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Debonding along the fixed anchor length of a ground anchorage

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ABSTRACT

Ground anchorages are the main means of support used for safety aspects in mining and tunnelling industry. Poor installation of ground anchorages can result in partial debonding between the tendon and the grout. The effects of debonding on the load carrying capacity of a model anchorage are examined by pull out tests. The load carrying capacity is found to decrease with increasing length of pre-existing debonding at the tendon–grout interface. The fracture toughness of the tendon–grout and of the ground–grout interfaces is measured over a wide range of mixed-mode loading and the results are used to assess the likelihood of debonding at the interfaces in a ground anchorage system.

1. Introduction

Ground anchorages are safety critical elements for supporting structures like tunnels, mines and retaining walls. There are numerous ways of classifying anchorages: active or passive, depending on whether they are pre-stressed or used as reinforcement; and single or multi-strand, depending on whether the tendon is a bolt or a cluster of strands. This paper considers a single, active rock anchor system.

The main components of an anchorage system are the tendon, an anchor head assembly (bearing plate and a nut), and the grout [1] (see Fig. 1). The grout is made of resin (usually polyester based) or a cement mixture, while for a rock bolt, the tendon is usually made of steel.

Rock bolts are bonded to the surrounding rock mass along the fixed length (Fig. 1) and, if active, are tensioned. The role of the bond is to transfer the load from the tendon (e.g. steel bar or bolt) to the surrounding rock mass or ground. Thereafter, the terms rock and ground are used interchangeably to denote the surrounding material that is bonded to the tendon through the grout. The unbounded length the tendon is classified as free length (if within the ground) and protruding length (outside the ground), see Fig. 1. A pre-tensioned tendon induces a compressive stress in the surrounding rock mass which consequently inhibits cracking of the rock and thus enhances the stability [2]. Differential movement of the rock mass can also induce compressive stress in the surrounding rock.

During installation of an anchorage or in service, cracks may initiate and grow within the anchorage system leading to loss of load carrying capacity [2]. The cracks may initiate within the grout, at the tendon/grout interface or rock/grout interface, while the tendon may fail during installation especially in passive anchorages. Further, ingress of ground water may lead to corrosion of the tendon resulting in the development of tendon/grout interface crack [2]. The actual location of failure in a particular application depends on the mechanical and fracture properties of the materials, the characteristics of the interfaces, and the compatibility of the grout with the bolt and surrounding rock. For a steel tendon, the strength and toughness of the steel are much greater than the corresponding parameters for the grout, surrounding rock and the interfaces. It is not surprising therefore that most observed failures of anchorages in practice occur at one of the two interfaces: rock/grout and tendon/grout interfaces [3–5]. Thus, the strength and toughness of these interfaces play a major role in determining whether an anchorage can withstand the load they are designed to hold. It is therefore important to understand the role and characteristics of the interfaces since they influence significantly the overall performance of the anchor system. Surprisingly, the quantification of the interface toughness and the relationship of the toughness to failure mode and location has received little attention in the literature on ground anchorages.

Currently, the assessment of the load carrying capacity of ground anchorages is based on analysis of the induced stresses in a "perfect" anchorage (i.e. no defects). Consider an anchorage consisting of a tendon (e.g. steel bolt) and grout with Young's modulus E_s and E_c, respectively, and bolt and borehole diameter d_s and d_h, respectively. Let the Young's modulus of the surrounding rock

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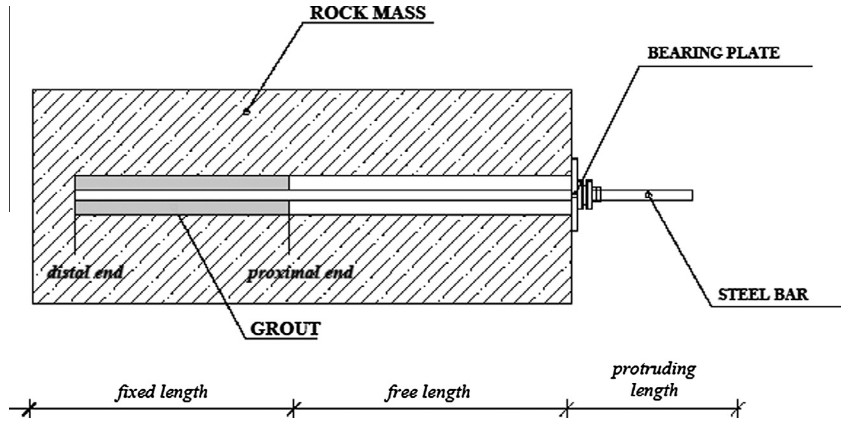

Fig. 1. A schematic diagram of a ground anchorage system.

mass or ground be E_g. When the tendon, which is assumed to be perfectly bonded to the grout along the fixed anchor length, is subject to a uniaxial tensile stress P, the induced interfacial stresses along the fixed anchor length are function of E_c/E_g and the relative diameter of the tendon to that of the borehole, d_s/d_h.

Linear elastic finite element analysis of a cylindrical anchorage with 'perfect' bonding shows that the shear stress at the ground/grout interface decreases in magnitude from the proximal end to the distal end of the anchor, while the magnitude of the maximum shear stress increases with decreasing value of E_c/E_g [6], see Fig. 2. For ground anchorages installed in hard rocks, E_c/E_g ranges between 0.1 and 1, which according to Fig. 2, produce a power-law distribution of shear stress along the fixed length. (Recall that E_c is the Young's modulus of the grout while E_g is the Young's modulus of the ground or rock mass.) However, design standard for ground anchorages, e.g. BS8081 [2], is based on a uniform shear stress distribution. For soft rocks ($E_c/E_g \geqslant 10$), the load distribution is more uniform. As the maximum shear stress occurs at the proximal end where the ground/grout interface intersects the free length section, interfacial debonding or crack is therefore more likely to initiate from that end.

The interfacial stresses in addition to being governed by elastic properties of the materials, are also influenced by the geometry of the borehole and tendon. For a given size of the tendon, the shear stress at the ground/grout interface becomes more uniform along

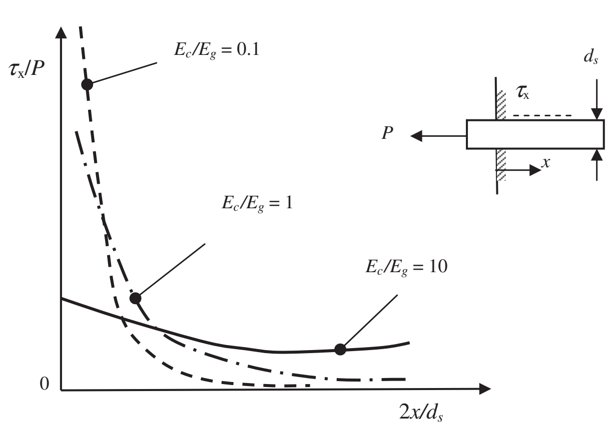

Fig. 2. A schematic of the normalised shear stress along the anchor length at the grout/ground interface as function of moduli ratio, E_c/E_g. Here E_c and E_g are the Young's modulus of the grout and the ground respectively, d_s is the bolt diameter, and other parameters are as defined in the insert. Adapted from Coates and Yu [6].

the interface and the magnitude of the stress decreases with decreasing diameter of the borehole resulting in increased load capacity of the anchor system as the borehole diameter is reduced [7–9]. Thus, for a given bolt size and grout type, the load capacity of the anchorage increases with decreasing borehole diameter (or decreasing radial thickness of the grout). This is consistent with the fracture response of adhesively bonded sandwiched joints where it has been shown for plane strain geometry subject to remote tension that the fracture stress increases with decreasing thickness of the adhesive layer [10,11]. Thus, a higher bond strength and anchorage load capacity can be achieved with a reduced annulus of a perfectly bonded anchor system. However, this has implications for the installation of anchorages as it limits the volume of grout available for bonding which could lead to the development of unbounded patches during installation. Consequently, there have been few experimental studies to examine the effects of dimensions and material properties on the load capacity of anchorages.

For example, Ivanovic and Neilson [12] carried out experiments using scaled laboratory model of anchor systems consisting of a concrete to simulate the ground, an epoxy resin grout and steel rebar; $E_c/E_g = 0.3$ and $E_c/E_s = 0.06$. The rebar had a diameter of $d_s = 22$ mm and the borehole had a diameter of $d_h = 30$ mm. The applied axial load for perfectly bonded rebar increases almost linearly with increasing axial displacement until failure occurred at the concrete/grout interface; the failure load increases with increasing fixed anchor length. There was a drop in load following the initiation of the debonding, and subsequently the sliding of the rebar occurred at almost a constant load. However, in a separate study by Benmokrane et al. [5] where cement grout was used ($E_c/E_g = 1$ and $E_c/E_s = 0.2$), and the diameter of the steel bar and borehole was 15.8 mm and 38 mm respectively, failure occurred at the tendon/grout interface. The difference in the location of the interface failure was believed to be due to the difference in the thickness of the annulus used in the two studies as well as the difference in materials used for grouting; but this was not verified.

The initiation and growth of debonding at the tendon/grout and ground/grout interface involves frictional sliding. Hence the load capacity of ground anchorages is influenced by the level of normal pressure on the interface. The effect of normal pressure on load capacity of anchorages is usually assessed either by applying a uniform constant confining pressure to a model anchorage or by using an outer shell with a relatively high stiffness to represent the surrounding rock mass [13–16]. In the latter, which is closer to what happens in the field, the magnitude of the radial confining pressure increases as the applied load increases due to the resistance to