Journal of Rock Mechanics and Geotechnical Engineering 6 (2014) 428–437

Contents lists available at ScienceDirect

Journal of Rock Mechanics and Geotechnical Engineering

journal homepage: www.rockgeotech.org

Full length article

Experimental study and stress analysis of rock bolt anchorage performance

Yu Chen*

Department of Geology and Mineral Resources Engineering, Norwegian University of Science and Technology (NTNU), Trondheim 7491, Norway

A R T I C L E I N F O

Article history:
Received 18 March 2014
Received in revised form
13 June 2014
Accepted 25 June 2014
Available online 7 August 2014

Keywords:
Rock bolt
D-Bolt
Pull-and-shear
Stress
Bending
Joint gap
Rock strength

A B S T R A C T

A new method was developed to apply pull-and-shear loads to the bolt specimen in order to evaluate the anchorage performance of the rebar bolt and the D-Bolt. In the tests, five displacing angles (0°, 20°, 40°, 60°, and 90°), two joint gaps (0 mm and 30 mm), and three kinds of host rock materials (weak concrete, strong concrete, and concrete-granite) were considered, and stress–strain measurements were conducted. Results show that the ultimate loads of both the D-Bolt and the rebar bolt remained constant with any displacing angles. The ultimate displacement of the D-Bolt changed from 140 mm at the 0° displacing angle (pure pull) to approximately 70 mm at a displacing angle greater than 40°. The displacement capacity of the D-Bolt is approximately 3.5 times that of the rebar bolt under pure pull and 50% higher than that of the rebar bolt under pure shear. The compressive stress exists at 50 mm from the bolt head, and the maximum bending moment value rises with the increasing displacing angle. The rebar bolt mobilises greater applied load than the D-Bolt when subjected to the maximum bending. The yielding length (at 0°) of the D-Bolt is longer than that of the rebar bolt. The displacement capacity of the bolts increased with the joint gap. The bolt subjected to joint gap effect yields more quickly with greater bending moment and smaller applied load. The displacement capacities of the D-Bolt and the rebar bolt are greater in the weak host rock than that in the hard host rock. In pure shear condition, the ultimate load of the bolts slightly decreases in the hard rock. The yielding speed in the hard rock is higher than that in the weak rock.

1. Introduction

Rock bolts have been widely used as the primary support element to stabilise the rock masses around tunnels, mines, slopes, and other structures in association with rock masses. For better understanding of rock bolt performance, several studies have been carried out by laboratory and field tests, analytical methods, and numerical analysis (Stille et al., 1989; Indraratna and Kaiser, 1990; Stillborg, 1994; Stjern, 1995; Huang et al., 2002; Cai et al., 2004; Malmgren and Nordlund, 2008; Carranza-Torres, 2009; Bobet and Einstein, 2011; Li, 2014; Lin et al., 2014). According to practical engineering experiences, rock bolts may be subjected to pull-and-shear loadings in field. Following this point of view, many studies focused on rock bolt performance under shear loading and different grout media (Bjurstroem, 1974; Hibino and Motojima, 1981; Spang and Egger, 1990; Holmberg, 1991; Jalalifar et al., 2006; Jalalifar and Aziz, 2010). There may be installation shortage of these tests if the angle between the bolt and the joint plane is less than 45°. The friction on the joint surfaces is not negligible as well.

The strain and stress distributions on the bolt surface are another interesting issue, and many researchers have examined the strain and stress distributions using either pull or shear conditions by laboratory tests and analytical methods (Ferrero, 1995; Stjern, 1995; Grasselli, 2005). Farmer (1975) carried out fundamental work on studying the axial behaviour of the bolt subjected to tensile load and demonstrated that the shear stress at the bolt–grout interface would attenuate exponentially from the loading point to the far end of the bolt before decoupling occurs. Li and Stillborg (1999) presented a model of the shear stress distribution along a fully encapsulated rock bolt in tension. In their model, the elastic, softening, and debonding zones were taken into account. Grasselli (2005) analysed the strain gauge data recorded during shear test and verified that the plastic hinges operate as obstacles to stress propagation. The formation of hinges is characterised by compression and tension on both sides of the bolt.

The aim of this paper will concentrate on the performance of rebar bolt and D-Bolt with the influence of displacing angle, rock strength, and joint gap. A new method is developed to apply a

* Tel.: +47 73594808.
E-mail addresses: joyidol1013@hotmail.com, yu.chen@ntnu.no, joyidol@163.com.

Peer review under responsibility of Institute of Rock and Soil Mechanics, Chinese Academy of Sciences.
1674-7755 © 2014 Institute of Rock and Soil Mechanics, Chinese Academy of Sciences. Production and hosting by Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.jrmge.2014.06.002

combined pull-and-shear loading to the bolt specimens, and strain distribution on the bolt surface is recorded during the test.

2. Analytical aspect

When a bolted rock joint is subjected to pull-and-shear loading, the bolt deforms with increasing joint displacement, and this can mobilise an axial load N and a lateral load Q (Fig. 1) (Marenče and Swoboda, 1995). In the elastic region, the bolt deforms as a curve and has two critical points: one in the bolt-joint intersection with zero bending moment (point O) and the other with the maximum bending moment with zero shear stress (point A) (Jalalifar et al., 2006; Jalalifar and Aziz, 2010). The stress resultants are decided by the bending moment M, the axial load N, and the lateral load Q. On the basis of the beam theory, the uniform stress distribution "$\sigma = N/A$" exists along the bolt. The bending moment produces a linearly varying stress $\sigma = \pm(My/I)$, with tension (positive) on the upper part of the bolt and compression (negative) on the lower part. The final distribution of axial stress is obtained as follows:

$$\sigma_1 = \frac{N}{A} + \frac{My}{I} \tag{1}$$

$$\sigma_2 = \frac{N}{A} - \frac{My}{I} \tag{2}$$

where σ_1 and σ_2 are the axial stresses acting on the upper and lower bolt surfaces, respectively; A is the area of bolt cross-section; I is the moment of inertia; and y is the distance to neutral axis.

By combining Eqs. (1) and (2), the bending moment can be calculated by

$$M = \frac{(\sigma_1 - \sigma_2)I}{2y} \tag{3}$$

The resulting strains and stresses in the bolt are directly related to the curvature of the deflected bolt (Fig. 1). Strain value was recorded by strain gauges in the bolt test. According to the stress–strain curve of standard tensile test, stress value can be calibrated from strain value. Thus, the bending moment can be obtained via Eq. (3). As the pull-and-shear loading increases, the surrounding medium generates a reaction on the bolt length. It increases progressively until the bolt reaches the yield limit.

3. Test design

3.1. Testing method and configuration

A new test method was developed to simulate the pull-and-shear loading condition on the NTNU/SINTEF bolt test rig (Fig. 2). The pull-and-shear loads are applied separately by two hydraulic cylinder systems. The angle between the pull displacement and the shear displacement is defined as *displacing angle* (α). The angle between the pull load and the shear load is defined as *loading angle* (θ). Previous shear tests of rock bolts (Ludvig, 1984; Spang and Egger, 1990; Jalalifar et al., 2006) showed that the angle between the bolt and the joint surface (i.e. displacing angle) may not be less than 45° practically for installation. In order to overcome this shortage, the displacing angle (α) in our study is designed to be adjusted in the range from 0° (pure pull) to 90° (pure shear) by distributing the pressurised oil to the pull-and-shear cylinders individually. Another advantage of this test method is that no joint friction is involved because two concrete blocks are apart from each other during testing.

The rock mass is simulated by two cubic concrete blocks with a side length of 0.95 m. The concrete cubes were placed in the frame of the test rig after a curing period of at least 30 days. Boreholes were then pneumatically drilled with 33-mm drill bits. After that, cement mortar with a water-to-cement ratio of 0.32 was pumped into the boreholes, and the bolt specimen was inserted into the hole. The strength of the cement grout is about 65 MPa after 3 days of curing. The plate load was recorded by a load cell under the bolt plate. Roller bearings were installed between the blocks and the frame of the rig, aiming to get rid of the frictional resistance between them as well as to guide the blocks. The roller bearings and frame can also prevent the rotation of the concrete blocks during the test. The loading capacity of the two axial cylinders for pull is 500 kN (2 × 250 kN), and the capacity of the lateral cylinder for shear is 600 kN.

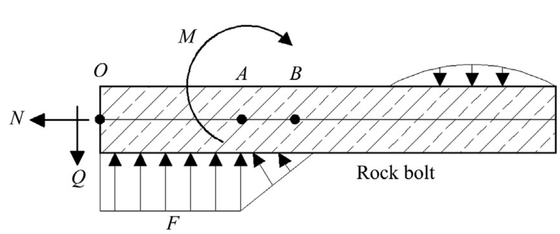

Fig. 1. Loading condition of bolt during pull-and-shear loading (Marenče and Swoboda, 1995).

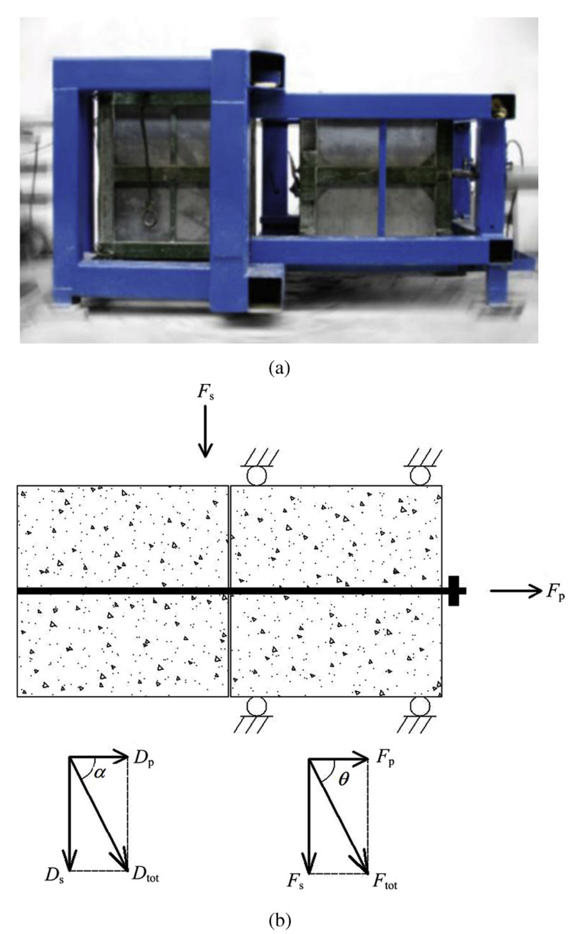

Fig. 2. SINTEF/NTNU bolt test rig. (a) Full-scale test rig in laboratory; (b) Top view sketch.