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A new optical sensing technique for monitoring shear of rock bolts

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ABSTRACT

In addressing limitations of conventional ground support measurement, a novel optical strain sensing technique is presented that is capable of measuring strain at increments as low as 0.65 mm along the entirety of an optical sensor affixed to a support element. The technique considers monitoring three sensing lengths along the profile of a fully grouted rock bolt element using a single optical fiber, which, in turn, allows the derivation of both the principle strain and principle strain direction along the bolt. A series of three experiments, which include: symmetric bending, combined axial load and bending, and double shear loading are presented and highlight the potential of the technique to capture bolt behaviour under such generalized rock bolt loading conditions. Analogized as a distributed strain rosette, the optical technique can distinguish both the coaxial and bending induced constituents of the total strain in the bolt regardless of load orientation.

1. Introduction

Fully grouted rock bolts are a commonly used reinforcement technique in underground mining and civil projects. The bolting system consists of a steel rebar element which is inserted into a borehole, encapsulated with either a cementitious or a resin grout, and fastened to the excavation surface with the use of a nut and face plate assembly. In many cases, a low level of post-tension (~25% of the bolt's yield capacity) is applied coaxial with the rock bolt after installation. This tension acts to provide a level of immediate active support to the excavation surface by transferring load to more competent rock further within the rock mass. However, fully grouted rock bolts are primarily passive reinforcement elements. This implies that the majority of the bolt's reinforcement capacity is mobilized as a result of the subsequent rock mass movements. Therefore the distribution of the rock mass displacements (continuous versus discontinuous), dictates the induced load profile along the rock bolt.

Rock bolts will routinely be installed into jointed and fractured rock masses where the bolt will not take on a continuous load distribution that has been discussed conceptually by Farmer (1975) and Freeman (1978). Instead, the load distribution will be reflective of a number of localized discontinuity movements (Björnfot and Stephansson, 1983; Hyett et al., 1996; Li and Stillborg, 1999), which may act coaxial and/or transverse to the bolt axis. In general, the rock bolt will be subjected to a combination of axial, bending, and shear loads depending on the relative orientation of the bolt and the loading. It is well established that the global strength of a jointed or blocky rock mass will be improved with the addition of fully grouted rock bolts (Fairhurst and Singh, 1974; Bjurström, 1974; Haas, 1976; Azuar, 1977; Dight, 1982; Spang and Egger, 1990), yet the support response to rock mass displacements that are non-coaxial to the bolt remains poorly understood, despite being of critical design significance. Various field investigations (e.g. Turner, 1987; Stillborg, 1994; Signer and Lewis, 1998; Li, 2010) have presented bolts subjected to in situ bending and shearing after a failure of ground, Fig. 1. This is often referred to as the "dowel" reinforcement effect (Spang and Egger, 1990; Ferrero, 1995; Grasselli, 2005; Li et al., 2016a) and is typically observed as an S-like or double bend of the bolt.

Hyett et al. (2013) noted that monitoring the dowel effect of a rock bolt subjected to shearing between planes is a particular challenge due the locality of its effect on the bolt; often within 2.5–6.25 bolt diameters from the intersection with the discontinuity (Ferrero, 1995; McHugh and Signer, 1999; Aziz et al., 2005; Grasselli, 2005). In this regard, it may not be realistic to assume that an array of conventional discrete

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Nomenclature

ε_{Total}	total strain at a given segment of the bolt at the outer fiber (maximum when orthogonal to neutral axis when bending is present)
$\varepsilon_{coaxial}$	coaxial strain component at a given segment of the bolt
$\varepsilon_{bending\ moment}$	bending (lateral) strain component at a given segment of the bolt at the outer fiber
N	normal force
E	elastic modulus of the given bolt
A	cross-sectional area of the given bolt
M	bending moment
z	orthogonal distance from a given location on the bolt cross section to the neutral axis
I	second moment area of the given bolt
r	radius of the given bolt
α	angular distance from orthogonality with the neutral axis
ε_i	total strain at a given sensing length, i
θ	angular distance between the direction of lateral loading and first sensing length (i.e. the angular distance from orthogonality with the neutral axis)
φ	angular distance between the specified sensing length and first sensing length (i.e. 1 = 0°, 2 = 120°, and 3 = 240°)
w	lateral deflection of the given bolt
x	distance along the given bolt

stress and/or strain measuring techniques can be used to capture localized shearing mechanisms, especially without a prior knowledge of discontinuity locations and corresponding movement vectors. The ability to capture the potentially complex and highly variable load distribution of a fully grouted rock bolt will, therefore, require a sensing technique with the capability to: (i) measure the reinforcement response at a fine spatial resolution, (ii) distinguish between coaxial and lateral components of reinforcement, and (iii) derive the orientation of the reinforcement vector, which in turn allows the true magnitude of reinforcement to be resolved.

This paper describes the development of an innovative rock bolt strain sensing technique using a Rayleigh based optical frequency domain reflectometer (OFDR) to measure a distributed strain profile across the entirety of a reinforcement member at a millimeter scale. The technique has been developed within the framework of providing a research and industry solution for capturing the three-dimensional response of loaded rock bolts, and most notably, the response to shear. The potential of this optical technique to accurately capture the behaviour of a fully grouted rock bolt under generalized in situ loading conditions is demonstrated through a series of laboratory tests.

2. Rock bolt measurement techniques

Currently, a diverse set of sensing techniques exist which can be employed for the assessment of rock mass support systems. In general, there are two manners in which a support member can be measured or monitored: (1) Extrinsically using methods such as extensometers, inclinometers, and surveying to infer support member behaviour, and, (2) Intrinsically, whereby instrumentation is coupled directly with the support member of study. In regards to a fully grouted rock bolt, the response to shear movements of the rock mass will be influenced by the many physical and interface variables of the host rock medium, the encapsulating grout, and the bolt material and typology (Haas, 1976; Azuar, 1977; Spang and Egger, 1990; Ferrero, 1995; Aziz et al., 2005; Grasselli, 2005; Jalalifar and Aziz, 2010; Chen and Li, 2014; Li et al., 2016b). Three-dimensional considerations of the bolt inclination with respect to the movements of pre-existing joints and newly formed fractures will also dictate the bolt response. A sensing technique that is not inherent to the bolt will, therefore, not be a suitable solution due to the uncertainties introduced by inferring bolt behaviour. However, there are significant challenges to an intrinsic monitoring solution as the chosen sensing technique must be coupled with the bolt, be protected, and it cannot substantially modify the bolt's physical dimensions in order for the measurements to be meaningful. This has been approached both in controlled laboratory experiments and in situ most commonly using discrete sensing techniques such as foil-resistance strain gauges.

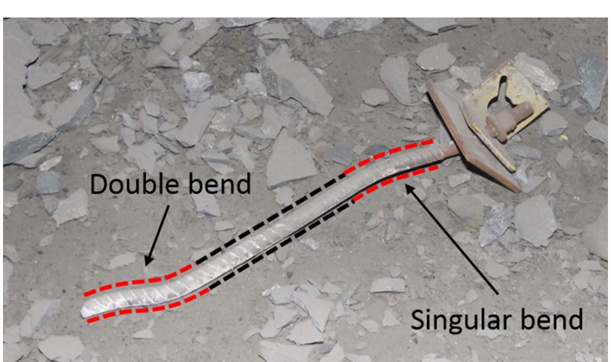

Fig. 1. Failed rock bolt segment. Permanent lateral deformation is shown in the form of a singular bend at the bolt head and a double bend at the failure location (Image courtesy of Brad Simser, Glencore).

Early efforts to study the mechanisms of fully grouted rock bolts considered surface mounting an array of foil-resistive strain gauges to a machined surface along the length of rebar specimens (Farmer, 1975; Karabin and Debevec, 1976; Freeman, 1978). The distribution of coaxial strain along the encapsulated member could, therefore, be determined through the interpolation of discrete measurements provided by each strain gauge. Two major improvements to this sensing technique are demonstrated in Fig. 2. This includes the consideration of strain gauge pairs on opposing sides of the rebar (Radcliffe and Stateham, 1980) and the positioning of such pairs into diametrically opposed grooves machined along the length of rebar specimens (Serbousek and Signer, 1987; Johnston and Cox, 1993). This provides additional protection for the sensors and lead wires and also allows the interpolated strain distribution to be separated into coaxial and lateral components through a comparison of the measured strain along opposing sides of the bolt. However, the short base-length of each strain gauge results in large sections of the bolt being left unmonitored. Consequently, localized loading features (such as shear) along the bolt are prone to being underestimated and possibly omitted. This impediment has been overcome to an extent in a number of laboratory experiments studying shear by concentrating the position of strain gauges within the region of shearing (Ferrero, 1995; Mchugh and Signer, 1999; Grasselli, 2005; Jalalifar, 2006; Chen and Li, 2014). Yet, the maximum number of measurement points along the entirety of the bolt will ultimately be limited by the economic and spatial requirements of adding additional sensors. The success of such a technique to capture shear in situ will, therefore, be contingent on the loading mechanism occurring within the location of one of these discrete measurement points on the bolt. This will similarly be true for comparable load cell techniques (e.g. Rodger et al., 1996) and methods which consider monitoring the exposed head of bolt at the excavation periphery (e.g. Mitri, 2011).

With regards to sections of the bolt remaining unmonitored, a similar technique where the short base-length resistive strain gauges have been replaced with long base-length (commonly 200–600 mm) inductive strain gauges has been presented (Spearing et al., 2013;