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Pull-out capacity of adhesive anchors: An analytical solution

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ABSTRACT

An analytical model for predicting the pull-out capacity of an adhesively bonded anchor loaded monotonically in tension is presented. The multi-layered axisymmetric assembly consists of an anchor, adhesive interlayer and the brittle matrix in which the anchor is embedded. The anchor is considered either as a transversely isotropic or an isotropic linear elastic material, while the adhesive is regarded as an isotropic continuum. Equilibrium equations in the radial and axial directions are uncoupled to obtain a pair of governing partial differential equations in terms of unknown displacements (radial and axial). The theoretical results are consistent with those obtained from finite element simulations. Analytical pull-out capacity predictions are also in good agreement with experimental results. A systematic parametric study is conducted using the developed mathematical model to study the influence of geometric and material parameters on the pull-out capacity of adhesive anchors. This study provides insights into the mechanics of stress transfer through the adhesive layer, influence of boundary condition at the embedded end of the anchor on stress fields and the design aspects of adhesive anchors.

1. Introduction

Fastening systems are very popular in the design and strengthening of concrete structures in construction projects where either the storeys are added in stages or there is a need for extension in current buildings. Anchorage systems are also extensively used for supporting tunnels, mines and for retaining walls. Broadly, anchorage systems are classified into three main categories, namely, cast-in and post-installed mechanical anchors, and adhesively bonded anchors. The load transfer between the rebar and the concrete in mechanical anchors is mainly achieved by either bearing or through friction whereas in adhesively bonded anchors load transfer occurs through shearing of adhesive layer along the entire bond length. Pre-installed cast-in anchors provide enhanced properties, however, adhesive anchors are more popular as they permit adjustments in location and allow for more flexibility. In some cases a single-bolt is anchored into the concrete whereas there are applications where a cluster of reinforcing bars is used.

The adhesive anchors are generally assembled by inserting a threaded rod or reinforcing bar into a drilled hole in hardened concrete [1,2]. Thermosetting structural resin such as epoxy, vinylester or polyester is then pumped into the hole to act as a bonding agent between the concrete and the reinforcement. Adhesive anchors are widely used in new constructions as well as for rehabilitation of structures because of their cost effectiveness and curing speed. The basic design criterion is to ensure that the adhesive layer has sufficient strength so that it can sustain the service loads. In a typical anchor, the reinforcing rod diameter is 13 or 16 mm, the adhesive layer thickness is 3.2–12.7 mm and the embedment length is more than 10 times the rod diameter [3].

The anchors are designed to sustain axial loads and the load transfer from the reinforcement rod to the concrete mainly occurs through shearing of lateral surfaces and interfacial tearing at the bottom (see Fig. 2(a)) of adhesive interlayer. Although for typical structural adhesives, the interfacial tensile strength is significantly higher than the interfacial shear strength, the tensile stress at the interface between the adhesive and the rod can reach beyond the tensile strength due to high stiffness of the reinforcements for smaller embedment lengths. In such cases, debonding can occur at the bottom of the adhesive where the anchor rod is bonded to the concrete. For anchor assemblies with larger embedment lengths and thin adhesive layers, the debonding may occur due to maximum shear stress at the lateral surface close to the loaded end which eventually propagates to the bottom surface. Another two possible failure modes include concrete failure (concrete cone failure) and the failure of anchor (steel breakage) itself (see for instance [4]). In Fig. 1 two possible failure mechanisms are depicted. Fig. 1(a) shows failure at the steel/adhesive interface whereas in Fig. 1(b) failure at

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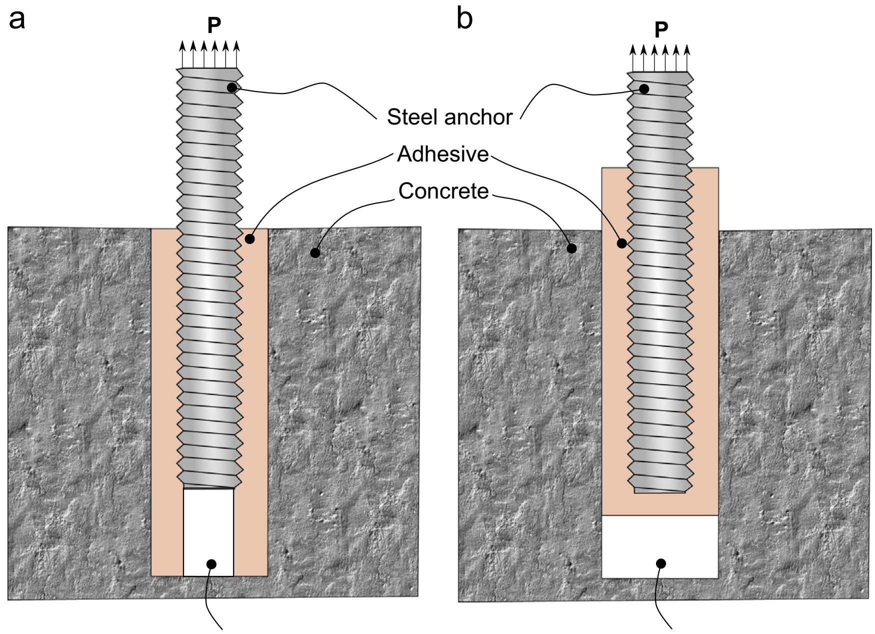

Fig. 1. Failure mechanisms in an anchorage system: (a) steel/adhesive bond failure and (b) concrete/adhesive bond failure.

concrete/adhesive interface is shown. Although it is cost effective to have smaller embedment lengths, the industrial anchor design specifications recommend larger embedment lengths with a thin layer of adhesive. Therefore, failure due to shear stress at the lateral bonded surface becomes very important.

Several researchers examined the anchor assembly problem experimentally. For instance, Colak et al. [5] conducted a series of experiments to study the effect of various design parameters such as embedment length, bondline thickness and the type of adhesive on the pull-out strength for both single and multiple anchors. Similarly, Stheeman [6] obtained a relationship between anchorage bolt parameters and the pullout strength by a thorough parametric study. Solomos and Berra [7] tested concrete anchors under tensile dynamic monotonic loading, relating to structural impact and blast conditions, employing the Hopkinson bar technique, for two different anchor diameters. Their investigation concluded that the anchors exhibit better strength properties under high strain rates as compared to the static loading conditions. Epoxy based adhesives exhibit viscoelastic behavior and therefore creep effects cannot be ignored. However, such effects are not significant for thinner adhesive layers but if the thickness of the adhesive layer is comparable to rod radius, creep effect needs to be considered especially when subjected to prolonged loading [8]. The long-term creep behavior of adhesive anchors under sustained tensile loads in combination with different environmental conditions has been studied very recently by Chin et al. [9] and their study indicated that the creep displacements under ambient conditions were insignificant, however, adhesive layer experienced noticeable creep deformation when exposed to moisture.

In an effort to understand the stress transfer across the interfaces several analytical solutions have been proposed for the anchor problem [10–15]. Many of these models assumed a uniform shear bond stress and therefore the spatial variation of shear stress as well as other possible failure modes was ignored [16]. Steel et al. [17] presented an analytical model considering different boundary conditions across the interface using shear-lag theory. Serrano et al. [18] obtained the tensile resistance of rock anchors using Euler's variational method in conjunction with a rock mass failure criterion of Hoek and Brown type. Their study also investigated the rupture surface shape though the rock mass. Using a simple tri-linear constitutive model for the shear bond slip, Benmokrane et al. [19] derived an equation relating the pullout strength and the embedment length. Continuing this work further they conducted cyclic tests on both pre-stressed and passive anchors with different embedment lengths.

Several studies have been conducted to study the stress transfer mechanism through the adhesive interlayer using finite element method. For instance, Kim et al. [20] studied the anchor problem numerically and conducted a series of finite element studies to provide insight into the load transfer mechanisms across adhesive interface. An elasto-plastic finite element analysis was conducted to predict the failure characteristics and the numerical results were compared with experiments. Recently, Prieto-Muñoz et al. [21] presented an elastic solution for anchorage system under tensile load for both bonded and debonded conditions which was further extended for viscoelastic materials [22] using correspondence principle.

Although there has been a significant body of literature, the load transfer and induced failure within the assembled anchor constituents is not fully understood. The most important aspect of an adhesive anchor design is the axial pull-out capacity which depends on the material and geometric properties of anchorage assembly. The task is to develop a theoretical framework so as to predict stress field in the entire assembly. Damage emanated from the location of peak stresses can potentially lead to adhesive/cohesive failure in the adhesive layer and/or the anchor rod. Therefore, this paper also focuses on the pull-out capacity of a single-bolt adhesive anchorage assembly.

2. Problem definition

Consider a cylindrical rod (steel/fiber reinforced plastic (FRP)) anchored into a concrete structure with an adhesive layer as shown in Fig. 2(a) and (b). The system is referred to a cylindrical coordinate system (r, θ, z) with origin at the bottom of the anchor as shown in Fig. 2(b) and (d). The radius of the anchor is a and the embedment length is L. P is the applied tensile load and σ_0 is the corresponding stress applied to the anchor. Here, thickness of the adhesive layer (denoted as t) is small compared to other dimensions of the anchor assembly. These types of anchor assemblies are designed to carry loads primarily in the axial direction. Therefore,