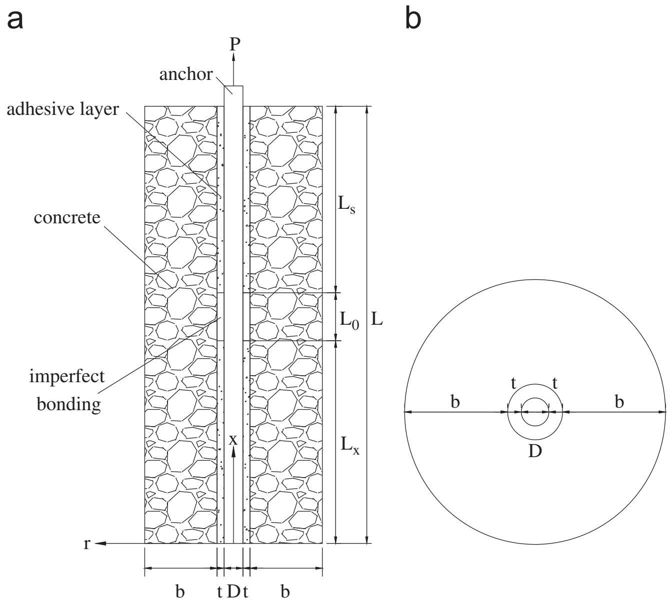

Fig. 1. Schematic illustration of the proposed anchor system (where L_x represents the length of the bottom bonded portion of the anchor system): (a) anchor–epoxy layer–concrete anchorage system and (b) details of cross-section.

cylindrical matrix with a radius b and bonded with a layer of epoxy with a thickness t. An imperfectly bonded length L_0 exists at a distance of L_s from the exposure surface. A two dimension plane coordinates (x, r) is used, in which the x-axis corresponds to the axis of the anchor. The epoxy layer and the anchor are free at bottom. The bottom of concrete is fixed and the anchor is subjected to a pulling force at the top, as shown in Fig. 1.

2.2. Fundamental assumptions

Both the anchor and the concrete are treated as linear elastic materials with elastic modules E_S and E_C, respectively. The epoxy–anchor interface is considered to be perfectly bonded without any slip. A simple mechanical model for the epoxy–anchor interface is adopted as,

$$\tau = \begin{cases} k\delta(0 < \delta < \delta_m) \\ \tau_r(\delta > \delta_m) \end{cases} \tag{1a, b}$$

where τ is shear stress; τ_r is residual friction stress; δ is shear slip at the anchor–epoxy interface; k is the interfacial shear modulus of anchor–epoxy interface; δ_m is the peak-load shear slip corresponding to the interfacial shear strength.

2.3. Solutions for stress distributions

Two infinite small elements are taken out from Fig. 1 and shown in Fig. 2. From Fig. 2a, we have τ expressed in a differential form from the consideration of the equilibrium of infinite small elements in an anchorage system

$$\tau = \frac{D\,d\sigma_s}{4dx} \tag{2}$$

where σ_s is the tensile stress in the anchor cross-section, x is the coordinate along the anchor, and D is the diameter of the anchor rebar.

Moreover, the variation of the shear stress in the epoxy layer along the radial direction can be obtained through the analysis of the cylindrical shell element in the epoxy layer of Fig. 2b

$$\frac{1}{\tau_s}\,d\tau_s = -\frac{1}{r}\,dr \tag{3}$$

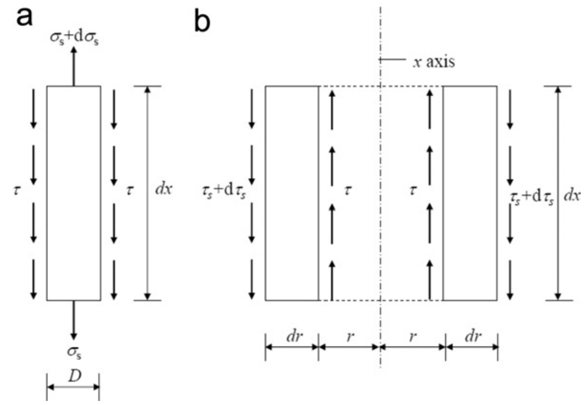

Fig. 2. Infinite small elements of anchorage system [1]: (a) anchor cylindrical element and (b) epoxy layer cylindrical shell element.

where τ_s is the shear stress in the epoxy layer at a distance r from the x-axis. Integrating two sides of Eq. (3), we have

$$\tau_s = \frac{D\tau}{2r} \tag{4}$$

The relationship between u and τ_s can be expressed as follows:

$$\frac{du}{dr} = -\frac{\tau_s}{G} = -\frac{D\tau}{2rG} \tag{5}$$

where u is the axial displacement of epoxy at a distance r from the x-axis, G is the shear modulus of epoxy.

Substituting Eq. (4) into Eq. (5) and integrating both sides of the equation, we obtain

$$u = u_m + \frac{D\tau}{2G}\ln\frac{D}{2r} \tag{6}$$

where u_m is the longitudinal displacement of epoxy at the anchor–epoxy interface.

The displacement of the concrete at the anchor–epoxy interface in the x direction from the origin defines as u_c. Based on the fundamental assumptions, the u_c can be expressed as follows:

$$u_c = u_m + \frac{D\tau}{2G}\ln\frac{D}{D+2t} \tag{7}$$

Obviously, the difference between the anchor displacement along the positive direction of x-axis at a distance x from the origin, represented as u_s, and u_m, is equal to the bonding slip at the anchor–epoxy interface, so

$$u_s - u_m = \delta \tag{8}$$

If the anchor–epoxy interface behavior follows Eq. (1a), we have

$$\tau = \frac{2kG}{2G - kD\ln(D/(D+2t))}(u_s - u_c) \tag{9}$$

Differentiating τ in Eq. (9) with respect to x yields,

$$\begin{aligned} \frac{d\tau}{dx} &= \frac{2kG}{2G + kD\ln((D+2t)/D)}\left(\frac{du_s}{dx} - \frac{du_c}{dx}\right) \\ &= \frac{2kG}{2G + kD\ln((D+2t)/D)}(\varepsilon_s - \varepsilon_c) \\ &= \frac{2kG}{2G + kD\ln((D+2t)/D)}\left(\frac{\sigma_s}{E_s} - \frac{\sigma_c}{E_c}\right) \end{aligned} \tag{10}$$

where σ_c is the tensile stress of concrete at the epoxy–concrete interface. The function of σ_c can be obtained from [2]:

$$\sigma_c = \frac{P}{\pi b}A - \frac{D^2 A}{4b}\sigma_s \tag{11}$$