Testing and modelling on an energy absorbing rock bolt

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Abstract

Dynamic loads on underground structures, such as tunnels, may be caused by blasting during nearby construction work or bomb detonations on the surface above e.g. a rock shelter. These loads give rise to vibrations that propagate as stress waves through the rock, possibly causing damage to structures and installations or even causing fragments or pieces of rock to be thrown out from the rock surface. A common and important energy absorbing component in rock support is steel rock bolts.

A new type of energy absorbing rock bolt has been developed and dynamically tested. The bolt consists of a smooth steel bar with impressions made over a section of its length to provide required anchorage when fully grouted. When subjected to a dynamic load, the adhesive bond between bar and surrounding grout is lost and the bolt is able to absorb energy by plastic lengthening. The dynamic tests were performed as free-fall tests of rock bolts in concrete cylinders. As a follow up, the problem has been analysed using numerical stress wave propagation models.

A statically, or quasi-statically, loaded rock bolt shows evenly distributed elongation. The tests performed with dynamically loaded rock bolts show that the distribution of plastic strain along the length of a fully grouted bolt is not constant. For the tested type of rock bolt to absorb a reasonable amount of energy, the permanent plastic strain must be allowed to propagate an appropriate distance along the bolt. This propagation is governed by the impulse time and the shape of the dynamic stress-strain curve of the bolt material.
1. Introduction

Rock burst problems and potential bomb load threats are the most extreme of loads that can occur on a rock support system based on rock bolts. The energy absorption capacity of rock bolts depends on the properties of plastic yielding of the steel material, i.e. conversion of kinetic energy to strain energy. The ability to yield is for conventional rock bolts often limited due to e.g. cement grouting. Types of more sophisticated and expensive rock bolts are therefore used in energy absorbing rock support systems. The most simple type of energy absorbing rock bolt consists of a rebar, partly covered by a casing to prevent adhesion between bolt and grout. The two main disadvantages with this solution are that holes of an unnecessarily large diameter have to be drilled into the rock and that it is difficult to provide a full protection against corrosion.

1.1 The tested energy absorbing rock bolt

An energy absorbing rock bolt, based on a different principle, without casing, has been developed and tested by Holmgren [1] and Ansell [2]. The project was partly supported by the Swedish Armed Forces. The bolt, shown in Figure 1, consists of a smooth steel bar with impressions made over a section of its length to provide required anchorage when fully grouted. When subjected to an impact load, the lengthening of the steel bar leads to a decrease in diameter whereby the adhesive bond between bar and grout is lost and the bolt is able to absorb the energy by plastic lengthening. A rock bolt based on this principle will, when fully grouted in cement, be given a very good protection from corrosion. For the principle to work, the anchorage must hold and the bolt must be able to yield freely along its smooth section. The load is taken by a circular disc and a nut welded onto the outer end of the bar. The tested bolts consisted of steel bars of a diameter of Ø16 mm from a mild steel with a yield stress of 300 MPa. The smooth sections were either 1000 or 2000 mm, followed by a 1000 mm anchorage.

1.2 Previous static tests

The energy absorbing rock bolt have previously [1] been statically tested. A static load was applied at a rate of 0.1 m/s on the outer end of bolts cast in concrete prisms until plastic yielding occurred. These tests resulted in strain distributions that were almost constant along the smooth, yielded length of the bolts. The conclusions were that the principles, on which the rock bolt is based, are valid for for static or slow dynamic loads, if a soft steel quality is used and that a sufficient anchorage can be provided.
2 Test program

Within the project, dynamic tests have been performed, aiming at investigating the performance of the rock bolt when subjected to yielding at about 10 m/s.

2.1 Dynamic tests

The dynamic test series consisted of fully grouted rock bolts, using concrete cylinders to simulate cement grouting and the weight of a section of ejected rock. The main interest was to measure the length of the plastically yielded section of the bolt and the variation within this section. To achieve a loading velocity of about 10 m/s, a test set-up involving a heavy falling weight provided a number of practical problems and was thereby omitted in favour of a set-up using free falling test specimen. A total of five tests was carried out, one with a higher

Figure 1: Energy absorbing rock bolt with a Ø150 mm curved circular disc.
impact velocity of 12 m/s. In the following, a test at 10 m/s with a 1000 mm long smooth, yield section is considered.

2.2 Test specimen

One specimen consisted of a rock bolt cast in concrete, using a Ø150 mm cardboard tube. The weight of the specimen was 111 kg. Marks were made at a

![Figure 2: Test set-up for dynamic testing of rock bolts. Measurement in mm.](image)
spacing of 50 mm along the smooth section of the bolt, to facilitate measurement of the plastic yield distribution. Accelerometers were placed on top of the transverse beam and on top of the concrete cylinder to provide registrations of the retardation phase.

2.3 Test set-up

The test specimen was dropped, with the outer end of the bolts facing upwards, from a height of 5.1 m by using a pneumatically controlled hook. The drop was halted by an impact at 10 m/s between the transverse beam and two large steel beams spanning across the shaft that was used for the drop. The 1.5 m transverse beam was attached to the nut of the rock bolt and to the hook prior to the drop, as seen in Figure 2.

3. Test results

An acceleration history of 50 ms around the instant of the impact is shown in Figure 3. The measured plastic strain distribution is given in Figure 4. There were no indications of anchorage slip or failure at the nut of the bolt.

Figure 3: Accelerations on concrete cylinder. The rectangle is the retardation.
4. Evaluation and numerical modelling

The evaluations of the test results have given rise to the assumption that the effect of adhesion and friction between steel and concrete can be neglected. The energy loss due to friction and adhesion was observed to be small. This is possibly due to the fact that stress waves travelling along a steel bar also cause a decrease in the diameter of the bar. Thus, the bond to the surrounding concrete dissolves in a direction almost perpendicular to the direction of elongation of the bar. Apart from the results presented in the following, further modelling work has been performed and are presented in [2].

4.1 Plastic stress waves

In both dynamic and quasi-static loading, plastic stress waves may appear. If an elastic–plastic material is loaded by a pulse with an amplitude exceeding the elastic limit of the material, both elastic and plastic waves will start to propagate through the material. The energy absorbing capacity of a steel bar is obtained as the surface under a curve in a dynamic $\sigma$-$\varepsilon$ diagram, by integration up to the ultimate stress of the material [3]. When the stress load is removed, an elastic unloading wave will start to propagate. Eventually, it overtakes the slower moving plastic wave fronts, reducing their amplitudes.
4.2 The plastic yield process

According to e.g. Fischer [4], the yield process is often illustrated by a space–
time (or location) diagram as shown in Figure 5, corresponding to the results
presented in Figure 4. The diagram consists of a time axis and an axis showing
the length of the steel bar, starting at the impacted end. Each loading state is
given by numbers. In the space–time domain, the propagation of elastic and
plastic wave fronts, representing loading and unloading waves, are represented
by straight lines. These lines are given by the velocities of the propagations of
disturbance \( c \), obtained from:

\[
\begin{align*}
\eta_{el}^2 &= \sqrt{\frac{E_{el}}{\rho}} \\
\eta_{pl}^2 &= \sqrt{\frac{E_{pl}}{\rho}}
\end{align*}
\]

where \( \rho \) is the density of the material, \( E_{el} = E \) is the elastic modulus and \( E_{pl} \) are
the local slopes of the \( \sigma-\varepsilon \) curve within the plastic range, written as:

\[
E_{pl} = \frac{d\sigma}{d\varepsilon}
\]

Since \( E_{pl} < E_{el} \), elastic wave fronts propagate faster than plastic fronts in the
same material, i.e. \( c_{pl} < c_{el} \). The stress–strain relation of the steel quality used in
the laboratory tests have been approximated by first an elastic linear relation,
corresponding to \( E_{el} = E \), followed by three linear sections of decreasing slopes. These slopes correspond to three values of \( E_{pl} \) valid up to 5%, 10% and 15%
tension of the steel, respectively. The shape of the \( \sigma-\varepsilon \) curve will be further
discussed in the following section.

It can be seen that one elastic and three plastic loading wave fronts start to
propagate simultaneously, leading from loading state 6 to 10. During this phase,
plastic loading wave fronts travels through the bar until an elastic unloading
wave cuts off the plastic yield process. The plastic yield created, is shown at the
upper part of the diagram with strain–length axes. This is in good agreement
with the measured strain distribution in Figure 4. Initially, the transverse beam
first bends down 1–2–3 followed by an upward bend 3–4–5, corresponding to
negative forces. This is followed by a downward bend 5–6–10, corresponding to
a force and a particle velocity high enough to plastically deform the bar 10.

The time of the elastic loading phase corresponds to the first bending mode of
the transverse beam, with a natural frequency close to 500 Hz and a period time
of 2 ms, also verified by a frequency spectrum of the accelerations in Figure 3.
4.3 A numerical model

A numerical method using a graphical scheme have been adapted for calculating the permanent strain distribution of an elastic–plastic bar subjected to an impacting tensile velocity at its lower end, \( x = 0 \). The input of the model is the stress–strain curve of the bar material. The solution is step-wise found by in sequence plotting six graphs, describing the relations between stress \( \sigma \), strain \( \varepsilon \), stress gradient \( d\sigma/d\varepsilon \), velocity of propagation of disturbance \( c \) and particle
velocity \( v \). The length of the bar subjected to plastic yielding can be determined from the \( \varepsilon-c(\varepsilon) \) graph by using the relation:

\[
c(\varepsilon) = \frac{|x|}{t}
\]

in which \( |x| \) is the distance along the bar, travelled by a wave front moving with \( c(\varepsilon) \) during the time of impact \( t \).

By starting from the strain distribution of the yielded rock bolt, a dynamic stress–strain curve of the steel material can be calculated. This requires knowledge of \( t \), which can be found from the acceleration–time record in Figure 3. Further, the impact velocity will be obtained during the process, fitting all six graphs together. As a first step, a polynomial curve is fitted to the discrete, measured strain distribution described by the bar plot in Figure 4. This enables numerical calculations with an approximative but more dense numerical representation than originally given by the measured results. The elastic contribution is omitted, i.e. the resulting stress–strain curve represents the part above the yield stress. This can be done due to the reversal of the elastic part of the yield during unloading. In Figure 6, it is seen that the maximum particle velocity corresponding to the plastic yield process is 6.3 m/s. The remaining part of the impacting 10 m/s is thus 3.7 m/s, corresponding to the elastic part of the process, not included in the six graphs.

![Graphs showing stress-strain relationship](image)

Figure 6: Numerically obtained strain distribution for a free steel bar.
5. Conclusions

The plastic strain along the length of a grouted rock bolt of the type tested is not constantly distributed when dynamically loaded. The measured strain distribution showed that the section where plastic yielding was allowed, was not fully utilised. The modelling was based on the assumption of the rock bolt behaving as an infinitely long bar, *i.e.* no reflection of stress waves was considered. As longitudinal vibrations enters the anchorage section, the motion is prohibited causing the wave amplitude to be damped. If the allowed amplitude is almost infinitesimal, as for a grouted rock bolt, the energy of the wave will *e.g.* be transformed to friction or dissipate into the concrete. Thus, the effect of grouting mainly effects the reflection of stress. For the rock bolt to absorb a reasonable amount of energy, the permanent plastic strain must be allowed to propagate an appropriate distance along the bolt. This is always possible if the applied load is a long-duration static load. For a dynamic load, the propagation is governed by the impulse time and the shape of the dynamic $\sigma$–$\varepsilon$ curve of the bolt material.

References


