Quasi-static laboratory testing of a new rock bolt for energy-absorbing applications

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A B S T R A C T

High stress in the surrounding rock mass can cause serious stability problems. The applied support system used under high in situ stress condition should be able to carry high loads and also to accommodate large deformation without experiencing serious damage. This paper presents a specifically designed rock bolt for energy-absorbing applications, which can provide support for squeezing and burst-prone rocks often encountered during underground excavation in the tunneling and mining community. The bolt mainly consists of a smooth steel bar with an anchor near the bottom end of its body. The anchor is firmly fixed within a borehole using either cement grout or resin, while the smooth section of the bolt inserted in the anchor can slide in response to rock deformation once the load exceeds the pre-set capability. Static pull tests on the new bolt show that it can elongate to any expected length at a high load level, thereby absorbing a large amount of energy to maintain the stability of surrounding rock.

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1. Introduction

The increased demand for minerals over the past years has driven mine development to deeper levels and into regions that have previously been considered inaccessible and unstable. At the same time tunneling for transportation and energy recovery expands into more sensitive areas as the need for further infrastructure extension continues (Neugebauer, 2008). These extreme conditions greatly increase the difficulty of underground supporting, and puts towards a higher request on the underground supporting technology.

The major stability concern is rock falls under gravity at shallow depths. Loosened rock blocks are usually stabilized by installing rock bolts. In low stress conditions, the bolts are required to be strong enough to sustain the dead weight of the loosened block (Hoek, 2007). The strength of the bolt is therefore a crucial parameter in rock support design. As the most widely used rock bolt in geotechnical engineering, fully encapsulated rebar bolt is verified to be a satisfactory type of bolt for this purpose since it fully utilizes the strength of the bolt steel (steel reaches the ultimate tensile strength prior to failure (Li, 2012)).

Many mines around the world, for example those in China, Germany, Australia, and South Africa, are currently being operated at depths greater than 1000 m (Amusin, 1998; Li et al., 2012). The essential difference between rocks at greater depth and rocks at shallow depth is the significant increase in the in situ rock stresses. As a consequence of this increase in stresses, rock burst may occur in hard rocks, or large squeezing deformation may appear in soft and weak rocks (Ortlepp, 2001; Ansell, 2005; Li, 2010). It is observed that some of the conventional bolts fail when experiencing large shear and opening displacement at rock joints/fractures (Ortlepp, 2000; Li et al., 2011). The premature failure of the rebar bolts implies that rebar is too stiff to sustain rock dilations in high stress rock masses. The conventional support devices are thus not suitable for large deformation conditions and dynamic condition (Stilleborg, 1994; Hoek et al., 1995).

Under high stress conditions, the loading for the support system is a displacement controlled process rather than a dead-weight controlled. Wall convergence can be induced by both rock squeezing and the dilation of fractures. The magnitude of rock displacement is influenced by the support system, which is usually composed of both internal and external support devices. The loading process is well described by the Ground Response Curve (GRC) (Carranza and Fairhurst, 2000). The more displacement allowed, the less the requirement for support pressure to stabilize the ground. This can be illustrated by the example of a “flexible support system” consisting of shotcrete linings with deformation slots together with rock bolts. Whilst the shotcrete lining is...
which is also very dangerous. The desired type of bolt for rock sup-
ough, the surrounding rock can experience large displacement,
not flexible enough. However, if the support resistance is not en-
ough, the surrounding rock can experience large displacement,
also very dangerous. If the support resistance is not suffi-
ient, the surrounding rock can experience large displacement,
ning the desired type of bolt for rock support.

In this paper, we first review the history of energy-absorbing rock bolts. After that, we introduce a new rock bolt for energy-
absorbing applications in details, including its layout and principle.
This paper focuses on the static performance of the new bolt and
its deformation characteristics are demonstrated by theoretical
analysis and static pull tests.

2. A review of energy-absorbing rock bolts

Cook and Ortlepp (1968) first proposed the use of yielding sup-
port in the deep gold mines of South Africa. The applied support
system used in deep mines should be able to carry high loads
and also accommodate large deformations without experiencing
serious damage; that is, they should be capable of absorbing a large
amount of energy prior to failure. The energy-absorbing bolt has
been studied over the 20 years around the world. Windsor and
Thompson (1992) first proposed the concept of an ideal reinforce-
ment device. The device should have the strength of rebar and the
deflection capacity of Split Set bolts (Fig. 1), with the ability to be
rapidly mobilized to a load level similar to the strength of the
material. It should be capable of deforming over a long distance
while the load remains high. This concept has been recognized
early, but it has been difficult to technically manufacture such de-
vices. Since 1980, extensive research and development work on
yielding rock support has been conducted. Some energy-absorbing
bolts have been successively developed and applied in mines. So
far there have been dozens of energy-absorbing bolt types, and
the yielding mechanism of them can be summarized as structural
components sliding and steel deformation as shown in Fig. 2.

The first energy-absorbing rock bolt, the so-called cone bolt,
was designed in South Africa (Jager, 1992). The cone bolt consists
of a smooth steel bar with a flattened conical flaring forged onto
one end. The bolt is fully encapsulated with either cement grout
or resin in a borehole. The dilation of the rock between the cone
and the bolt plate induces a pull load in the bolt shank. The cone
is designed so that the conical end ploughs through the grout when
the pull load exceeds a pre-defined value. Its energy absorbing
capacity is the sum of compression of the grout and steel deforma-
tion. Its performance is closely controlled by the interaction
between the cone and the grouting agents which in turn is signifi-
cantly influenced by the properties of the grout material, the
diameter of drill hole, the mixing efficiency and the encapsulation
condition. In most cases these factors are not completely under
control, the effect of a cone bolt (or modified cone bolt) therefore
is less consistent and reliable (Gillerstedt, 1999).

D bolt is a steel deformation bolt designed based on the yielding
mechanism (Li, 2010). It is a smooth steel bar with a number of an-
chors along its length. The anchors are firmly fixed within a bore-
hole using either cement grout or resin, while the smooth sections
of the bolt between the anchors can deform freely in response to
rock dilation. Failure of one section does not affect the reinforce-
ment performance of other sections. The bolt is designed to fully
use both the strength and the deformation capacity of the bolt material along the entire length. The bolt has large load-bearing
and deformation capacities. Static pull tests and dynamic drop
tests show that the bolt length elongates by 14–20% at a load level
equal to the strength of the bolt material, thereby absorbing a large
amount of energy. While, field measurements show that resin mix-
ing is critical to ensure that the anchors do not move in extreme
conditions underground, according to technical information data
shifts by Chantale and Benoit (2012).

Roofex is another energy-absorbing bolt that was developed by
Atlas Copco (Salzburg, 2009). The bolt is based on a steel-stone
interaction with a high quality steel bar traveling through a energy
absorbing element (energy absorber) fixed with resin or cement
grout inside the borehole. The energy absorber receives a total of
six cemented carbide slightly engraved into the steel bar and per-
form a cold rolling process, deforming the original round shape to a
hexagonal shape, whilst the steel bar travels along its sliding path.
Roofex is a rock bolt that can absorb movements with excellent
performance and predictability for both yielding and rock burst
prone grounds. However, the “energy-absorber” unit makes the
bolt inherently cost expensive due to its complex structure. As ce-
mented carbide pins are slightly engraved into the steel bar, struc-
tural damage of the bar was inevitable.

All the existing bolts have advantages and disadvantages, and
there are more and more industrial requirements on developing
a performance-reliable and cost-effective yielding rock support
system.

3. Layout and principle of the new bolt

Since 2010, the authors have been conducting extensive re-
search and testing to develop a new energy-absorbing rock bolt
suitable for dynamic and/or large convergence ground conditions
(Wang et al., 2012). The appearance of the new bolt is similar to
Roofex, but the structure of the “energy-absorber” unit is simpler
and more stable, which can provide a larger resistance (a load level

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**Fig. 1.** Concept of the ideal bolt and definitions of strength, ductile and energy-
absorbing rock bolts. All data sections are redrawn from Li CC [6].

**Fig. 2.** Yielding mechanism of energy-absorbing rock bolt: (a) structural components sliding and (b) steel deformation.
similar to the tensile strength of the rod material). It is designed to dissipate and control large amounts of energy liberated from the rock mass deformation and therefore suitable for extreme conditions at depth.

As shown in Fig. 3, the new rock bolt for energy-absorbing applications mainly consists of a drawing rod and a drawing die. The drawing rod is a metal bar with varying diameter. The drawing die, made of hard metal, has an inner diameter smaller than the thick end of the steel bar. It also functions as an anchoring point fixed inside the borehole with either cement grout or resin. However, the smooth bar has no or very weak bonding to the grout.

The deformation mechanism of the new bolt is just similar to drawing operations that involve pulling the thick metal bar through a smaller diameter hole by a tensile force applied to the exit side of the die. The dilation of rock will induce a pull load in bolt and there will be relative sliding trend between the drawing die and the rod. As the drawing die orifice diameter is smaller than the thick end of drawing rod, there will be extrusion pressure between them and plastic deformation will be caused by the compression force. Once the pull load exceeds the defined drawing force, the rod will be pulled out slowly. The simplified cold drawing process is applied to the new bolt for elongation purpose, that is, the new bolt utilizes the high load and the relative sliding during cold drawing operations. On the other hand, the diameter of thick segment can be variable, resulting different sliding loads for one bolt in different stages. For example, it is possible for a yielding bolt with a low loading capacity at first allows the rock mass to deform and to ensure proper functioning of the designed sliding process. The slender segment of the drawing rod has smooth sections, so it easily detaches from the grout under pull loading. To further guarantee satisfactory separation, the surface of the smooth bar can be coated with a lubricant media, such as plastic pipes or wax. However, the results presented below show that coatings have a limited effect on the detachment at the bolt–grout interface.

4. Calculation of load capacity

According to metal plasticity theory, there are many theoretical methods to calculate the drawing load such as the slab method, sliding line method, upper-bound method and finite element method. The drawing schematic is shown in Fig. 4. According to the slab method (Rowe, 1965), the drawing stress can be expressed as

$$\sigma_t = \sigma_i \left(1 + \frac{\tan \alpha}{f} \right) \left[1 - \left(\frac{D_0}{D_1}\right)^{\frac{a}{\tan \alpha}}\right]$$

where $\sigma_t$ is the drawing stress, or the working stress of the bolt, which is the rod axial stress at the exit end of drawing die; $\sigma_i$ is the average deformation resistance before and after the drawing; $\alpha$ and $f$ are the die angle and the coefficient of friction; $D_0$ and $D_1$ are the diameters of the undrawn rod and the drawn rod. The constant support pressure that the yielding device provides can be calculated accordingly.

According to the Eq. (1), the drawing stress will increase linearly with the tensile strength of the rod, and the drawing stress has linear relationships with the reduction of area. It is worth noting that the calculation presented above is based on the conditions of industrial production, where the steel bar requires heat treatment, pickling, and lubrication, etc. However, none of the above steps is included in the drawing process involved in the energy-absorber, so the actual load obtained will be larger than the calculated results. Therefore, it is necessary to correct the calculation through experiments, and the modified computing method will be presented in the following sections.
5. Static pull tests

Direct quasi-static pull tests were performed to examine the performance of the new bolt. Short samples had to be used due to the space limitation of the test machine. Also, the faceplate and the combined mixing and stop element are not included. Three series of experiments were prepared in this study, and a total of fourteen pull tests were performed.

The arrangement of the tests is shown in Fig. 5. The samples were pulled on a test rig specially constructed for bolt testing. The steel tube is 74/54 mm in outer/inner diameter and 460 mm in length. The internal surface of the tube was shallow grooved to simulate the roughness of the borehole wall. The drawing dies (the anchors), are firmly fixed within the borehole using resin grout. Fig. 6 shows one of the bar sample and the corresponding drawing die used in the testing.

The first series experiments included specimens BS1–BS4, which had the same total length of 510 mm, sliding length of 130 mm, and diameter of the slender end of 22 mm. The bolt samples used in this test were made from bearing steel that has a tensile strength of 900 MPa with no obvious yield point. The only difference lies in the diameter of the sliding section, which distributed between 24.0 mm and 26.5 mm, to study the relationship between the cross-sectional reduction rate and the sliding load. In addition to the diameters, area reduction ratio corresponding to different sizes and pullout force obtained through Eq. (1) are also listed in Table 1.

The second series experiment, including specimens BS5–BS8 as shown in Table 2, was conducted to examine the impact of various factors on the drawing process. All the samples except BS5 were coated with a thin shrink pipe to examine the effect of surface conditions. BS6 has a shorter sliding length than other samples. Sample BS7 has a small size, whose diameter is 23.4/19.4 mm at thick/slender section. It has a cross section reduction ratio of 31.1%, the same as sample BS4, BS5 and BS6. Sample BS8 with different diameters in the thick segment is designed to have two-stage loading capacities.

The third series experiment was conducted to examine the impact of various steels on the drawing process as shown in Table 3. A total of six samples were manufactured from three different steels. Every sample has three sliding sections with varying diameter increased by degrees. The length of every sliding section is 45 mm. The diameter of the sliding section, which distributed between 22.5 mm and 29.0 mm, varies greatly to study the bolt performance for very small and very large area reductions. The relationship between cross-sectional reduction rate and the sliding load for different steels will be well illustrated in these tests.

During the test, one end of the steel tube was fixed, and the bar samples were pulled longitudinally by the testing machine. The samples were loaded at a speed of 30 mm/min. The displacement of the bolt was recorded relative to the applied load during testing. All the measurement instruments were connected to an automatic data acquisition system.

Fig. 7 shows the photos of sample BS5 during testing. The sample is 510 mm long with a sliding length of 130 mm. Its detailed dimension before and after testing is shown in Fig. 8. Fig. 9 shows the photos of sample BS14, which has failed because of too large area reduction ratio. The load–displacement curves of samples in the three series tests are presented in Figs. 10–12, respectively. The energy absorbed by a bolt is represented by the area under the load–displacement curves.

6. Discussions

6.1. Load capacity

As shown in Fig. 10, the bolt load increases linearly in the early stage before reaching a sliding load. Once the sliding load is reached, the load will remain constant and displacement continues to increase.

Specimens in the first series have different diameters at their thick ends and this scenario is used to study the influence of the rod cross-section reduction ratio on sliding load. The results in Fig. 10 show that the pulling force increases with the cross-section reduction ratio. Therefore, it is appropriate to design bolt with different bearing capacities by changing the area reduction ratio. The bearing capacity of the specimen BS4 reaches 272 kN, with a corresponding stress of 717 MPa, which is close to the tensile strength of the steel bar.

As shown in Fig. 11, specimen BS7 has the same cross-section reduction ratio (31.1%) as other specimens of the second series, but with a smaller section size. The results show that its drawing stress (about 700 MPa) is similar with other specimens that have the same cross-section reduction ratio, indicating that the size effect is not significant in the drawing process. BS8 has a different diameter at the thick segment (22.2/23.4 mm), and the loading capacity is changed accordingly. This property is of significance both in experimental research and field applications, as well as the designing of reinforcement system intelligently.

As shown in Fig. 12, the sliding load increased by degrees for different sliding sections. The sample BS12 and BS14 failed in the third stage at slender segment. So it is reasonable to conclude that the bolt can provide a large resistance close to the tensile strength of the rod material.

6.2. Ultimate displacement

As shown in Figs. 10 and 11, the carrying capacities of specimen BS4 and BS6 are basically the same, indicating that the sliding
length has little effect on the load-bearing properties and stability of the anchor. Therefore, the maximum displacement is variable and can be fully adjusted to the specific rock mass type.

The pre-set sliding length is 130 mm in these tests except the sample BS6, while they are stopped at displacements of 140–160 mm that is larger than the pre-set value. The ultimate displacement of the new bolt is composed of three parts: sliding length between the anchor and the steel bar, the plastic flow of the thick segment due to drawing and plastic elongation in the slender segment, as shown in Figs. 8 and 9. The first part is constant and equal to the length of thick segment, while the second part is related to the area reduction ratio as the volume of steel will not change in the drawing process, and the third part is associated with plastic capacity of steel.

### 6.3. Comparison with other yielding rock bolts

The static test results of the new bolt (19.4/23.4 mm) are presented in Fig. 13 together with the results of other yielding rock bolts. All the data except those in above test are taken from a presentation by Wang (2010). The lines with different colors describe the relationship between the displacement and the loads for different bolts. Cone bolt absorbs energy through both ploughing of the cone in the grout and plastic elongation of the bolt steel. However, its loading capacity is unstable because of the heterogeneity of the cement grout or resin. D bolt has a high loading capacity and absorbs energy through plastic elongation of the bolt steel. Both the new bolt and the Roofex absorb energy mainly through steel-steel interaction. As shown in Fig. 13, the constant load of the new bolt is very large compared to other types of yieldable rock bolts, so the energy absorbing capacity will properly be much bigger.

### 6.4. Effect of surface conditions

As shown in Figs. 10 and 11, the load–displacement curves of sample BS4 and BS5 were similar in both yield load and ultimate displacement, even though BS5 was installed without coating. The initial load of BS5 increased more quickly, and the rod was detached from the grout at a load level of approximately 100 kN. Although the increase in the peak load may be due to the friction between the rod and resin grout, the increment of 4% is marginally small, indicating that the surface condition has limited effect on the load-bearing properties of the bolt.

### Table 1
Bar samples for the first static pull tests.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Diameter of slender segment (mm)</th>
<th>Diameter of sliding section (mm)</th>
<th>Cross section reduction ratio (%)</th>
<th>Calculated stress (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BS1</td>
<td>22.0</td>
<td>24.0</td>
<td>16.0</td>
<td>230.8</td>
</tr>
<tr>
<td>BS2</td>
<td>22.0</td>
<td>24.5</td>
<td>19.4</td>
<td>283.4</td>
</tr>
<tr>
<td>BS3</td>
<td>22.0</td>
<td>25.5</td>
<td>25.6</td>
<td>383.1</td>
</tr>
<tr>
<td>BS4</td>
<td>22.0</td>
<td>26.5</td>
<td>31.1</td>
<td>476.2</td>
</tr>
</tbody>
</table>

### Table 2
Bar samples for the second static pull tests.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Diameter of slender segment (mm)</th>
<th>Diameter of sliding section (mm)</th>
<th>Sliding length (mm)</th>
<th>Coating</th>
</tr>
</thead>
<tbody>
<tr>
<td>BS5</td>
<td>22.0</td>
<td>26.5</td>
<td>130</td>
<td>No</td>
</tr>
<tr>
<td>BS6</td>
<td>22.0</td>
<td>26.5</td>
<td>110</td>
<td>Yes</td>
</tr>
<tr>
<td>BS7</td>
<td>19.4</td>
<td>23.4</td>
<td>130</td>
<td>Yes</td>
</tr>
<tr>
<td>BS8</td>
<td>19.4</td>
<td>22.2/23.4</td>
<td>130</td>
<td>Yes</td>
</tr>
</tbody>
</table>

### Table 3
Bar samples for the third static pull tests.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Steel</th>
<th>Diameter of sliding section I (mm)</th>
<th>Diameter of sliding section II (mm)</th>
<th>Diameter of sliding section III (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BS9</td>
<td>16Mn</td>
<td>22.5</td>
<td>23.5</td>
<td>24.5</td>
</tr>
<tr>
<td>BS10</td>
<td>16Mn</td>
<td>27.0</td>
<td>28.0</td>
<td>29.0</td>
</tr>
<tr>
<td>BS11</td>
<td>40Cr</td>
<td>22.5</td>
<td>23.5</td>
<td>24.5</td>
</tr>
<tr>
<td>BS12</td>
<td>40Cr</td>
<td>27.0</td>
<td>28.0</td>
<td>29.0</td>
</tr>
<tr>
<td>BS13</td>
<td>35CrMoA</td>
<td>22.5</td>
<td>23.5</td>
<td>24.5</td>
</tr>
<tr>
<td>BS14</td>
<td>35CrMoA</td>
<td>27.0</td>
<td>28.0</td>
<td>29.0</td>
</tr>
</tbody>
</table>

Fig. 7. Sample BS1 during testing.

Fig. 8. Sample BS1 before and after testing.

Fig. 9. Sample BS14 before and after testing.

Fig. 10. Load versus displacement curves from test results of the first series of samples.

Fig. 11. Load–Displacement curves

Load/kN

Displacement/mm

0 30 60 90 120 150 180

0 50 100 150 200 250 300
6.5. Modified computing method

It is obvious that the calculated results vary greatly with the measured values because of the different application conditions. However, there appears a linear relationship between drawing stress and cross-section reduction ratio for every single steel material as shown in Fig. 14. Therefore, the relationship between them can be simplified as:

\[
\sigma_L = a\psi + b
\]

where \(\sigma_L\) is the modified sliding stress, \(\psi\) is the cross-section reduction ratio, \(a\) and \(b\) are parameters associated with ultimate tensile strength of the steel material and drawing conditions. The drawing conditions for all the tests shown in Fig. 14 are identical, and the only difference lies in the material. According to results in this study, the parameters are not the same for different steels. With linear regression method, they can be determined as \((1121.5, 68.4), (1599.9, 95.6), (1587.9, 147.4), \text{ and } (2099.4, 76.5)\) for \(16\text{Mn}, 40\text{Cr}, 35\text{CrMoA}\) and bearing steel, respectively. All the values of \(R^2\) are greater than 0.99, indicating that the results are accurate for every specified steel material.

Tests for very small and very large area reductions have been conducted to illustrate the deformation characteristics of bolt in cold drawing process. However, it is inappropriate for a bolt with very small or very large area reductions. Too small area reduction will result in a small load capacity, and the strength of the steel is not fully utilized. Failed of the bolt may happen when the area reductions is too large, which should be avoided in engineering practice. Considering economy and safety factors, the area reductions ratio is suggested to distribute in \(0.25\text{–}0.35\).

6.6. Other issues that need special attention

In the application of the bolt, the outer diameter of the drawing die is an important parameter. If the outside diameter of the drawing die is too small, squeezed crack may occur under high stress. If it is too large, the diameter of anchor hole will be increased accordingly. Industrial drawing die was used in this study, which had a larger diameter than expected because of its high safety factor. However, when used in anchor hole, the periphery of the drawing die is limited by the surrounding rock, reducing the possibility of damage, so its diameter can be further reduced. Hard alloy is used greater than 0.99, indicating that the results are accurate for every specified steel material.
considered as a suitable material for manufacturing of drawing dies. The vital parameter for structural components sliding bolt is load-bearing capacity during sliding process. The sliding load of the new bolt depends on the area reduction, which has nothing to do with the length, and the stability of the new bolt has been confirmed in these tests. Therefore, it is reasonable to use short samples to study the static performance of the new bolt. The only consequence of using short samples is that the ultimate displacement in this test is decreased accordingly. Rock bolts are loaded in situ either statically by time-dependent rock dilation, or dynamically by rock bursts. In the case of rock bursting, the bolt would be loaded in a more complicated manner than under static loading condition. The dynamic tests should be done to examine the shock-resistant performance and energy absorption capacity of the new bolt subjected to dynamic loading in the future, and direct dynamic impact test method (Li, 2010) is preferred.

7. Conclusions

The new rock bolt for energy-absorbing applications utilizes the high load and the relative sliding during cold drawing operations. The bolt mainly consists of a smooth steel bar with an anchor near the bottom end of its body. The drawing rod is a metal bar with varying diameter. The anchor is firmly fixed within a borehole using either cement grout or resin, while the smooth sections of the bolt inserted in the anchor can deform in response to rock dilation once the load exceeds the pre-set capability. The maximum displacement is variable and can be fully adjusted to the specific rock mass environment.

Static pull tests have shown that the bolt load increases linearly in the early stage before reaching a sliding load. Once the sliding load is reached, the load will remain constant and displacement continues to increase. It is seen that the constant load of the new bolt is very large compared to other types of yieldable rock bolts, and the energy absorption capacity is potential to be larger as well. The results also confirmed that there appears a linear relationship between the drawing stress and the cross-section reduction ratio, and a regression formula to calculate the drawing load is present.

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