

Characterization of Internal Insertion Pressure During Installation of Fully Grouted Bolts

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ABSTRACT

The installation procedure of fully grouted rebar bolts requires that the bolt be pushed through the resin grout until it is fully inserted in the borehole. Resin grout is a highly viscous fluid that is forced to flow through the annulus between the bolt and the borehole as the bolt advances. Variables such as bolt insertion speed, bolt vs. borehole diameter and grout viscosity determine the magnitude of the pressure generated ahead of the bolt tip. Under weak rock conditions, the magnitude of the pressure of bolt insertion is often sufficient to initiate hydraulic fracturing along joints or bedding planes that allow injection of grout into the strata leading to significant loss of bolt encapsulation. The grout pressure front has also been linked to gloving, a bolt installation problem that reduces bolt effectiveness. A series of tests were conducted to characterize the pressure of bolt insertion during bolt installation under various conditions. Analysis of the data shows three distinct stages of pressure build up during bolt installation. Understanding of the mechanisms involved may allow development of strategies for controlling the pressure buildup and its negative impact during roof bolting under weak rock conditions.

INTRODUCTION

As part of a research program sponsored by NIOSH aimed at improvement of rock bolt performance in mines with low strength roof rock, Raytheon UTD has performed pull testing of grouted bolts at several coal mines. Loss of grout during bolt insertion and gloving were two the problems observed during testing. Recent studies have linked these problems to the pressurization of the grout during roof bolt installation. Compton and Oyler (2005) conducted research on the topic and measured grout pressures during bolt insertion of between 4,000 and 5,000 psi. They suggested that either high installation pressures or resin extrusion are normal conditions during resin bolt installation. Campbell and Mould (2003) attributed the gloving problem to the pressurization of the cartridge before rupturing. Additionally, they measured grout pressures considered to be sufficient in magnitude to induce hydraulic fracturing of the strata. In this study, a new approach was used to estimate the magnitude and observe the behavior of the pressure front during roof bolt insertion.

TEST PROCEDURE

Originally, the test was intended to identify a bolt diameter, hole diameter, grout type and insertion speed combination that could guarantee complete bolt encapsulation. The data collected during testing would characterize the forces required for bolt insertion for various resin types, insertion speeds, and annulus sizes. Analysis of the results would help to understand how these parameters interact to generate the pressure front ahead of the bolt tip and allow estimation of the magnitude of this pressure. The pressure front is thought to be the precursor to hydraulic fracturing of the roof followed by resin loss which in turn reduces the length of bolt encapsulation.

Testing consisted of pushing a standard bolt at constant speed without rotation into the grout filled borehole using the drill head of the bolter as shown in Figure 1. Insertion without rotation was necessary because of limitations of the instruments used. A load cell was installed between the drill head and the bolt to measure load. An extensometer was used to measure displacement. Values of load and displacement were simultaneously measured by a data acquisition system and recorded by a laptop computer for analysis. The bolts were subsequently extracted and the length of bolt encapsulation was recorded by measuring the length of bolt that had been wetted by the grout.



Figure 1. Test Configuration

25th International Conference on Ground Control in Mining

The plan called for three bolting systems employing standard rebar bolts of two diameters, grout from two major manufacturers and two insertion speeds. Twelve combinations of these parameters are possible and two (2) tests were to be performed for each combination for a total of 24 tests. The bolt systems were: (a) a #6 bolt in 1.03" diameter hole, (b) a #6 bolt in 1.25" diameter hole and (c) a #7 bolt in 1.375" diameter hole, all using 6-foot long standard headed rebar bolts. The grout types tested were Minova LIF and Fasloc low viscosity, both with a two (2) minute set time. The long set time allowed insertion and removal of the bolts before hardening of the resin. Grout cartridges of 0.9, 1.125 and 1.25 inches in diameter and 6-foot in length were used to match each of the bolting systems. Since the grout cartridge length was constant, there was, respectively, 36%, 11% and 20% excess grout required for full bolt encapsulation. The insertion speeds selected for testing were 4.5 and 7 inches per second. Table 1 shows a matrix of the possible tests. Fasloc grout packaged in 1.125" diameter cartridges was not available for testing.

Bolt System	Grout Type & Cartridge Diameter	Insertion speed
(a) #6-1.03"	LIF Minova 0.9" dia.	7 in/sec
		4.5 in/sec
	Fasloc 0.9" dia.	7 in/sec
		4.5 in/sec
(b) #6-1.25"	LIF Minova 1 - 1/8" dia.	7 in/sec
		4.5 in/sec
	Fasloc 1 - 1/8" dia.	7 in/sec
		4.5 in/sec
(c) #7-1.38"	LIF Minova 1 - 1/4" dia.	7 in/sec
		4.5 in/sec
	Fasloc 1 - 1/4" dia.	7 in/sec
		4.5 in/sec

Table 1. Matrix of tests performed during testing.

RESULTS

As expected, the force required to push the bolt into the grout-filled borehole increased with the depth of bolt insertion. Observed load curves were similar for the two types of grout without significant load range difference. Load of insertion vs. depth was plotted for each of the tests. The plots exhibited a common behavior and three distinct load regions were identified (Figure 2).

The insertion load increased with a constant low rate up to a point around 20 inches of insertion (region I). At this point, the load increased at an accelerated rate for a short interval (region II) after which the load rate reduced to a rate slightly higher than the initial (region III). Region I is well defined in most of the tests. Regions II and III have more variability and in some cases region III is not clearly defined.

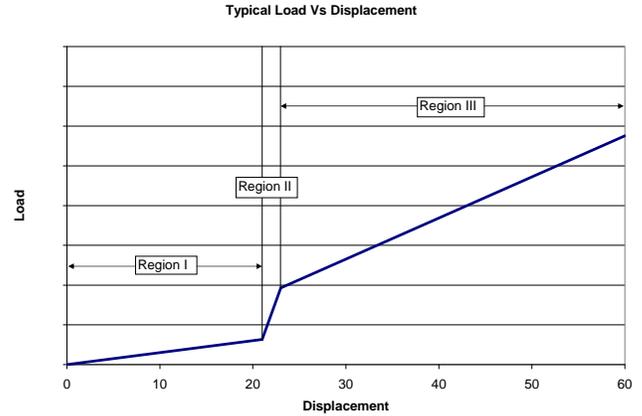


Figure 2. Typical load behavior during bolt insertion

Examination of the plot of load vs. displacement indicates that the following effects take place. In Region I there is a compression of the intact grout cartridge with a Poisson effect on the cartridge. That is, as the length of cartridge is compressed it swells within the hole until the first region transition is reached. Simultaneously, the grout pressure increases until the burst strength of the Mylar package is overcome at the end of region I transition. Once the Mylar package has burst, fluid flow of the resin takes place (region II) akin to flow of water in a pipe, albeit the fluid is much more viscous than water. The flow rate remains constant since the speed of insertion was maintained constant and the load increases proportionally to the length of bolt insertion. The end of region II occurs when pressure reaches a critical level and produces hydraulic fracturing of the roof rock. Region III is characterized by a lower pressure gradient than region II. This lower pressure gradient is a result of the relief provided by the flow of grout into the strata.

The maximum insertion force recorded for all the tests of the three bolt systems ranged between 1900 lb and around 3800 lb with an average value of around 3000 lb. Bolt systems with large annulus such as (b) and (c) showed grout return during bolt insertion (indicative of 100 % encapsulation) while bolt system (a) showed varying levels of bolt encapsulation from 50 to 90.8%.

In an attempt to visualize behavioral differences between the various bolt systems and speeds of insertion, the data for each individual test was manipulated as follows. As a first approximation, it was assumed that the measured force was mainly a result of the pressure build-up in front of the bolt. Using this assumption, the loads measured were divided by the sectional area of the bolt to obtain insertion pressure. Then the insertion pressure data for each combination of bolt system and insertion speed (normally 4 data sets for each) were averaged to obtain a characteristic curve for each set of variables. The results are presented in Figure 3.

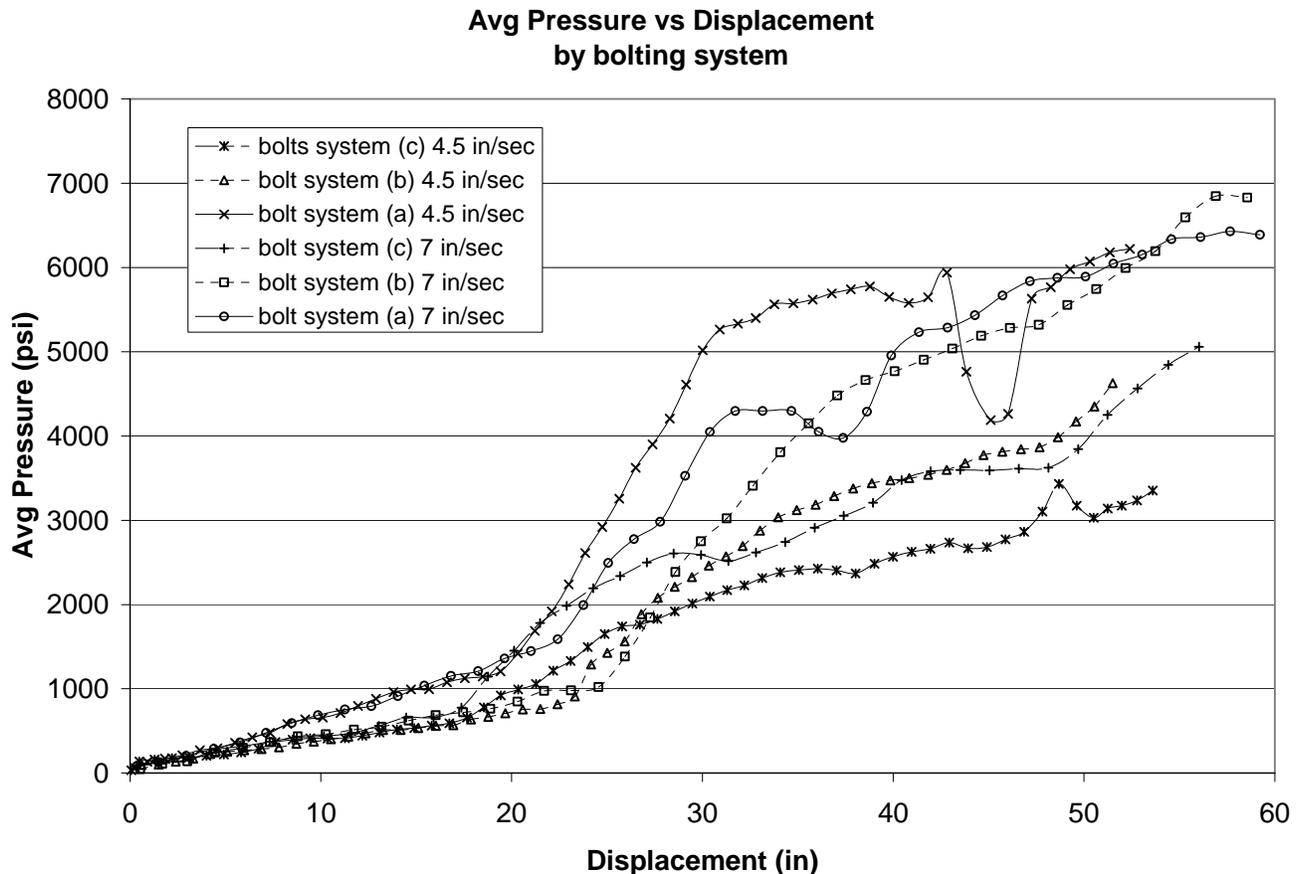


Figure 3. Characteristic curves of Pressure vs. Displacement (bolt insertion distance) for various bolt systems and speeds of insertion.

The calculated maximum pressures were around 3500 psi for system (c) at the low insertion speed and nearly 7000 psi for system (b) at the high insertion speed. These pressures are sufficient to induce hydraulic fracturing of the strata in the test area and are of the same order of magnitude of the measurements made by Compton and Oylar (2005). One variable that cannot be controlled in the mine environment is the rock strength or the existence of joints. This may explain in part the apparent contradictory results for system (a) in which the higher insertion speed recorded lower pressure than the same system at the high insertion speed.

The curves in Figure 3 seem to be a good representation of the various systems and insertion speeds. In general, systems with greater annulus around the bolt as well as slow installation speeds for each system present lower insertion pressures. The single exception to this general observation was evidenced when comparing the results of bolt system (a) in which the slower insertion speed produced higher insertion loads. Bolt system (a) was the only system that did not produce resin return during insertion. It was also observed during the system (a) experiments that tests that produced higher insertion pressures resulted in longer bolt encapsulation than the ones with lower pressures. This might be indicative of a more competent rock being able to sustain higher pressure. A likely explanation is that once a fracture has developed in the roof, the pressure does not increase since the grout has opportunity to escape. A stronger roof is able to sustain a higher pressure and allow longer encapsulation of the bolt. Additionally, it should be noted that the tests were conducted in an area of the

mine that had been previously mined and had time to relax and produce roof separation. Consequently it is reasonable to expect that bolts installed in recently mined areas exhibit better encapsulation than the test bolts installed in locations mined well in advance of test execution.

The three curves from the graph that exhibited the highest pressures, system (a) and the high insertion speed system (b), clearly present the three typical regions described above. The threshold pressure that produces the transition to region III and therefore hydraulic fracturing is in the order of 4000 to 5000 psi for this particular mine. The transition to region III for the high insertion speed system (b) shows a shift to the right compared with system (a), which is likely to be a contributing factor to the observed grout return during the test. The three remaining curves, that is system (c) and the low insertion speed system (b), don't show a clear transition to region III possibly indicating that hydraulic fracturing did not take place. The pressure toward the end of insertion of the high insertion speed system (c) and the low insertion speed system (b) reached magnitudes around 4500 and 5000 psi without evidence of pressure drop. Grout return was observed in all three instances for low speed system (b) and both insertion speeds for system (c).

Given the conditions at this particular test site, bolt system (a) generates insertion pressures capable of creating fractures in the roof. As a consequence, the bolt does not produce full encapsulation. The length of encapsulation varies from site to site

depending on the physical characteristic of the immediate roof rock. Bolt systems (b) and (c) produced full bolt encapsulation during the test and, although system (b) bolts inserted at the high speed of 7 in/sec generated maximum pressures similar to those obtained with the (a) system, the peak values were reached towards the end of the bolt insertion limiting the exposure of the roof to the high pressures and reducing opportunity for loss of grout. Table 2 summarizes the encapsulation results by bolting system.

Bolt System	Bar size	Hole Diameter (in.)	Avg. Encapsulation (%)
(a)	#6	1.03	68.6
(b)	#6	1.25	100
(c)	#7	1.375	100

Table 2. Measured Encapsulation for the various bolting systems.

These observations are consistent with those of Pile et. al. (2003). They measured length of bolt encapsulation for various annulus sizes and determined that the smaller the annulus, the smaller the actual bolt encapsulation length adding that the grout losses have a greater effect on bolt encapsulation when the annulus is small.

MATHEMATICAL MODEL

In this discussion a mathematical model of the behavior observed in region I is developed and numerical calculations test the validity of the model. In region I the grout cartridge is compressed axially by the bolt pushing up and expands pushing radially against the borehole. Expressions for the volume of grout in a hole and the volume of grout available in the cartridge are as follows:

$$V_h = \frac{\pi D^2}{4} \cdot L_f \tag{Equation 1}$$

Where:
 V_h = the volume of grout in the hole
 D = diameter of the hole
 L_f = length of the grout filled section of hole

$$V_g = \frac{\pi d^2}{4} \cdot L_g \tag{Equation 2}$$

Where:
 V_g = the volume of the grout cartridge
 d = diameter of grout cartridge
 l_g = length of grout cartridge

Therefore, the length of the hole filled by the grout cartridge (illustrated in Figure 4) can be found by the following equation:

$$L_f = L_g \cdot \frac{d^2}{D^2} \tag{Equation 3}$$

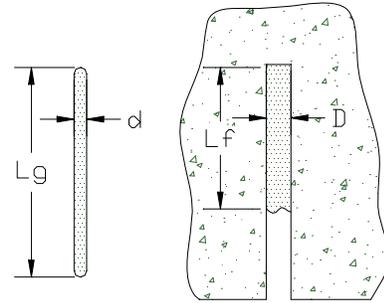


Figure 4. Volume in the hole occupied by the grout from the cartridge.

Up to this point the grout has undergone expansion to occupy the top of the borehole while compression takes place. The distance that the bolt has traveled into the borehole is the total length of the hole minus the length of hole filled with grout (L_f). Using actual numbers from one of the tests, a 0.9” diameter grout cartridge, 66” in length was used. The average hole diameter was found to be 1.051”. Solving for L_f = 48”. Therefore, the insertion before the grout cartridge fills the hole would be 66-L_f or 66-48 or 18 inches. Cartridge end conditions are not included in this calculation but could easily account for the variation in the data of the length of bolt insertion at the point where region I ends and region II begins.

The pressure build up in region I is limited by the strength of the Mylar film that encases the grout. The pressure required to burst the film is dependent on the cross sectional area of the film as well as its physical properties. Bursting pressure is reached when:

$$P = S \cdot \frac{A_f}{A_s} \tag{Equation 4}$$

Where:

P = bursting pressure
 S = the tensile strength of the film
 28 ksi min 34 ksi max
 A_s = cross sectional area under pressure
 A_f = film cross sectional area

This equation can be reduced to:

$$P = \frac{2t \cdot S}{(R - r)} \tag{Equation 5}$$

Where:

t = thickness of Mylar film
 R = radius of hole
 r = radius of bolt

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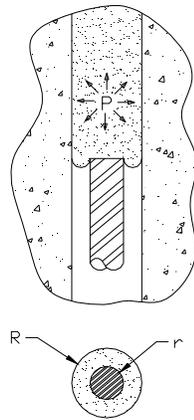


Figure 5. Schematics showing grout pressurization before the rupture of the cartridge takes place.

Solving the equation the bursting pressure based on the range of tensile strength given results in a range of 750 psi to 900 psi for a bolt system using a 0.75" bolt in a 1-1/32" drilled hole. The pressure range calculated from the model is very close to the estimated pressure range from the test that fluctuated around 1000 psi indicating that the pressure increase in region I is a result of the bursting strength of the cartridge.

The mechanisms involved in regions II and III are more difficult to model and solve numerically. Each bore hole presents a particular set of specific conditions that varies from those of the other boreholes. A model to describe the behavior of the pressure front in regions II and III should consider geometry, insertion speed, rock mechanical properties and should account for joints and borehole roughness which has a significant effect on the grout flow through the annulus.

CONCLUSIONS

A series of tests were conducted to characterize the pressure of bolt insertion during bolt installation under various conditions. Analysis of the data shows three distinct stages of pressure build up during bolt installation. The tests showed that grout from the two major manufacturers behave similarly under this type of test. Results showed that the pressure front reaches higher levels when the annulus between the bolt and the hole is small. Also, the higher the speed of bolt insertion, the higher the pressures recorded. The pressures reached during bolt insertion are sufficient to induce hydraulic fracturing of the roof rock. As a consequence, there is loss of grout resulting in reduced bolt encapsulation. Understanding of the mechanisms involved may allow development of strategies for controlling the pressure buildup and its negative impact during roof bolting under weak rock conditions.

ACKNOWLEDGEMENT

Cooperative Agreement Number R01 OH007727-03 from Centers for Disease Control and Prevention (CDC - NIOSH) supported this paper. The paper's contents are solely the responsibility of the authors and do not necessarily represent the official views of CDC.