Full Length Article

Laboratory pull-out tests on fully grouted rock bolts and cable bolts: Results and lessons learned

Isabelle Thenevin a,*, Laura Blanco-Martín a, Faouzi Hadj-Hassen a, Jacques Schleifer a, Zbigniew Lubosik b, Aleksander Wrana b

a MINES ParisTech, Department of Geosciences, PSL Research University, 35 rue Saint Honoré, Fontainebleau Cedex, 77305, France
b Department of Extraction Technology and Mining Support, Central Mining Institute (GIG), Katowice, Poland

A R T I C L E   I N F O

Article history:
Received 27 January 2017
Received in revised form 3 April 2017
Accepted 25 April 2017
Available online 8 August 2017

Keywords:
Pull-out test
Fully grouted bolts
Laboratory-scale
Confining pressure
Embedment length
Bolt-grout interface

A B S T R A C T

Laboratory pull-out tests were conducted on the following rock bolts and cable bolts: steel rebars, smooth steel bars, fiberglass reinforced polymer threaded bolts, flexible cable bolts, IR5/IN special cable bolts and Mini-cage cable bolts. The diameter of the tested bolts was between 16 mm and 26 mm. The bolts were grouted in a sandstone sample using resin or cement grouts. The tests were conducted under either constant radial stiffness or constant confining pressure boundary conditions applied on the outer surface of the rock sample. In most tests, the rate of displacement was about 0.02 mm/s. The tests were performed using a pull-out bench that allows testing a wide range of parameters. This paper provides an extensive database of laboratory pull-out test results and confirms the influence of the confining pressure and the embedment length on the pull-out response (rock bolts and cable bolts). It also highlights the sensitivity of the results to the operating conditions and to the behavior of the sample as a whole, which cannot be neglected when the test results are used to assess the bolt-grout or the grout–rock interface.

© 2017 Institute of Rock and Soil Mechanics, Chinese Academy of Sciences. Production and hosting by Elsevier B.V. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

1. Introduction

Fully grouted rock bolts and cable bolts are two reinforcement techniques widely used in civil and mining engineering. These support systems combine efficiency, flexibility, ease of installation and low cost (Stillborg, 1994; Fine, 1998). Due to these assets, they are extensively used in the underground to improve safety along roadways and large openings.

In general terms, a rock bolt or cable bolt consists of a bar inserted in a borehole that is drilled into a soil or rock mass and anchored to it by means of a fixture (Windsor, 1992; Windsor and Thompson, 1996). Fully grouted bolts comprise four elements: the bar, the surrounding ground, the internal fixture to the borehole wall and the external fixture to the excavation surface. The main characteristic of fully grouted bolts is that they only provide support action if the surrounding ground tries to deform; thus, they are passive reinforcement systems (Tincelin and Fine, 1991).

Worldwide experience suggests that failure of fully grouted bolts most likely occurs at the bolt-grout interface, by means of a debonding process that starts if the axial force on the bar exceeds a critical value, and then propagates along the interface (Goris, 1990; Hyett et al., 1992, 1995; Kaiser et al., 1992; Stillborg, 1994; Li and Stillborg, 1999; Moosavi et al., 2005). Analytical solutions for the debonding process were proposed recently (e.g. Li and Stillborg, 1999; Ren et al., 2010; Blanco-Martín et al., 2011). However, these solutions do not account for the interface normal behavior explicitly. With the support of the European Commission’s Research Fund for Coal and Steel (RFCS), a new pull-out bench was designed and calibrated in the context of the PROSAFECOAL programme (Papanichalos et al., 2010) to gain more insight into the response of fully grouted bolts (axial and normal directions). This bench, described in Blanco-Martín (2012) and Blanco-Martín et al. (2013, 2016), allows testing several bolts, and investigating the influence of a wide variety of parameters, such as the confining pressure, the embedment length, the roughness of the borehole wall or the thickness of the grout annulus. Additionally, failure at the bolt-grout or the grout–rock interface can be studied. Blanco-Martín et al. (2013) suggested a procedure to assess the response of the bolt-grout interface from experimental results and...
theoretical considerations, and proposed a semi-empirical formulation of the interface behavior (axial and normal directions) for resin-grouted steel rebars and fiberglass reinforced polymer (FRP) rock bolts.

As mineral resources are decreasing in Europe, mining companies are searching deeper underground to meet customers' needs and maintain their activities. At large depth, stresses are higher and support systems must be intensified. In this context, a new laboratory pull-out set-up has been conducted within the framework of the RFCS AMSSTED research programme (Hadj-Hassen et al., 2015). In this set-up, a large range of bolt types has been tested, and attention has been focused on the influence of the confining pressure and the embedment length, since it has been previously shown that these parameters have a strong effect on the pull-out response (Bennmokrane et al., 1995; Hyett et al., 1995; Moosavi et al., 2005; Blanco-Martín et al., 2013). Moreover, the execution of the tests has demonstrated that pull-out results are very sensitive to the operating conditions and the response of the sample as a whole (for instance, damage of the rock sample markedly affects the measured pull-out response). Fifty-two tests on rock bolts and thirty-two tests on cable bolts have been carried out, and the main findings are presented here.

This paper is organized as follows. First, we describe the experimental bench used at laboratory-scale and the set-up designed to prevent unscrewing when testing cable bolts. Then, we present the samples preparation procedure, as well as the main characteristics of the bolts, the grouting materials and the rock type used to prepare the samples. Later, the main results obtained for rock bolts are presented, followed by the results for cable bolts. For a given bolt type and dimensions, our results compare well with past investigations (Benmokrane et al., 1995; Hyett et al., 1995; Moosavi et al., 2005; Ivanovic and Neilson, 2009). The experimental data presented here extend the available database of pull-out test results, and can be used both as a technical reference under the specified conditions, and as a means of comparison between model predictions (which include operating conditions, and sample components and behavior) and laboratory-scale data.

2. Laboratory-scale pull-out bench

2.1. Bench description

A pull-out bench based on the double-embedment principle was recently designed by MINES ParisTech (Blanco-Martín, 2012), considering existing benches (Hagan, 2004; Reynolds, 2006). Fig. 1 shows a cutaway section of the bench and an overview of the experimental facility in the laboratory (the parts listed in the figure are presented in italics in this paragraph). The bench can be divided into two main parts: in the lower part, the bolt is grouted by means of a grouting material (resin, cement grout) to a cylindrical rock sample over a variable length (embedment length). An end plate is placed on top of the rock sample to constrain the rock and grout annuli vertically at point \( Z = L \). In the upper part, a steel metallic tube is grouted along the bolt length that protrudes from the rock borehole. The metallic tube is considerably longer than the embedment length; therefore, any axial slip is more likely to occur in the rock borehole, while the bolt remains anchored to the metallic tube. In the rock sample, the embedment lengths tested are calculated so that the bolt remains in the elastic phase throughout the entire duration of the test.

As it can be seen in the cutaway section, the bolt links together the upper and the lower parts of the bench. The biaxial cell is used to apply a lateral confining pressure to the rock sample. Hydraulic oil is used as confining fluid. To prevent the formation of pore pressures and to ensure a proper distribution of the confinement, a cylindrical bladder is placed around the rock sample. The confining pressure can be varied or held constant during the test, so that the tests can be conducted under constant outer radial pressure, or under constant outer radial stiffness conditions. When the tests are conducted under constant outer radial pressure conditions, a hydraulic accumulator is connected to the biaxial cell to keep the confining pressure constant. On the other hand, when the tests are carried out under constant outer radial stiffness conditions, the biaxial cell is a closed system (constant mass of hydraulic oil) and consequently the confining pressure can change. In this case, it is the stiffness of the confining fluid that remains constant, while the
stiffness of the sample is constant only if fractures are not created during the test. Note that this configuration is different from field conditions, in which the stiffness at the borehole wall is constant. Finally, the maximum confinement that the bench can withstand is 25 MPa.

The axial force on the bolt is applied by a hollow ram jack, which is placed above the confining cell, on the upper piston. The force is transferred to the metallic tube (thus, to the bolt) via a threaded plate that is screwed on the tube. A customized load cell provided with a load bearing/distribution plate is placed between the jack piston and the threaded plate. The axial displacement is measured by three linear variable differential transformer (LVDT) sensors, and the average is computed. The LVDTs support is installed on the threaded plate and is fixed by a lock nut.

The set-up shown in Fig. 1 is completed with some additional parts when a cable bolt is tested. Indeed, it is well known that the process of unscrewing that occurs for short embedment lengths could distort the results of a laboratory pull-out test on a cable bolt (Bawden et al., 1992). In fact, as a consequence of their helical structure and low torsional rigidity, cable bolts may unscrew from the grout annulus during a short-length pull-out test. Unscrewing is an unrealistic phenomenon because cable bolts cannot unscrew in real field situations. In order to avoid unscrewing, some additional parts have been designed for the bench. First, the rock and the fixed part of the hydraulic jack are interdependent and hence no relative rotation is allowed between them. Second, two pins are inserted between the jack piston and the threaded plate, so that any possible relative rotation between that piston and the metallic tube (thus, the cable bolt) is blocked. In this situation, the only possible relative rotation would take place between the fixed part of the jack and its piston. In order to prevent such relative movement, a metallic ring is screwed around the fixed body of the jack and blocked in rotation using three cone-point screws. The threaded plate is linked to this ring by two 20 mm diameter steel rods that are fixed to the ring and go across the plate (i.e. the plate can slide along the two rods). Fig. 2 shows the set-up designed to prevent the relative rotation between the two parts of the jack. Under these circumstances, as the jack piston moves upwards during the test, all the parts of the bench will rotate together, should any rotation occurs.

Fig. 2. Tools to prevent unscrewing (cable bolts). The circled areas show the parts designed to prevent relative movement (left: between the rock sample and the jack; center: between the bolt and the jack piston; right: between the fixed part of the jack and its piston).

Furthermore, the cable will untwist itself (rather than unscrew from the borehole) during the pull-out process, thereby simulating the field conditions of a rock block sliding off an unplated cable.

2.2. Samples preparation and test execution

A laboratory pull-out test sample consists of the bolt (rock bolt or cable bolt), the rock sample, the metallic tube and the materials used to grout the bolt to the rock and to the tube. The proper preparation of the samples, in particular the accurate coaxiality of all elements, is very important to ensure the correct assemblage of the experimental bench. The main steps in the preparation of a laboratory sample are:

(1) Drilling of the rock sample and central borehole. The borehole radius depends on the bolt type and the desired annular space. In this study, the ratio between the radius of the borehole and the bolt remains practically constant.

(2) In order to facilitate decoupling at the bolt-grout interface, the borehole wall is rilled to improve the bond between the rock sample and the grouting material.
Preparation of the metallic tubes (cutting, rifling of the internal surface and external threading).

Grouting of the bolt into the borehole (resin or cement grout).

Grouting of the bolt into the metallic tube (fast cure adhesive).

Once the sample is ready, the bench is assembled. We note that in the case of smooth bars, a barrel and wedge system is installed above the metallic tube to prevent the tube from sliding off the bolt. In fact, in the case of rough bolts, the bolt profile (plus the grooves made along the metallic tube inner surface) makes the slip inside the metallic tube difficult. However, a smooth bar makes such slip easier, especially if the confining pressure applied to the rock sample is high. In the case of cable bolts, a barrel and wedge system is also used to avoid any possible relative slip between the bolt and the tube (the embedment length within the rock sample is longer for cable bolts). Fig. 3 shows a barrel and wedge system mounted on a sample containing a Reflex cable bolt.

Once a pull-out test is finished, the pressure of the jack is relieved before relieving that of the biaxial cell, in order to prevent failure of the rock sample.

### 3. Testing materials

#### 3.1. Rock type and grouting materials

All the pull-out tests have been conducted using sandstone samples and all the bolts have been grouted with either resin (Minova Lockset Sis SF-L 32/500) or a cementitious grout (Portland cement and water). For grouts with water/cement ratio \( w/c = 0.35 \), Chryso’s Fluid Optima 175 fluidifier has been added to improve the workability of the mixture. The dosage used is 1% in mass of the weight of cement. Table 1 shows the relevant mechanical properties of the rock and the grouting materials used.

<table>
<thead>
<tr>
<th>Medium</th>
<th>Density (kg/m³)</th>
<th>Young's modulus (MPa)</th>
<th>Poisson's ratio</th>
<th>Uniaxial compressive strength (MPa)</th>
<th>Tensile strength (MPa)</th>
<th>Cohesion (MPa)</th>
<th>Friction angle (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sandstone</td>
<td>2130</td>
<td>25,600</td>
<td>0.26</td>
<td>62.4</td>
<td>3.1</td>
<td>12.4</td>
<td>46</td>
</tr>
<tr>
<td>Resin</td>
<td>1987</td>
<td>11,450</td>
<td>0.31</td>
<td>67.1</td>
<td>12.1</td>
<td>20.2</td>
<td>28</td>
</tr>
<tr>
<td>Cement ( w/c = 0.35 )</td>
<td>1958</td>
<td>17,500</td>
<td>0.27</td>
<td>44.1</td>
<td>3.2</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

### 3.2. Rock bolts

Three types of rock bolts have been tested:

1. 25 mm diameter steel rebars: HA25 bars conforming to NF EN 10080 (2005) and NF A35-080-1 (2010), manufactured by Riva Acier SA in steel grade B500B, referred to as HA25 rock bolts;
2. 25 mm diameter FRP rock bolts: Power thread bars manufactured by Minova-FiReP, referred to as FRP rock bolts;
3. 25 mm diameter smooth steel bars: type SS 316L, manufactured by Acieries de la Seine, referred to as SSB.

### Table 2

Relevant mechanical properties of the tested rock bolts.

<table>
<thead>
<tr>
<th>Bolt type</th>
<th>Nominal diameter (mm)</th>
<th>Young’s modulus (GPa)</th>
<th>Tensile capacity (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HA25</td>
<td>25</td>
<td>160</td>
<td>620</td>
</tr>
<tr>
<td>FRP</td>
<td>25</td>
<td>40</td>
<td>1060</td>
</tr>
<tr>
<td>SSB</td>
<td>25</td>
<td>193</td>
<td>600</td>
</tr>
</tbody>
</table>

### Fig. 4.

Profiles of the tested rock bolts. Note that HA25 rock bolts are characterized by two series of sharp indentations uniformly distributed along the bar perimeter and separated by two longitudinal ribs.

### Fig. 5.

Geometrical characteristics of indentations.

---

Table 1

Relevant mechanical properties of the sandstone and grouting materials.

<table>
<thead>
<tr>
<th>Medium</th>
<th>Density (kg/m³)</th>
<th>Young’s modulus (MPa)</th>
<th>Poisson’s ratio</th>
<th>Uniaxial compressive strength (MPa)</th>
<th>Tensile strength (MPa)</th>
<th>Cohesion (MPa)</th>
<th>Friction angle (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sandstone</td>
<td>2130</td>
<td>25,600</td>
<td>0.26</td>
<td>62.4</td>
<td>3.1</td>
<td>12.4</td>
<td>46</td>
</tr>
<tr>
<td>Resin</td>
<td>1987</td>
<td>11,450</td>
<td>0.31</td>
<td>67.1</td>
<td>12.1</td>
<td>20.2</td>
<td>28</td>
</tr>
<tr>
<td>Cement ( w/c = 0.35 )</td>
<td>1958</td>
<td>17,500</td>
<td>0.27</td>
<td>44.1</td>
<td>3.2</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>
Table 3
Geometrical characteristics of the indentations of HA25 and FRP rock bolts (see variables in Fig. 5). For HA25 bolts, values in parentheses correspond to the lower profile of this bar in Fig. 4.

<table>
<thead>
<tr>
<th>HA25</th>
<th>FRP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ribs height, (h_i) (mm)</td>
<td>FRP</td>
</tr>
<tr>
<td>Ribs thickness, (t_i) (mm)</td>
<td>(h) (mm)</td>
</tr>
<tr>
<td>Indentations top</td>
<td>Indentations orientation, (\beta) (°)</td>
</tr>
<tr>
<td>thickness, (\ell) (mm)</td>
<td>Indentations spacing, (c) (mm)</td>
</tr>
<tr>
<td>Indentations height, (h) (mm)</td>
<td></td>
</tr>
<tr>
<td>Indentations angle, (\alpha) (°)</td>
<td></td>
</tr>
</tbody>
</table>

1.04–0.35 2.7 2.6 (2.4) 2.4 (2.1) 45 (46) 69–53 (62) 32.6–7.8 (16.3) 1.6 25 8

Table 4
Relevant mechanical properties of the tested cable bolts.

<table>
<thead>
<tr>
<th>Bolt type</th>
<th>Nominal diameter (mm)</th>
<th>Young’s modulus (GPa)</th>
<th>Tensile capacity (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reflex</td>
<td>23</td>
<td>188</td>
<td>500</td>
</tr>
<tr>
<td>Mini-cage</td>
<td>16.2 (cage diameter: 25)</td>
<td>195</td>
<td>300</td>
</tr>
<tr>
<td>IR5/IN</td>
<td>25.7 (intermediate section)</td>
<td>206</td>
<td>460</td>
</tr>
</tbody>
</table>

Fig. 6. General profiles of the Reflex and Mini-cage cable bolts.

Table 5
Geometrical characteristics of the indentations of Reflex bolts (see variables in Figs. 5 and 6).

<table>
<thead>
<tr>
<th>(R_{\text{ave}} (R_{\text{long wire}})) (mm)</th>
<th>Pitch length, (l_p) (mm)</th>
<th>(t) (mm)</th>
<th>(h) (mm)</th>
<th>(\beta) (°)</th>
<th>(c) (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.8 (8.9)</td>
<td>300</td>
<td>1.65</td>
<td>0.1–0.2</td>
<td>50</td>
<td>7.5 (±0.5)</td>
</tr>
</tbody>
</table>

The first two rock bolts are commonly used as support in long wall mining (Barley and Windsor, 2000). The SSB have been tested to study the influence of the bolt profile. The mechanical properties of these three rock bolts are listed in Table 2, and their profiles are shown in Fig. 4. As it is visible from this figure, the indentations in FRP rock bolts are smoother and more regular than those in HA25 rock bolts. Fig. 5 and Table 3 display the geometrical characteristics of the indentations.

3.3. Cable bolts

Three types of cable bolts have been tested:

1. 23 mm diameter flexible cable bolts: indented seven-wire strands manufactured by Osborn Strata Products, referred to as Reflex cable bolts;

2. 16.2 mm diameter Mini-cage cable bolts: flexible, smooth seven-wire strands with a flow bulb construction for better grout migration, manufactured by Osborn Strata Products;

3. IR5/IN special cable bolts used in Polish coal mines and manufactured by PPUH Interram.

The mechanical properties of the three cable bolts are listed in Table 4, and the profiles of the Reflex and Mini-cage bolts are shown in Fig. 6. The geometrical characteristics of the indentations of Reflex bolts are listed in Table 5. A detailed description is given for the IR5/IN cable bolt as it is not conventional.

The IR5/IN cable bolts were provided by Gliwny Instytut Gornictwa in Poland and Jastrzebska Spolka Weglowa SA (a Polish mining company). This support is totally different from the cable bolts commonly used in coal mines. As far as design is concerned, this cable bolt is very similar to the Megastrand bolt produced by Megabolt Australia Ltd., but the wires are smooth. A typical 8 m length cable bolt is composed of three parts from right to left (see Fig. 7):

1. A 1.1 m long section equipped with an injection head;
2. An intermediate 5.6 m long and 25.7 mm diameter section composed of eight smooth steel wires around a central injection tube. Due to the light twist of the strand, the wires are kept in position with steel rings installed along the total cable length. Note that the grout can spread across the gaps between the wires;
3. A 1.3 m long and 22 mm diameter section with only the eight smooth steel wires, welded at the end to a steel cap dedicated to resin mixing.

4. Pull-out tests on rock bolts

The pull-out tests performed on SSB, HA25, and FRP rock bolts are listed in Table 6. The embedment lengths tested for rock bolts are controlled within the recommended range of about \([6R_b, 10R_b]\), where \(R_b\) is the bolt radius. Two short embedment lengths, 90 mm and 130 mm, were used in most tests and different confining pressures, up to 15 MPa, were applied. In Table 6, CRS refers to constant radial stiffness conditions and CRP refers to constant radial pressure conditions. Note that for CRS tests, the value of confining pressure \((P_{cr})\) listed corresponds to the beginning of the
test. For CRP tests, the confining pressure \( (P_r) \) is constant during the test. At the beginning of the experimental campaign, the tests were performed at CRP conditions, and it was later decided to move to CRS conditions in order to study the radial behavior more accurately. The goal of the tests was to create debonding at the bolt-grout interface.

For a given test, results are presented in the form of two curves: axial load versus axial displacement, and confining pressure variation versus axial displacement.

### 4.1. Load-displacement response

The load–displacement response of HA25 and FRP bolts can be divided into four stages (Figs. 9a, 10a, 11a and 12a). Each stage is associated with a particular mechanism:

1. A quasi-linear response for small values of axial displacement. In this stage, interface adhesion, mechanical interlock and friction contribute to the bolt-grout bond.
2. The axial stiffness drops and the load–displacement response becomes nonlinear before the peak force is reached. This stage is associated with the development of a joint, which damages the bolt-grout bond gradually, thereby decreasing its bearing capacity.
3. The axial load reaches a maximum value.
4. The load decreases steeply initially, followed by a residual phase. The damage of the interface is believed to occur in an unstable manner in this stage. The residual load depends on both the confining pressure (friction) and the mechanical interlock (due to the bolt profile).

### 4.2. Main results

Fig. 8 shows the load–displacement curves for three tests performed on smooth bars using the same embedment length and different confining pressures. In this figure, the pull-out response presents an initial phase until a peak force, followed by a sudden load drop and subsequent load increase. Next, a second peak is attained, and then the force decreases sharply to a residual value. The first phase is due to failure inside the metallic tube at the bar-

### Table 6
Pull-out tests conducted on rock bolts.

<table>
<thead>
<tr>
<th>Bolt type</th>
<th>Confining pressure (MPa)</th>
<th>Embedment length (mm)</th>
<th>Grout type</th>
<th>Test conditions</th>
<th>Rate (mm/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HA25 (29 tests)</td>
<td>0–15</td>
<td>90–325</td>
<td>Cement (3 tests)</td>
<td>CRP (6 tests)</td>
<td>0.84 (13 tests)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Resin (26 tests)</td>
<td>CRS (23 tests)</td>
<td>0.02 (16 tests)</td>
</tr>
<tr>
<td>FRP (18 tests)</td>
<td>0–15</td>
<td>90–170</td>
<td>Cement (2 tests)</td>
<td>CRP (3 tests)</td>
<td>0.84 (10 tests)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Resin (16 tests)</td>
<td>CRS (15 tests)</td>
<td>0.02 (8 tests)</td>
</tr>
<tr>
<td>SSB (5 tests)</td>
<td>0–5</td>
<td>100–130</td>
<td>Resin</td>
<td>CRP</td>
<td>0.02</td>
</tr>
</tbody>
</table>

Fig. 8. Effect of confining pressure on smooth steel bars (SSB) \((L = 130 \text{ mm}, \text{CRP tests}, \text{rate} = 0.02 \text{ mm/s})\).
grout interface. Failure of the bar-grout bond corresponds to the first peak in the curves in Fig. 8. Thereafter, the barrel and wedge system starts to act, gripping itself to the smooth bar, thereby blocking the relative displacement between the tube and the bar. This process corresponds to the second ascending branch in the curves. The second peak load corresponds to failure of the bolt-resin bond inside the rock sample. Overall, the peak force and the corresponding axial displacement increase with the confining pressure. After the peak, the load decreases sharply due to the loss of interface adhesion and the absence of mechanical interlock (smooth profile), and finally the residual phase is attained.

Debonding also occurred at the bolt-grout interface in the case of HA25 rock bolts. The effects of the embedment length and the confining pressure are shown in Figs. 9 and 10, respectively. As it can be seen, an increase of one of these parameters leads to an increase of the peak force and the peak displacement. As opposed to the smooth bars, the post-failure behavior is characterized by progressive softening followed by a residual phase. In the tests held under CRS conditions, the confining pressure variation can be used to estimate the radial displacement (Blanco-Martín et al., 2013, 2016). This is advantageous in the current bench configuration since the radial displacement of the sample is not measured directly. Finally, note that the pressure variation under CRS conditions follows the same trend as the axial force (link between axial and radial behaviors).

The same overall behavior is obtained for FRP rock bolts, although some differences are visible in the post-failure phase (see Fig. 11 for the effect of the embedment length, and Fig. 12 for the effect of the confining pressure). The oscillations (due to the bolt profile) are clearer for FRP than for HA25 bolts at every pressure tested (note however that the amplitude decreases with the applied confining pressure). The main reason for this difference is the bolt profile, which is smoother (in terms of angle of indentations) for the FRP bars. As a result, the bolt imprints are less sheared, and the failure interface is not smooth, but reproduces the bolt profile quite well, even at the end of the test (this has been proved by the visual observation of the samples after the tests). Finally, as it can be seen from Figs. 11b and 12b (and also Figs. 9b and 10b), the radial pressure variation follows closely the oscillations in the axial force.

Regarding the state of the samples after the test, radial fractures were observed in the rock and grouting material at low confining pressures. This well-known phenomenon affects the pull-out response and makes the study of the bolt-grout interface difficult.
(Kaiser et al., 1992; Hyett et al., 1995; Blanco-Martín et al., 2013). In order to study the interface response accurately, radial fractures should be avoided, and the bench configuration should be kept as simple as possible to reduce uncertainty in the measurements and the processes underneath.

4.3. Summary of tests conducted on rock bolts

The results obtained on rock bolts are analyzed in terms of the following parameters: yield bond strength, defined according to the British Standard Institute (BSI, 1996) as the load at which the slope of the load–displacement curve falls below a stiffness of 20 kN/mm; axial stiffness (slope of the load–displacement curve) in the load range between 40 kN and 80 kN; peak or maximum load, and residual load, measured at an axial displacement of 50 mm. These results are given as a function of the confining pressure in Fig. 13, for HA25 and SSB bolts ($L = 130$ mm), and for FRP bolts ($L = 90$ mm). Since the tested embedment lengths ($90$ mm and $130$ mm) are quite similar, only results for one length per bolt type are displayed.

As shown in Fig. 13, a clear tendency of increase is observed for the bond strength and the maximum load. This tendency is

Fig. 12. Effect of confining pressure on FRP rock bolts ($L = 90$ mm, CRS tests).

Fig. 13. Summary of results of HA25, FRP and SSB rock bolts as a function of the confining pressure. Note that results for FRP bolts are displayed for $L = 90$ mm.
less pronounced for the residual load and the axial stiffness. Also, the SSB rock bolts have lower characteristics and are considered here only to illustrate the influence of the bolt profile.

5. Pull-out tests on cable bolts

Table 7 lists pull-out tests performed on Reflex, Mini-cage and IR5/IN cable bolts. The embedment length ranges from small (90 mm) to relatively high (400 mm), and the confining pressure ranges from 0 to 20 MPa. Most of the tests were performed under CRS conditions. The same resin used for rock bolts was employed as grouting material for all cable bolts. We note that debonding occurred at the bolt-grout interface in all cases.

5.1. Tests on Reflex cable bolts

Figs. 14–16 show typical results obtained on Reflex bolts. Before the peak, the bolt-grout bond seems to be provided by the same mechanisms as that for rock bolts (i.e. interface adhesion, friction and mechanical interlock). However, significant differences are observed in the post-peak phase. After a small load drop (likely due to the cable geometry), the residual phase is characterized by a very progressive reduction of the axial load, much more progressive than that observed for rock bolts. Note that for a given embedment length and confining pressure, the residual load is higher than that of rock bolts. Small oscillations (due to the strands profile) are present in the residual phase; their evolution depends not only on the confinement but also on the cable structure (slight untwisting).

5.2. Tests on Mini-cage cable bolts

The Mini-cage cable bolts were tested with a bulb located at the center of the embedment length. As a consequence, the axial displacement during the pull-out test is accompanied by a significant outer radial displacement induced by the bulb. After around 10 mm of axial displacement, a radial fracture occurred in the rock sample. The failure of the rock samples did not allow to investigate with confidence the effect of the confining pressure on the post-failure phase. In the same way, the radial displacement, which is governed by the dilatancy induced by the bulb, is totally disturbed by this failure. On this basis, only the phase preceding the creation of the fractures has been analyzed (see Section 5.4).

5.3. Tests on IR5/IN cable bolts

IR5/IN cable bolts are designed to be used in prestressed conditions; unfortunately, it was not possible to prestress the cables in our laboratory-scale bench. Therefore, the results obtained for IR5/IN cables should not be considered for comparison purposes or as a reference in other situations.

Owing to the smooth profile of the wires, a process similar to the SSB occurred during the tests, i.e. the bolt-grout bond within the metallic tube failed at an early stage, and subsequently the barrel and wedge system started to act, causing a second increasing phase of the axial load corresponding to the bolt-grout interface inside the rock sample. After failure of this bond, the load decreases steeply.

Different set-ups were tried in order to test the influence of the steel ring welded at the extremity of the cables (see Fig. 7). Fig. 17 displays three load–displacement curves corresponding to three different configurations (no steel ring, a ring welded in four diametrically-opposed points, and a ring welded on the
whole perimeter). As it can be seen, the results are totally dependent on the steel ring (the welding fails and only the wires are sheared during the pull-out test, while the ring remains at its initial position). Moreover, dilatancy induced by the ring leads to the development of major horizontal fractures within the rock sample. As the pull-out test results should focus on the global response of the bolt, it was decided not to install this welded ring in subsequent tests. Note that the results without welded end displayed in Fig. 17 compare well with past investigations on classic, smooth seven-wire cable bolts (Benmokrane et al., 1995).

5.4. Summary of tests conducted on cable bolts

The results of the tests conducted on Reflex cable bolts are summarized in Fig. 18. Given the wide range of embedment lengths tested (wider than that for rock bolts, see Fig. 13), results are presented for several lengths.

Overall, the four parameters displayed increase with the confining pressure and the embedment length (tendency less obvious for the axial stiffness). For Mini-cage cable bolts (Fig. 19, \( L = 325 \text{ mm} \)), although the experimental conditions limit the range
of observations, the bond strength shows a tendency to increase with the confining pressure.

6. Conclusions

This paper presents pull-out test results performed at laboratory-scale on three types of rock bolts and three types of cable bolts. Each bolt has been tested using different embedment lengths and confining pressures. Resin and cement have been used as grouting materials, and in all cases, the bolts have been grouted into a sandstone sample. The tests have been performed using a pull-out bench that allows testing a wide range of parameters. Constant confinement or constant radial stiffness has been used as boundary conditions. The study presented has been performed in static conditions, and its main goal is to investigate debonding at the bolt-grout interface.

Experimental results show that interface adhesion, friction and mechanical interlock (threaded bars) contribute to the bolt-grout bond. The comparison between pull-out results of smooth and threaded bolts clearly shows that the bolt profile plays an important role: not only the maximum load is greater for threaded bolts, but also the post-peak phase shows a more gradual force decrease. Moreover, the bolt profile is reflected in the oscillations measured in the post-peak phase, whose periodicity matches the indentations of the tested bar.

Results for HA25 and FRP threaded bolts show overall similar trends, with a stiff, quasi-linear pre-peak phase, followed by a drop of stiffness, a maximum force and finally a post-peak phase in which the axial force decreases towards a residual value, much

Fig. 18. Summary of results of Reflex cable bolts as a function of the confining pressure and the embedment length.
lower than the peak force. Depending on the confining pressure, oscillations on the load occur according to the bolt profile; these oscillations are less clear for high pressures, for which the grout between the bolt asperities is sheared. The operating conditions in the radial direction affect both the radial and the axial responses. In the current bench configuration, the advantage of using constant radial stiffness conditions is that the confining pressure variation can be used to estimate the radial displacement. Results obtained for cable bolts are also consistent and show similar trends to rock bolts. Two likely reasons to this difference are the bar type (solid against initially twisted wires) and the bolt profile (geometry of indentations).

Regarding the Mini-cage cable bolts, their profile induced severe damage to the rock sample. In the case of the IR5/IN bolts, pull-out results were very sensitive to the configuration at the free end. These results, together with the radial fracturing that often occurs at low confining pressures (rock bolts and cable bolts), highlight the difficulty of assessing the bolt-grout interface behavior from raw pull-out data, and also the importance of addressing the behavior of the sample as a whole before focusing on the interface. In order to study the interface response accurately, the bench configuration should be kept as simple as possible to reduce uncertainty in the measurements and the processes underneath (fracturing, rock response, bench calibration, etc.).

The results presented are consistent with previous pull-out test results on similar rock bolts and cable bolts, and provide an extensive database of laboratory-scale results, focusing on the influence of the confining pressure and the embedment length on the pull-out response of fully grouted bolts. These data can be used both as a technical reference under the specified conditions, and as a means of comparison between model predictions (which include operating conditions, and sample components and behavior) and laboratory-scale data.

Conflict of interest

The authors wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

Acknowledgments

This work has been supported by the European Research Fund for Coal and Steel in the AMSSTED Programme RFCR-CT-2013-00001. During this research, the contribution of all partners and reference studies of Lorraine Kent and colleagues of Golder-UK were highly appreciated.

References

Barley A, Windsor CR. Recent advances in ground anchor and ground reinforcement technology with reference to the development of the art. In: ISRM international symposium. ISRM; 2000.


Isabelle Thenevin has been involved in geo-mechanical experimentations and research programs at the Geosciences Department of the Ecole des Mines de Paris since 1993. In 1992, she passed an engineering degree in geology and mining and a master degree in mining and civil works. In 1998, she graduated with a PhD. She was appointed as training manager at the French Ministry of Industry in 2006. To date, she has been involved in geohazards research applied to infrastructures: design of the cover of nuclear waste storages, development of winter sport resort threatened by debris flow and now support systems for deep underground mining activities. Her abilities cover geological observations, monitoring systems, data analysis, modeling and design. From 2000 to 2012, she developed and managed international training programs in engineering geology and mining project evaluations. In recent years, she was co-investigator in a research program on support systems for tunneling with conventional method (soil nailing and pipe umbrella). At present, she is senior lecturer in both Mines-ParisTech and Ponts-ParisTech (two state-owned high academies) for Masters and other educational programs in the fields of engineering geology. She is active member of professional organizations including “la SIM” (French Society for Mineral Industry).