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Full Length Article

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

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ABSTRACT

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.

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 (Papamichalis 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

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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 (Benmokrane 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

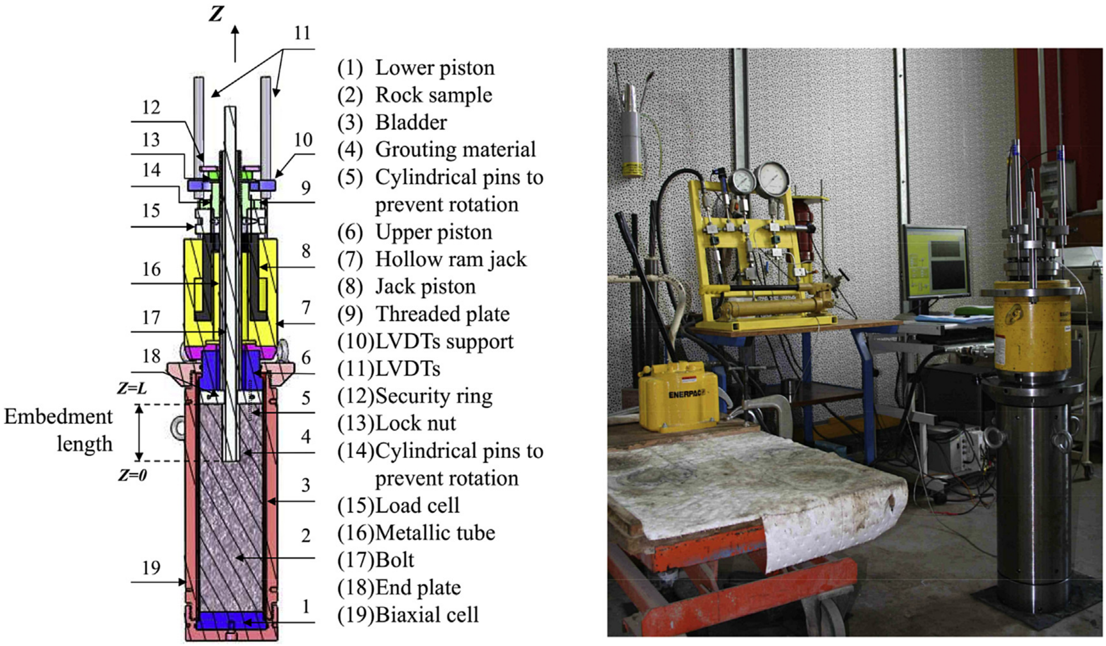

Fig. 1. Cutaway section of the pull-out bench and overview of the laboratory facility.