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Analytical model of shear behaviour of a fully grouted cable bolt subjected to shearing

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ABSTRACT

A fully grouted cable bolt is normally loaded at rock joints by a combination of the axial and shear forces causing both axial extension and shear deformation of the cable. The proposed analyses presented here attempts to predict the joint shear strength and shear displacement. The analyses are based on the statically indeterminate beam theory and some basic findings and conclusions of other researchers. Parametrical investigation is performed on four influence factors including bolt pretension, joint friction angle, concrete strength and bolt installation angle. Although the true plastic moduli of the cable bolt deflecting section at failure are the essential parameters in this analysis, they are practically impossible to determine. Thus, the average cable moduli obtained from the cable tensile strength tests were used. The proposed analytical model was compared with the experimental results, showing a good agreement. This analytical work aims to develop a simple tool for the practicing geotechnical engineer to effectively evaluate the cable shear behaviour and the influence of fully grouted cable bolts on joint shear resistance.

1. Introduction

Rock bolting (rebar bolting and cable bolting) is a widely used technique for reinforcing rock masses both in mining and civil engineering projects[1,2]. Rebar bolt is a single solid steel tendon, while cable bolt is a flexible tendon composed of multi-wire strand which is normally installed and grouted in drilled holes to provide reinforcement in rock masses[3]. The main feature of rock bolting is to reinforce unstable rock strata. Naturally, in the past attention was given mainly to the tensile behaviour of rebar bolts and cable bolts on the studying of the axial stress distribution in bolts and the load transfer mechanism along the bolt–grout interface. However, a better understanding of the bolt performance in tension and shear is essential to optimise the bolt design and to assess a reinforcing system. This is important for reinforcement of weak or sedimentary rock especially in areas of thinly-laminated strata, high horizontal stress or highly jointed and faulted rock mass.

In recent times, attentions have been given to the lateral interaction between bolts and surrounding rock due to the increasing understanding of the axial load transfer mechanism of rock bolting. Several early publications in the 1970's[4–6], 1980's[7–14], and 1990's[2,15–19] described the shear behaviour of rebar bolts across rock joints. However, during this period, fewer experts devoted themselves on cable bolting. The earliest published tests on the interaction of joints and cable bolts were conducted by Goris[20] as well as Dolinar[21] in 1996, followed by Craig and Aziz[22,23].

The shear behaviour of cable or rebar bolts and their contribution to joint shear strength is heavily influenced by a number of factors, such as the strength of host material[2,15,22,24,25], annulus grout thickness[26], axial pretension load[2,7,8,24], grouted or ungrouted bolt[20], bolt installation angle[5,7,8,11,15,27,28], joint roughness coefficient (JRC)[13,15,20,22], loading rate, loading time (creep effect), bolt diameter[15] and cable strength. Some of these factors have been studied in depth, whereas others were rarely analysed. Due to a large number of factors influencing the bolt performance, some of the conclusions in these reported publications contradict each other. For example, in the analysis of the influence of bolt installation angle on bolted joint, Azuar[27], Spang and Egger[15], Ge and Liu[29], and Grasselli[28] pointed out that bolt installation angle clearly influenced the shear strength of bolted joint, whereas Hibino and Motojima[8] stated that the bolt installation angle did not increase the bolted joint shear strength. This may be due to researchers did not always systematically consider the relevant factors influencing the bolt behaviour.

A theoretical model concerning the behaviour of a single grouted cable bolt was developed with consideration of various factors mentioned above. The performance of a cable intersecting a joint was investigated and a theoretical relationship between the axial and lateral load components was mathematically derived. The maximum joint shear resistance and joint shear displacements were determined by

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combining the cable failure criteria and the loading state derived from structural mechanics analysis.

The effect of all related influencing factors mentioned above were analysed and compared with the existing studies[2,15]. In addition, this analytical model was also compared with experimental test results to confirm its validity.

2. Mechanical model

When a grouted rebar bolt or cable bolt in rock is subjected to shearing, the bolt deforms and two plastic hinges form at both sides of the joint plane. For the slow rate of loading, reaction forces in the host material (grout and rock) are mobilised and all forces are in equilibrium. Both the bolt and the host material experience the elastic stage and the plastic stage successively.

During loading, the reinforcement bolt and the host material progress from the elastic stage to the plastic stage. In the elastic stage of the host material, the reaction force is roughly proportional to its elastic compression[30,31]. According to Ferrero's study[2], the shape of the bolt deflecting section can be approximated with a parabolic equation. Thus it is reasonable to assume the reaction force distribution exhibits the same shape in the elastic stage. In the plastic stage of the host material, the reaction force remains constant since the bolt crushes into the host material[32]. Thus a constant uniform distribution of the reaction force is assumed for the plastic stage of the host material.

During shear loading, the bolt moduli decrease from the perfectly elastic state to the fully plastic state along the bolt length, and the reaction force varies from a parabolic distribution to a constant distribution.

According to the analysis of plastic hinge formation, the distance from joint to plastic hinge is normally less than 3–4 times the bolt diameter for most commonly used bolts. In Jalalifar's tests[33] on steel rebar bolts, this length was normally less than 60 mm which is less than three times the bolt diameter. In addition, when a bolt deflects due to shearing, the tension and compression loads between bolt and the host material are produced on the top and bottom sides. Since the cohesion between the host material and the bolt is very small, the grout on the tension side can easily detach from the bolt surface. After the grout and rock yields within the compressive zone, the host material is crushed and unable to bear higher compressive load. Based on the above analysis, the frictional effect between the host material and the bolt is negligible as assumed in several previous studies[18,34].

An assumption is made here that the deflecting section of a bolt between two plastic hinges is statically indeterminate with two fixed ends. Two different mechanical models with elastic reaction and plastic reaction are shown in Fig. 1, respectively.

3. Bolt contribution to joint shear strength

There have been various analytical and experimental investigations undertaken looking at the cable and rebar bolts and their contribution to joint shear strength. These studies suggest that two types of contribution, the frictional effect and the dowel effect, are made by a bolt to the joint shear strength. Fig. 2 shows the typical loading state of a bolt–reinforced joint.

The bolt contribution to joint shear strength is:

$$R = N_o \cos(\alpha - \theta) + Q_o \sin(\alpha - \theta) + [N_o \sin(\alpha - \theta) - Q_o \cos(\alpha - \theta)] \tan \varnothing \quad (1)$$

where R is the bolt contribution to joint shear strength; N_o, Q_o are the tensile and shear force components of a bolt at the bolt–joint intersection, respectively; α is the bolt installation angle to the joint; θ is the deflection angle (bending) of bolt.

There are two different dowel effects. One is related to the combination of the parallel components of the axial and shear forces of the bolt to the joint[18,28,33]:

$$R_{dowel} = N_o \cos(\alpha - \theta) + Q_o \sin(\alpha - \theta) \quad (2)$$

The other one is connected to only the bolt shear force itself, including the normal component and the parallel component of the bolt shear force to the joint which produce indirect and direct contribution respectively to the joint shear strength[2]:

$$R_{dowel} = Q_o \sin(\alpha - \theta) - Q_o \cos(\alpha - \theta) \tan \varnothing \quad (3)$$

In this paper, the direct contribution of both the axial and shear forces is considered as the dowel effect, thus the first expression, Eq. (2), was used.

4. Theoretical analysis

4.1. Elastic stage of the Host material

To solve a statically indeterminate beam problem, first one needs to transform the original problem into a statically determinate beam by removing all redundant reactions[35]. In this problem, there are three redundant reactions that can be removed. Considering half of the beam, a combination of axial force R_1, shear

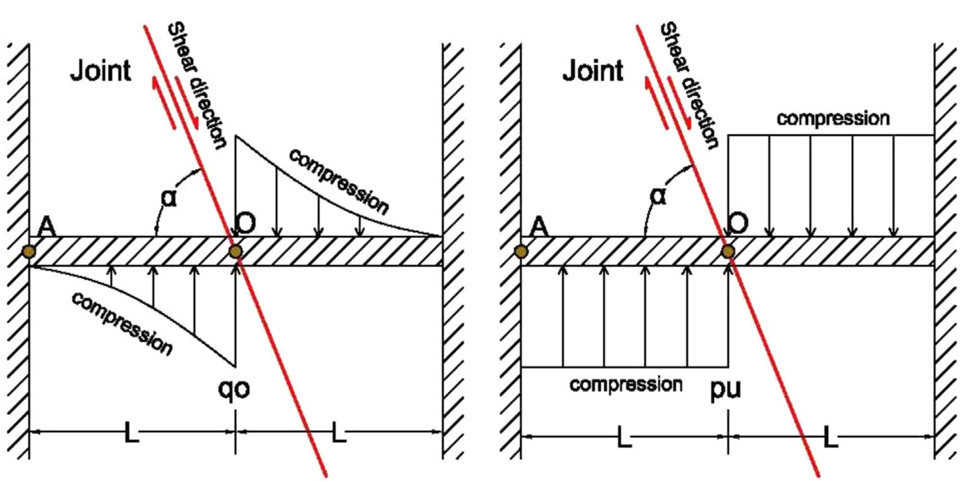

Fig. 1. Simplified mechanical models of a tendon subjected to shearing both in elastic and plastic subgrade.