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Effect of grout strength on the stress distribution (tensile) of fully-grouted rockbolts

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ABSTRACT

The paper deals with and axial stress distribution (ASD) obtained from pull-out tests of strain gauged rockbolts in high strength rock media. For this purpose, an experimental research was conducted considering the only axial forces acting on fully grouted rockbolts (FGR). Strain gauges were used to observe the behavior of rockbolts and to determine the load transfer mechanism of the bolts to rock mass. In the test, five grout mixture having different properties was prepared and stress–strain mechanism of the bolt-grout interface was investigated for these conditions. ASD was demonstrated elastic load transfer behavior from the rockbolt to the outlying rock under the applied load (for each grout type) and stress concentration was rather a high level at 70 mm distance from rock surface. Axial stress curves drawing with the aid of strain readings were showed the regular distribution with increasing of grout stiffness. The test results of strain gauged rockbolts show that the shear stress distribution (SSD) is uniform and, the style of the distributions along the rockbolt was similar under various loading levels for all grout types. Shear stress was rather a small amount at the pulling end of rockbolt but it reached the peak after a short distance away from the pulling end of rockbolt and subsequent to peak value decayed rapidly with the load increase. The results were showed that strength properties of grout played an important role in SSD and ASD along the rockbolt. The increase in grout strength and rigidity made the stress distributions regular along the rockbolt.

1. Introduction

Bolting provides stability by increasing the anchorage capacity of rock mass at the confines of an underground excavation. Rockbolts can combine support effects (shotcrete, steel mesh-arches) with reinforcement effects (bolting). Their use is usually the unrivalled way of supplying stability to excavations in problematic rock formations, before final concrete lining. Rockbolts are widely used as the main support instrument to stabilize the decoupled rock blocks around tunnels, dams, mines, slopes and other engineering construction apropos of rock masses. Yet another duty of rockbolts is restraining the deformation therein the rock masses. It is important to understand how rockbolts behave in deformed rock masses to improve bolting design. This can be accomplished by studies (laboratory tests, numerical and analytical studies and field modeling) to be conducted by researchers. For a better understanding of rockbolt performance and interaction between rockbolts and rock mass, several studies have been carried out using laboratory and in-situ test results.

A significant part of literature related rockbolts was focused on analytical methods and numerical analysis (Stille et al., 1989; Indraratna and Kaiser, 1990a, 1990b; Stillborg, 1994; Li and Stillborg, 1999; Cai et al., 2004; Carranza-Torres, 2009; Martin et al., 2011; Ma et al., 2013, 2016; Nie et al., 2018). In practice rockbolts are exposed to axial and shear loads. From this point of view, many researchers were attending to rockbolt performance under shear loading and different grout (Bjurstroem, 1974; Spang and Egger, 1990; Holmberg, 1991; Reed et al., 1993; Kılıç et al., 2003; Jalalifar and Aziz, 2010; Martín et al., 2013; Spearing et al., 2013). Another study issue was stress distributions along the bolt length. Some researchers have examined the deformation and stress distributions using either pull or shear conditions by laboratory tests and analytical methods (Farmer, 1975; Stjern, 1995; Hyett et al., 1996; Grasselli, 2005; Ivanović and Neilson, 2009; Chen, 2014).

Taking account of softening, elastic and debonding rock zones, Li and Stillborg (1999) presented three analytical model of the shear stress distribution (SSD) along with a full contact rockbolts in tension. The purpose of their analytical model was to explain the mechanical coupling at the interface of bolt-grout for fully grouted rockbolts (FGR) or

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between the bolt-rock for fractioned rockbolts. Ma et al. (2013) presented an analytical model for the FGR on which axial loads are effective. They based their model on the bond-slip relationship, which describes the mechanical interaction at the rockbolt-grout interface. They also derive formulas for the load-displacement curve, axial stress distribution (ASD) in the bolt and SSD at the rockbolt–joint interface. Martín et al. (2013) presented a method to attain the bolt-grout interface behavior of FGR under axial loading conditions at laboratory studies. Farmer (1975) carried out the first basic work and proposed an analytical solution for the axial behavior of the rockbolt under axial forces. The work of the Farmer showed that the shear stress at bolt-grout interface exponentially reduced towards the other end of the bolts from the load applied section before decoupling. This theory was valid only for rockbolts were subjected to low axial loads. Grasselli (2005) was conducted a series of experimental tests combined with numerical simulations. He has analyzed the strain gauge readings recorded during the shear test. Finite element modeling results and shear test results for reinforced with FGR and Swellex bolts shows that the two-rockbolt types deform in different ways while responding to shear loads.

Ivanović and Neilson (2009)'s non-linear bond-slip model was concerned with the behavior of rockbolts under dynamic load effects. Their model is the first method of describing the dynamic effects of debonding on a rockbolt without full-scale testing. For the first time in the 1970s, Freeman (1978) monitored loading process and the distribution of stress in Kielder experimental tunnel. Both in-situ and laboratory tests have shown that in most cases the failure of FGR takes place by debonding at the interface of grout-rock or bolt-grout. This study has pioneered other studies related to the understanding of the transfer mechanism of load between the ground and the rockbolt. The researchers had the idea that an internal gauge would be too expensive to be used as a tool with cables in underground excavations. Another problem is the possibility that the external gauges on cables may fail due to water flow cable-loading starts (Goris et al., 1993).

Signer (1990) is another researcher conducting field tests to understand the support interaction mechanism between coal mine roofs and FGR. Signer was aimed improving design and evaluation techniques. Signer was used fully grouted strain gauged rockbolts placed in shale formation at four mines in the US to determine how the load was transferred between the rock and bolt. Signer et al. (1997) continued the research using strain-gauged rockbolts in gate roads of the coal mine and determined that, even though the bolts were plated, they displayed the characteristic behavior predicted by the axial continuum theoretical model without a faceplate. Zhang et al. (2006) reported that tendons (fiber-reinforced polymer 9-bar) used their studies give effective results in post-tensioning applications. Some of the tools they use to determine the rockbolt behavior and the load transfer mechanism to the rock mass are embedded gauges, sensors, and displacement transducers. Zhao et al. (2015) were used the self-developed test apparatus to study the distribution of axial force and interfacial stress of rockbolts. Their study based on the force analysis and mechanical transmission mechanism of FGR.

The results of the field and laboratory tests conducted by various authors (Ostermayer and Scheele, 1978; Weerasinghe and Littlejohn, 1997) show that the bolt bond stresses are non-uniform for all level of axial forces. So that, it is necessary to determine the real mechanism of load distribution, displacement, and bond stress along the rockbolt in order to economical design the rockbolt with enough safety factor.

The performance of fully grouted rockbolts is understood quite well in a general sense, but it is not so clear how rockbolts behave in different grout media. The aim of this paper is to explain the axial and SSD behavior of FGR under axial load and different grout conditions. Unstable rock blocks and ground caused injuries-fatalities around openings continues to be a safety concern especially underground mines. For this reason, stability and design analyses should be conducted early in a mine. Strain gauged rockbolts using can contribute to solving such problems. Strain-stress values derived from close to underground openings by strain gauges will give design engineers a tool for the selection of support system for improving underground safety. By predicting the behavior of rockbolts in different grout media, economic and security problems can be avoided to the greatest extent possible.

Table 1
Physico-mechanical properties of intact rock (basalt) placed in rockbolts.

Rock properties	Unit	Averaged test results
Uniaxial compressive strength	MPa	142.21 ± 5.46
Young's modulus	GPa	38.42 ± 4.48
Brazilian tensile strength	MPa	14.17 ± 2.34
Flexural tensile strength	MPa	15.59 ± 0.76
Point load strength index	MPa	10.27 ± 1.60
Impact strength	MPa	18.40 ± 3.58
Double shear strength	MPa	13.18 ± 1.02
Schmidt rebound hardness	rebound	55.60 ± 2.10
Dry unit volume weight	gr/cm^3	2.700 ± 0.005
Effective porosity	%	2.968 ± 0.003
Water absorption	%	1.099 ± 0.003

2. Experimental methods

The monitoring of the axial force as a function of the distance to the loading point can be achieved by placing the strain gauges along the embedded length of the rockbolt. The data to be obtained in this way is very valuable in confirming analytical approaches (Martin et al., 2011). Pull-out tests were realized on strain-gauged rockbolts that embedded into massive basalt rock with grout to obtain stress distribution curves. Pull-out tests were also conducted to determine the bearing characteristics of the rockbolts. For the pull-out test, a high strength basalt was chosen to prevent rock failure. Basalt blocks (Table 1) were prepared smoothly and sized at a natural stone factory in Osmaniye/Turkey. The dimensions of each basalt block were 15 × 19 × 60 cm.

The strain-gauged rockbolts having 12 mm diameter were embedded in boreholes having 24 mm diameter. A manual hydraulic pull test device with a capacity of 150 kN was used to load the strain gauged rockbolts. In order to compare five different grout types to each other, all pull out tests were carried out at the same loading rates. A very low loading rate was applied to obtain reliable data from strain gauges (1 mm/min). The pulling loads and strain values were computed by a computer controlled data logger (TDG AI8b) with eight channels (Fig. 1).

The strain gauges were bonded to directly to the surface of rockbolts. Therefore, the strain experienced by the rockbolt was transferred directly to the strain gauge which responded with a linear change in electrical resistance. To measure these small changes in resistance, strain gauge configurations were based on the Quarter-Wheatstone bridge concept (Eq. (1)). The completion box was made that provided 5-V excitation voltage and completion resistors for the Wheatstone bridge circuits used to measure strain gauge voltage changes. When pulling loads exceeded the yield point of the rockbolt, voltage changes in the data logger were converted to strain readings, and these strain values (Eq. (2) and (3)) were used for the draw of stress distribution graphics.

$$V_0 = (GF \cdot \varepsilon \cdot V_i \cdot K)/4 \quad (1)$$

$$\varepsilon = (4 \cdot V_0)/(GF \cdot V_i \cdot K) \quad (2)$$

$$\varepsilon = \Delta L/L \quad (3)$$

where V_0; voltage change (volt), ε; strain, GF; gauge factor (The ratio of the fractional change in electrical resistance to the fractional change in length), V_i; excitation voltage (volt), K; channel gain coefficient of data logger; ΔL; change in length of rockbolt; L; embedded length of rockbolt.

A range of measures has been taken to reduce the effect of wiring.