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Review

A review on the performance of conventional and energy-absorbing rockbolts

Charlie C. Li [a,*], Gisle Stjern [a,b], Arne Myrvang [a]

[a] Department of Geology and Mineral Resources Engineering, Norwegian University of Science and Technology (NTNU), Trondheim 7491, Norway
[b] Statoil ASA, Stavanger, Norway

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ABSTRACT

This is a review paper on the performances of both conventional and energy-absorbing rockbolts manifested in laboratory tests. Characteristic parameters such as ultimate load, displacement and energy absorption are reported, in addition to load–displacement graphs for every type of rockbolt. Conventional rockbolts refer to mechanical rockbolts, fully-grouted rebars and frictional rockbolts. According to the test results, under static pull loading a mechanical rockbolt usually fails at the plate; a fully-grouted rebar bolt fails in the bolt shank at an ultimate load equal to the strength of the steel after a small amount of displacement; and a frictional rockbolt is subjected to large displacement at a low yield load. Under shear loading, all types of bolts fail in the shank. Energy-absorbing rockbolts are developed aiming to combat instability problems in burst-prone and squeezing rock conditions. They absorb deformation energy either through ploughing/slippage at predefined load levels or through stretching of the steel bolt. An energy-absorbing rockbolt can carry a high load and also accommodate significant rock displacement, and thus its energy-absorbing capacity is high. The test results show that the energy absorption of the energy-absorbing bolts is much larger than that of all conventional bolts. The dynamic load capacity is smaller than the static load capacity for the energy-absorbing bolts displacing based on ploughing/slippage while they are approximately the same for the D-Bolt that displaces based on steel stretching.

1. Introduction

Rockbolts are widely used today in order to secure underground excavation spaces. Conventional rockbolts include mechanical bolts (i.e. expansion shell bolts), fully-grouted rebars and frictional bolts (such as Split set and inflatable bolts, e.g. Swellex and Omega). Conventional rockbolts are used mainly to deal with instability problems under low or relatively low rock stress conditions. A new category of rockbolt has recently been developed with the aim of combating high-stress induced instability problems such as rockburst and rock squeezing. This category includes cone bolts, Garford solid bolts, Roofex, D-Bolts and Yield-Lok bolts, which are here collectively called energy-absorbing rockbolts but referred to as yield bolts in some literature. Based on their coupling mechanism, rockbolts can be classified as continuously mechanically coupled (CMC), continuously frictionally coupled (CFC), or discretely mechanically or frictionally coupled (DMFC) (Windsor, 1997). Fully-grouted rebars are mechanically bound to the grout/rock through the tiny ribs on the cylindrical surface of the bolt shank and are thus a type of CMC bolt. Split set and inflatable bolts such as Swellex and Omega are CFC bolts, since they are bound to the rock mass mainly via friction resistance along their entire length. Expansion shell and all energy-absorbing bolts are anchored in boreholes at one or more discrete points and are thus DMFC bolts.

On the other hand, rockbolts can also be classified as stiff, ductile and energy-absorbing from the point of view of bolt performance (Li, 2010). A stiff bolt displaces for a small amount prior to failure. This kind of bolt usually refers to fully encapsulated rebar bolts. It will be seen later in this paper that a fully encapsulated rebar bolt only can displace approximately 30 mm when subjected to fracture opening. The advantage of this type of bolt is its high load capacity which is equal to the strength of the bolt material. A ductile bolt can tolerate a large rock displacement but its load capacity is relatively

* Corresponding author. Tel.: +47 73594848.
E-mail address: charlie.c.li@ntnu.no (C.C. Li).
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low. Split set is a typical bolt of this type, which in principle can displace as much as the bolt length at a load level equal to the frictional resistance on the bolt cylindrical surface. An energy-absorbing bolt can carry a load equal or close to the strength of the bolt material and displace for a large amount so that it can absorb a good amount of energy prior to failure.

The performance of a rockbolt is dependent upon the loading conditions to which it is subjected. In situ loading conditions include the opening and shearing of single rock fractures, continuous rock deformation, or various combinations of the two. However, it is impossible, actually not necessary, to simulate every type of loading condition in the laboratory when evaluating the performance of a rockbolt. Among the loading conditions, the pull and shear caused by the movement of a single rock fracture are the most representative loading conditions for rockbolts. Therefore, it is widely acknowledged in the field of rock mechanics that laboratory pull and shear tests are generally the two most appropriate measures with which to examine rockbolt performance. Indeed, a good understanding of rockbolts performance is essential for their appropriate practical application. A great number of static pull and shear tests have been conducted in the Rock Mechanics Laboratory at the Norwegian University of Science and Technology (NTNU), Norway, over the past two decades (e.g. Stjern, 1995; Dahle and Larsen, 2006). In addition, many dynamic drop tests have also been conducted on energy-absorbing rockbolts, for example, at Canada Center for Mineral and Energy Technology (CANMET), Ottawa, Canada, and Western Australia School for Mines (WASM), Australia, during the past decade, with the first author involved in a number of these tests. The results of the tests, as well as some by others, are presented in this paper with the aim of providing a systematic illustration of the performances of all types of rockbolts.

2. Rockbolt loading models

The loading condition of a rockbolt is associated with its anchoring mechanism. Analytical loading models for conventional rockbolts were established by Li and Stillborg (1999) and Li (2008). In addition to these models, loading models for energy-absorbing rockbolts are proposed in this section. Such models are helpful in interpreting variation in test results between different types of rockbolts.

2.1. Two-point anchored rockbolts

An expansion shell bolt is a typical two-point anchored support device composed of a solid shank and an expansion shell at the far end of the bolt (Fig. 1). Anchoring of the bolt is achieved through friction and interlocking between the expansion shell and the borehole wall. The load-bearing capacity of this type of bolt is dependent upon both the tightness of the expansion shell and the strength of the rock. Vibrations and stress relaxation may lead to partial or entire loss of anchoring. Another type of two-point anchored bolt involves the far end of the bolt being grouted with resin, which guarantees more reliable anchoring than the expansion shell bolt.

Under a pull load at the bolt head, the shank of the bolt is stretched identically in every cross-section, resulting in a constant axial stress along the length of the bolt, as shown in Fig. 1. The shear stress on the shank surface is obviously zero because of the hollow annulus in the hole.

2.2. Fully-grouted rebar bolts

Fully-grouted rebar bolts are bound to the grout/rock via ribs on the bolt surface, with the main anchoring mechanism of the mechanical interlocking between the ribs and hardened grout. This

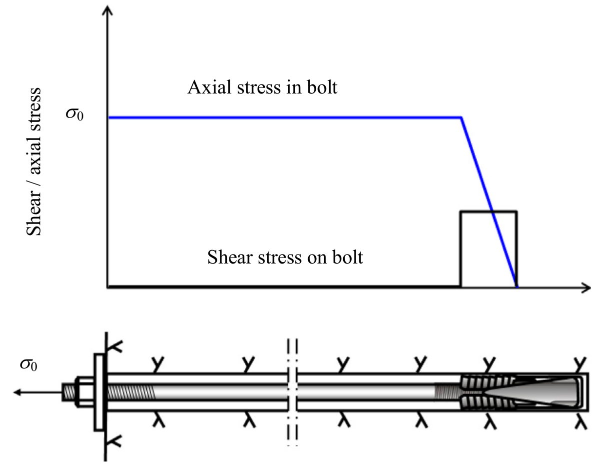

Fig. 1. Stress distributions along the length of a two-point anchored bolt when subjected to a pull load at the bolt head.

type of bolt is characterised by its reliable anchoring and high load capacity.

When the bolt is subjected to a pull load at the bolt head, the load is simply transferred to the rock by the ribs. The axial load in the bolt decreases with distance from the loading point when the applied load is low. Bond failure will commence at the loading point when the applied load is beyond a certain level, propagating toward the far end of the bolt with an increase in the applied load. The residual shear stress on the bolt surface depends on the extent of the failure at the bolt–rock interface. The general pattern of shear stress on the bolt surface is illustrated in the theoretical model shown in Fig. 2. In the model, the bond fails completely in the section immediately adjacent to the loading point, resulting in zero residual shear stress on the bolt surface. No bond failure occurs at the bolt–rock interface beyond the peak shear stress. The bond at the interface deforms elastically, with shear stress attenuating to zero with increasing distance from the loading point. The maximum axial load always occurs at the loading point. Laboratory tests have shown that the length of the de-bonding section is approximately 150 mm for a rebar with cement grout when the axial load reaches the strength of the bolt material. The advantage of rebar bolts is their high load capacity while the disadvantage is the high stiffness.

2.3. Frictional rockbolts

Split set and inflatable bolts (e.g. Swellex and Omega) belong to the class of frictional bolt (Fig. 3). A frictional bolt interacts with the

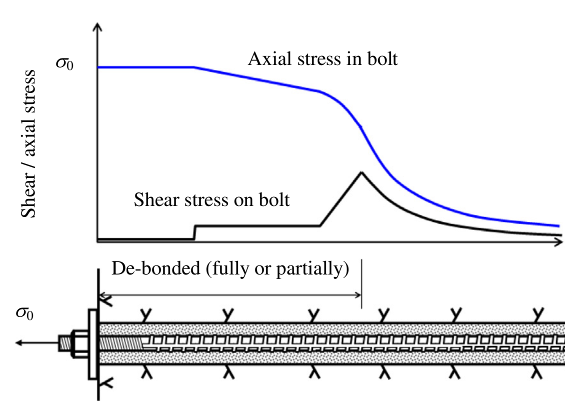

Fig. 2. Stress distributions along the length of a fully-grouted bolt when subjected to a pull load at the bolt head.