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Stress distribution in a passive fully grouted rock bolts

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Abstract: Rock bolts are widely used as a supplementary roof support system in hard-rock mining since a long time Since the performance of fully grouted passive bolts depends on bond strength, in the present investigation extensive laboratory pull-out as well as push-out tests were conducted varying the bolt diameter, length and cement-water mixing ratios of grout. The load-displacement curves were developed and were verified with the numerical results obtained from finite element analysis using ALGOR software. Numerical models were validated for push-out tests and a detailed analysis was carried out to know the displacement, stress, strain distribution along the bolt.

1. Introduction

Rock mass in its in situ form is composed of a system of rock blocks and fragments separated by discontinuities and the stability of any underground structure in these rock masses is mainly controlled by the strength of the discontinuities. Rock bolts have been used as a reinforcement measure to improve the strength of jointed rock masses. Ever since the introduction of the rock bolts into the mining industry, they have become effective supplementary support systems for large underground openings.

Bolts reinforce rock-mass through restricting the deformation in rock mass. The load is transferred from the bolt to the host ground generally in shear and the nature of load transfer depends primarily on the type of bolting system, the strength of the rock surrounding the bolt, and the characteristics of the cement grout material. In order to improve bolting design, it is therefore necessary to have a good understanding of the behavior of rock bolts in deformed rock masses. This can be acquired through field monitoring, laboratory tests and numerical modeling.

In the present work experimental investigations were conducted to know the influence of the bolt diameter, bolt length and the grout properties on the bond strength of the fully grouted bolt. The load-displacement curves were developed for different lengths of bolts. The numerical investigations were conducted to know the displacement, stress and strain distribution along the bolt.

2. Experimental Investigations

Experimental investigations were carried out in laboratory both by pullout as well as push out tests to find the bond strength of fully grouted bolts for various grout composition, bolt diameter and length. The significance of cement –water ratio was initially studied by Benmokrane *et al* [1].The variation in grout composition (cement: water) considered in the present study was 1:1, 1.5:1, 2:1, 2.5:1 and 2.66:1. Experiments with cement: water composition beyond 2.66:1 was not possible as thick grout ceased to flow into the bore hole. The bolt diameters of 9.525, 12.7, 19.05 and 25.4 mm for a single bore whole diameter of 33mm were considered to study the influence of both the bolt diameter as well as the grout thickness on the bond strength. After 28 days of curing, tests were performed on a pull out test set up fabricated in the laboratory. The bond strength was calculated by dividing the load at which the bolt failed by the surface area of the bolt.

3. Numerical Investigations

The finite element analysis was carried out using ALGOR with a primary objective to study the stresses and displacement developed along a passive fully grouted bolting condition, in order to understand the point of initiation of failure in cable and rock bolts. The present numerical model is designed for axi-symmetric loading of a cylindrical bolt with 2D elements and the stress analysis is restricted to elastic limits. This being the limitation of the analysis, the stress at the failure could not be estimated.

One of the methods of developing load-displacement curves for various bolt lengths in the laboratory is through push out tests [2] in which axial load is applied to the fully grouted bolt head by a compression testing system until the bolt is pushed out of the hole into a hallow specimen holder. Similar experiments were performed in the present investigations for various bolt lengths. The ratio of the bolt length and diameter was varied and they are: 4.25: 1, 8.5:1, 12.75:1, and 17:1. The push out tests was performed mainly to validate the numerical model by comparing the load- displacement curves obtained from both the experimental and numerical values.

In the push out test the bolt was pushed out of the grout into a hollow cylindrical base plate of the specimen holder. The boundary conditions fixed in analysis were that the base plate being rigid was constrained at the bottom and the bolt being symmetric about its axis, the movement along the main axis of bolt was considered free, while the movement and rotation in all the other directions were constrained.

Table 1. Mechanical properties of materials used in the investigation.

Material	Density (kN/m^3)	Young's Modulus (x 10^5 M Pa)	Poisson's Ratio	Shear Modulus (x 10^5 M Pa)
Steel Rod	77.00	1.8	0.29	0.75
Grout Mix	22.00	3.5	0.18	0.15
GI-Pipe	77.00	1.8	0.29	0.75
Base Plate	77.00	1.8	0.29	0.75

4. Influence of bolt diameter and length on bond strength

The bond strength has been defined as the ratio of pull out load to the contact area of the bolt [2]. Figure 1 shows the variation in the bond strength with the change in the bolt diameter. The bond strength is least for 9.5 mm diameter bolt and has steeply increased for 12.7 mm diameter bolt. The observation was that the bond strength increased marginally by 1.25 times from 12.7 mm to 25.4 mm bolt diameter. With smaller diameter rock bolts (16mm) the grout density was the highest, nevertheless, the contact area of the bolt being smallest, offered lowest bond strength values in the present set of experiments. Similarly the bond strength was found to be a maximum for cement: water ratio of 2.66 for any bolt diameter.. The effect of cement-water ratio was also studied by Benmokrane et al [1], they inferred that the compressive and tensile strengths increased significantly with the increase in the ration of cement-water. Furthermore, the modulus of elasticity and Poisson's ratio also increase with the increase in the ratio of cement-water. In the present investigations the cement-water ratio could not be increased beyond 2.66 as it was difficult for the flow of grout into the bore hole

Tests with the variation in the anchorage length to the bolt diameter were conducted to determine the effect of anchorage length on the load-carrying capacity of the bolt. The variation in the load bearing capacity with length: diameter (L/D) of bolt was found to be significant (fig. 2). The variation noticed was from 10 kN for L/D 4.25 to 60 kN for L/D of 17. It implies that the longer the bolts for any diameters greater would be the bond strength and in the design of rock bolts it is always the length which remains a variable compared to the diameter. Thus a fully grouted cable bolt offers more bearing strength than the rock bolt which is of a limited length. These results agree reasonably well with those obtained by Benmokrane *et al*[1], Goris [3] and Hassani *et al* [4], indicating that the maximum load carrying capacity increases with anchored length.

5. Comparison of experimental and numerical load versus displacement curves

The load versus displacements curves were drawn for both the experimental and numerical results. However for brevity the load-displacements curves for L/D equal to 8.5 and 17 have been shown in the fig.4. In the numerical analysis the material properties assumed were elastic, homogeneous and isotropic and also the numerical analysis does not take in to account the changes in the specimen at the time of failure and the failure condition and therefore the displacements obtained were linear. The load-displacement curve obtained for the experimental work indicated higher displacement up to a load of 2 to 3kN and thereafter followed a near linear variation, which is close to the numerical results.

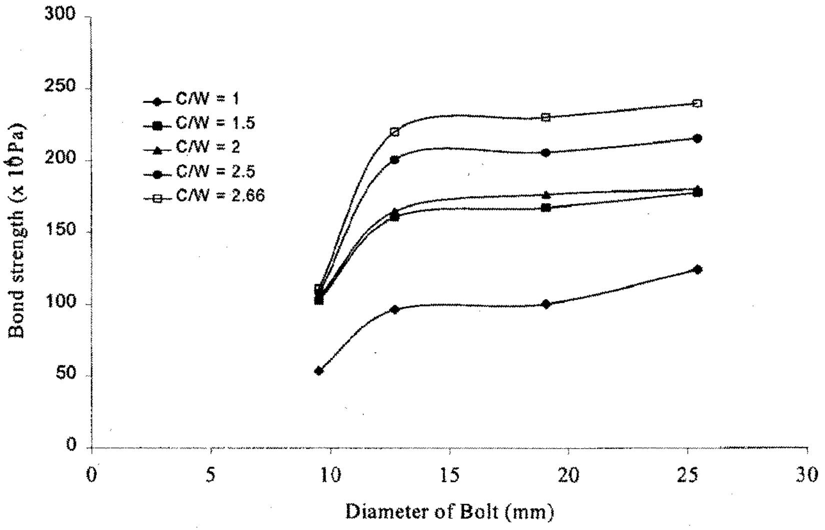

Fig. 1. Variation of bond strength with bolt diameter.

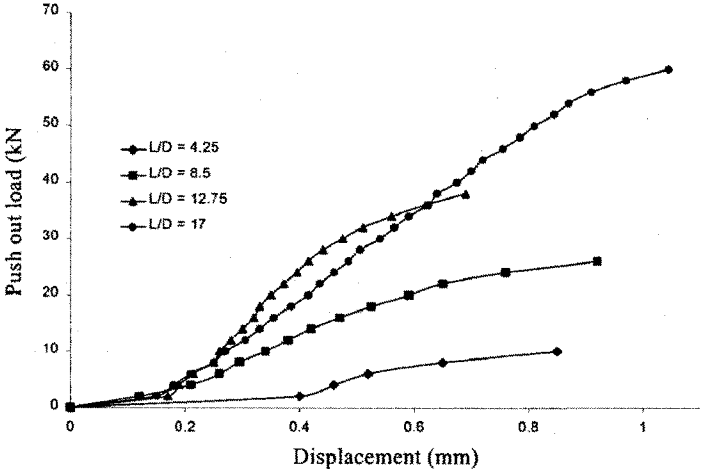

Fig. 2. Load displacement curves from the laboratory push out tests.

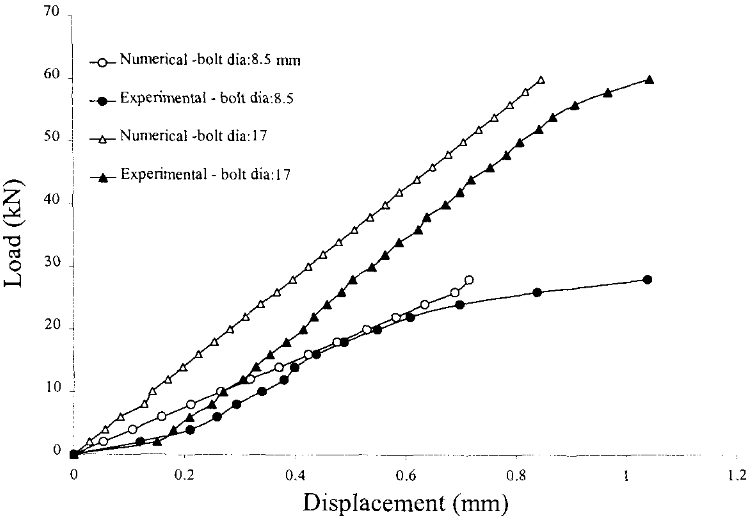

Fig. 3. Load versus displacement curves.

6. Numerical analysis for the stress and displacement along the bolt

A series of numerical investigations were carried out in ALGOR on the fully grouted bolts of 16, 18, 20 and 24 mm diameter of 1500 mm long and 20mm diameter bolt for 1200, 1500, and 1800mm long in a 28 mm diameter bore hole. The pull out loads of 20, 40, 60,100 and 140 kN were applied and the corresponding stresses and displacements were obtained.

The trend in the displacement along the bolt for all the dimensions of the bolt remained same, however the extent of displacement varied with the diameter and length of the bolt. The displacement is maximum at the point of application of the pull-out load, which is, at the collar zone of the fully grouted bolt and dropped exponentially until it is almost zero at a certain length into the bore hole. The zero displacement was in general remained between 300 to 400mm lengths from the collar end of the bolt. Maximum displacement was noticed for 16 mm diameter bolt and a minimum value was obtained for 24 mm diameter bolt. The displacement increased with the increase in magnitude of the pull-out load and the increase in displacement was 0.0136, 0.0116, 0.01, 0.0077 mm for every increment of 10 kN in pull-out load in16, 18, 20, and 24mm diameter bolts. In a fully grouted bolt the influence of diameter was found to be effective only up to 250mm and beyond this point the displacement was insignificant for any bolt diameter. Therefore in a fully grouted bolting system the effective length up to which a significant displacement occurs is 250mm from the point of application of the load, that is the collar end of the bolt (fig. 4).

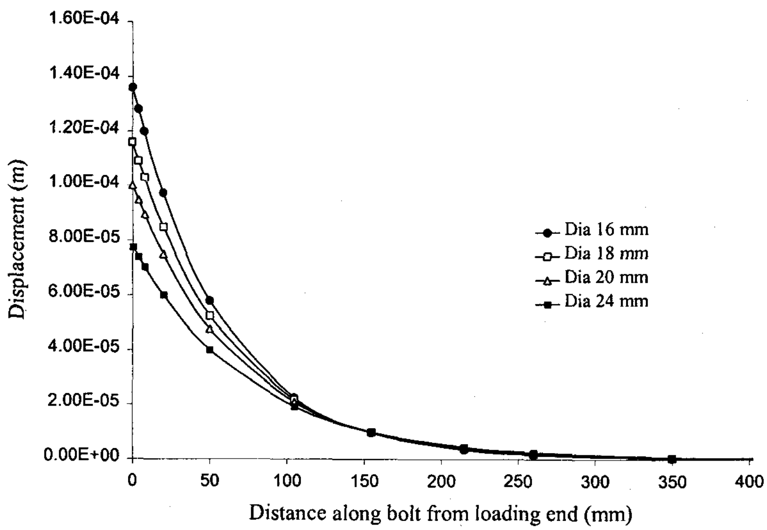

Fig. 4. Displacement for various diameters (Load = 100kN, Bolt length =1500mm).

The stresses and strains were found to be higher at loading interface and increased very steeply to a highest value with in a few divisions along the length of the bolt and decreased exponentially to a minimum insignificant value at bolt lengths between 300 to 400 mm for all the diameters considered in the present investigation(fig. 5 and 6).

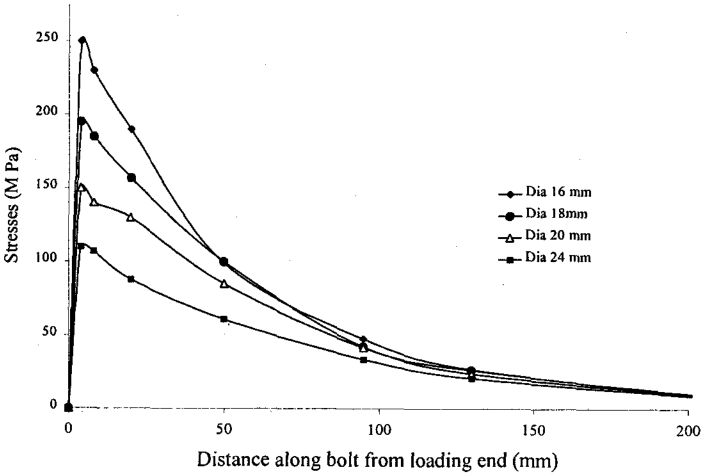

Fig. 5. Stresses for various bolt diameters (Load = 100 kN, Bolt Length = 1500mm).

The maximum stresses recorded were 250 M Pa, 195 M Pa, 150 M Pa and 110 M Pa for 16, 18, 20, and 24 mm diameter bolts respectively and in these cases the bolt length was taken as 1500mm. In fact in fully grouted bolt, the length of the bolt seems has little significance after 500mm length from the loading point. A similar observation was reported by Aydan *et al* [5], Li and Stillborn [6], and Farmer [7].

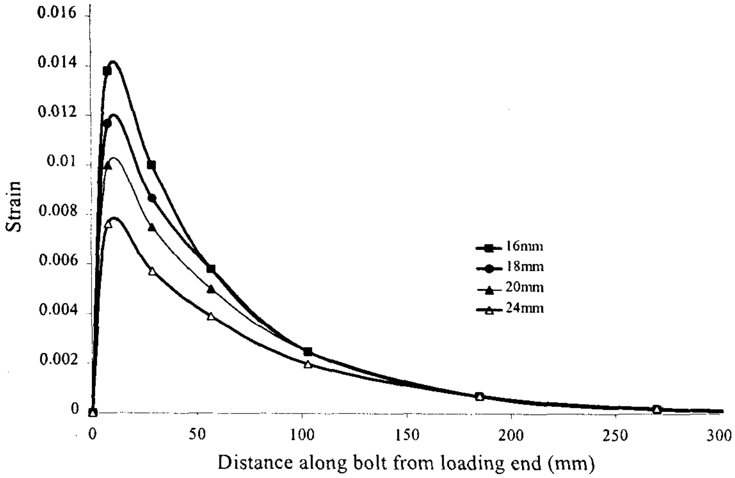

Fig. 6. Strain along the length of the bolt (Load = 100kN, bolt length = 1500mm).

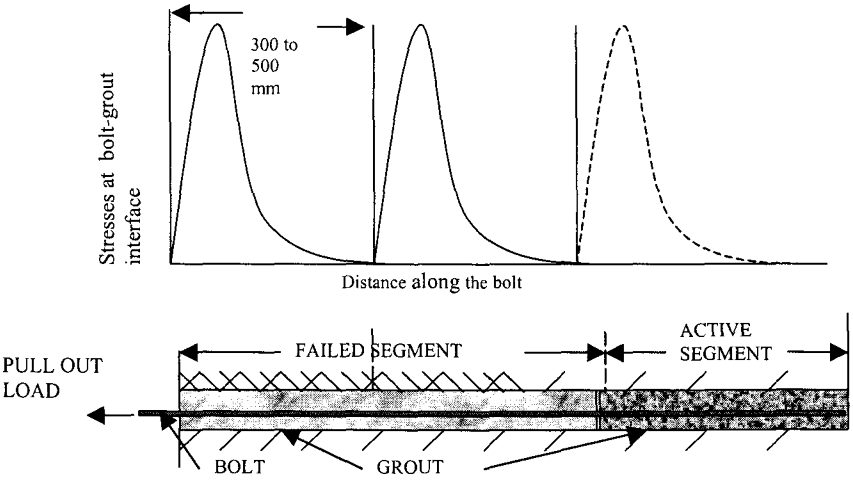

Fig. 7. Conceptual progressive failure model of fully grouted bolt.

7. Conclusions

In a fully grouted bolt the grout material provides a continuous mechanical coupling condition at the inter face. On application of a pullout load, shear stresses develop as shown in figure 5, just before decoupling occurs at the loading point and propagates along the bolt with an increasing applied load. A condition of failure may occur at the bolt-grout interface, in the grout medium or at the grout-rock interface, depending on which one is weakest.

Thus a fully grouted bolt is anchored all along the length of grout, unlike the conventional top anchored bolts. Therefore, the resistance to movement is initially offered by the first 300mm to 500mm segment. In general, the shear strength at the interface may likely comprise of three components: adhesion, mechanical interlock and friction and in a rock bolt with rough surface all the three effects together forms the shear stress at the interface. On the basis of this observation it can be concluded that the failure initiates in segments until the decoupling front attenuates at an increasing distance from the point of the applied load, which in the present case is around 300 to

500 mm. The failure progresses into the next segment in this sequence as the compatibility of deformation is lost across the interface as shown in the figure 7.

The predominant failure in the present investigation has been at the bolt -grout interface. The effect of increased density of grout by changing the bolt diameters has not resulted in any increase in the bond strength. It can therefore be inferred that for a bore-hole diameters between 28 mm to 34 mm, the suitable bolt diameter is 24 mm while the length variation plays a greater role in increasing the bond strength of the fully grouted bolts.

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