Geotechnical and Geological Engineering (2005) 23: 297–308
DOI 10.1007/s10706-004-9518-x

Experimental and numerical investigations of stresses in a fully grouted rock bolts

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(Received 19 May 2003; accepted 4 February 2004)

Abstract. Rock bolts are widely used for rock reinforcement in hard-rock mining and civil engineering since a long time. However the use of fully grouted rock bolts and cable bolts is limited in coal mines. In order to improve performance of the rock bolts as a supplementary roof support system for any type of roof condition in coal measured formations, it is necessary to have a good understanding of the behavior of the bolt–grout and grout–rock interactions as well as the mechanism of load transfer in rock bolts.

As the performance of grouted bolts depends on bond strength, extensive laboratory pullout as well as pushout tests were conducted in the present investigations with the variations in the bolt diameters, 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 pushout tests and a detailed analysis was carried out to know the displacement, stress, strain distribution along the bolt.

Key words. rock bolts, supplementary roof support system, pullout and pushout test, stress, strain and displacement.

1. Introduction

Ever since the introduction of the rock bolts into the mining industry, they have become effective supplementary support systems for large underground openings. Although cables have been used in hard-rock mines, the procedure is still new for underground coal mines in India since the roof strata conditions are significantly different. One of the many possible reasons for the failure of rock bolts in Indian coal mines in general is the lack of complete information about the condition of immediate roof and in particular, erroneous estimates of the extent of softened zone above the mine entry.

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

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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 laboratory experimental investigations were conducted on smooth bolts 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 using ALGOR focused at displacement, stress and strain distribution at the bolt–grout interface for pullout loads. The simplified numerical analysis ignored the *in situ* conditions where the influence of stress changes due to mining and also the influence of stress due to bed separation on the bond strength persist, due to the limitations of ALGOR package.

Extensive experimental, analytical, numerical as well as filed investigations on the performance of the rock bolts have been carried out and reported in the literature. Fuller and Cox (1975) (Benmokrane et al., 1995) observed that the smooth surface of the bolt reduces the bond-strength at the bolt–grout interface. Stheeman (1982) carried out a study on the effect of grout mixtures along with the variation in the bolt diameter, grade of steel and borehole diameter on the shear bond stress at the cable–grout interface. Similar studies were carried out by Goris and Conway (1987), Hassani et al. (1992). The effect of the strength of the host rock on the performance of cable bolts was investigated by Hassani et al. (1992), further they reported that a strong correlation exists between bond strength, grout mix and rock properties. Yazici and Kaiser (1992) stated that the bond strength of fully grouted bolts is primarily frictional and depends on the pressure at the bolt–grout interface which is influenced by the dilational effect caused by the rough surface of the twisted cable bolts.

Several parameters influence the bond strength of a purely frictional support system. The parameters that may influence the bond strength of grouted bolt are the Young's modulus of the rock and grout, strength of grout, borehole diameter and the frictional coefficient at the bolt–grout interface (Yazici and Kaiser, 1992). Benmokrane and Chekired (1995) inferred that the pull-out capacity of anchors is related to the grout compressive strength and the pull-out load was found increasing with the anchored length. Goris (1990) and Reichert et al. (1992) have established that low water:cement (w:c) grouts are associated with high bond capacities. Hyett et al. (1995) conducted a detailed tests using a modified Hoek cell and confirmed that cable bolt bond strength is related to frictional rather than adhesional resistance and further inferred that the bond strength depends on the pressure generated at the cable–grout interface, which in turn depends on the reaction force generated at the borehole wall caused by dilation during bond failure. In the cases where the borehole wall rock is either weak or fractured the bond strength is lower. The effectiveness of a grouted bolt depends on its length relative to the extent of the zone of overstressed rock or yield zone (Indraratna and Kaiser, 1990). The effects fully grouted rock bolts in a jointed rock mass were studied by Sharma and Pande (1988). Kaiser et al. (1992, 2001) presented a new perspective on the bond strength of fully grouted cable bolts and have demonstrated that a stress change induced by mining not only influences the demand on the rock support, it can also significantly affect the bond strength of a cable bolt under certain circumstances. The bond strength of cable bolts decreases as the stress decrease reduces the confinement and thus the grout–bolt interface pressure (Kaiser et al., 1992, 2001).

2. Experimental investigations

Experimental investigations on smooth surfaced bolts were carried out in laboratory both by pullout as well as pushout tests to find the bond strength of fully grouted bolts for various grout composition, bolt diameter and length.

The variation in grout composition (cement:water) considered 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 effect of grout thickness to the bolt diameter was attempted by changing the diameter of the bolt as the borehole was fixed at 33 mm diameter. The mechanical properties of the materials used in the present investigation are given in Table l. The bolt diameters of 9.525, 12.7, 19.05 and 25.4 mm for a borehole diameter of 33 mm were considered to study the influence of both the bolt diameter as well as the grout thickness on the bond strength. After curing for 3 weeks, pullout tests were performed on completely dried samples. The bond strength was calculated by dividing the load at which the bolt failed by the surface area of the bolt.

The laboratory pullout experiments were carried out in pre-cast cylindrical concrete blocks of a single composition of 150 mm diameter and 300 mm length with a central borehole of 33 mm, enclosed in a 3 mm thick steel casing. The steel casing was provided with a facility to firmly bolt the test blocks to the base plate of the anchorage testing apparatus used for pullout test. The effect of confinement due to steel casing was ignored in the present investigations. The bond strength values obtained by pullout tests for all the variations considered in the present study are given in Table 2.

One of the methods of developing load–displacement curves for various bolt lengths in the laboratory is through pushout tests (Aydan et al., 1995) 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 as shown in the

Table 1. Mechanical properties of materials used in the investigation

Material	Density (kN/m^3)	Young's modulus (GPa)	Poisson's ratio	Shear modulus (GPa)
Steel rod	77.00	180	0.29	75
Grout mix[a]	22.00	3.5	0.18	1.5
GI-pipe	77.00	180	0.29	75
Base plate	77.00	180	0.29	75

[a] Grout mix of cement:water concentration of 2.5:1.

Table 2. Bond strength values for various bolt diameters and grout concentrations

Bolt diameter (mm)	Bond strength (MPa)				
	C/W* ratio 1:1	C/W ratio 1.5:1	C/W ratio 2:1	C/W ratio 2.5:1	C/W ratio 2.66:1
9.525	0.5358	1.0280	1.0500	1.0798	1.1098
12.70	0.9644	1.6072	1.6480	2.0090	2.2050
19.05	1.0046	1.6740	1.7690	2.0580	2.3040
25.4	1.2446	1.7808	1.8032	2.1560	2.4000

C/W = cement–water ratio.

Figure 1. All the pushout tests in the present investigations were carried out on a 150 ton compression testing machine for bolts embedded in cement grout of composition 2.5:1 (cement:water). The tests were limited to 19.05 mm diameter bolts primarily to avoid any possible buckling of bolts. Further, the bond strength values of pushout tests, comparable with those obtained by pullout tests, were the only ones considered as reproducible values.

The ratio of the bolt length and diameter (L/D) was varied and they are: 4.25:1, 8.5:1, 12.75:1 and 17:1. The values of load–displacements and the bond strength are given in Table 3. The pushout tests were performed mainly to validate the numerical model by comparing the load–displacement curves obtained from both the experimental and numerical values.

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 fully grouted bolting

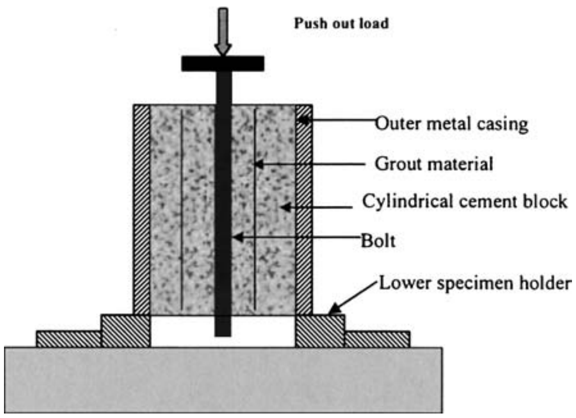

Figure 1. Schematic diagram of a laboratory pushout test facility (not to scale).

Table 3. Load-displacement values for both experiment pushout test and numerical investigations

Load (kN)	Displacement (mm) for various length-to-diameter (L/D) ratio of bolt							
	L/D = 4.25		L/D = 8.5		L/D = 12.75		L/D = 17	
	Expt.	Num.	Expt.	Num.	Expt.	Num.	Expt.	Num.
0	0	0	0	0	0	0	0	0
2	0.4	0.114	0.12	0.053	0.17	0.036	0.15	0.028
4	0.46	0.228	0.21	0.106	0.19	0.072	0.18	0.057
6	0.52	0.341	0.26	0.160	0.215	0.108	0.21	0.085
8	0.65	0.455	0.295	0.213	0.25	0.144	0.25	0.128
10	0.85	0.569	0.34	0.266	0.26	0.180	0.27	0.141
12			0.38	0.319	0.28	0.216	0.305	0.170
14			0.42	0.372	0.30	0.252	0.33	0.198
16			0.47	0.425	0.32	0.288	0.355	0.226
18			0.525	0.477	0.33	0.324	0.385	0.255
20			0.59	0.531	0.350	0.360	0.415	0.283
22			0.65	0.584	0.373	0.396	0.435	0.311
24			0.76	0.637	0.395	0.432	0.46	0.339
26			0.92	0.690	0.415	0.468	0.485	0.368
28			1.04	0.717	0.44	0.504	0.505	0.396
30					0.475	0.540	0.54	0.424
32					0.51	0.577	0.565	0.453
34					0.56	0.613	0.59	0.481
36					0.62	0.648	0.625	0.510
38					0.69	0.685	0.64	0.538
40					0.73	0.703	0.675	0.566
42							0.7	0.590
44							0.72	0.622
46							0.755	0.651
48							0.785	0.680
50							0.81	0.710
52							0.845	0.736
54							0.87	0.764
56							0.91	0.792
58							0.97	0.820
60							1.045	0.849

condition, in order to understand the point of initiation of failure in a fully grouted cable and rock bolt. 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.

In the pushout test the bolt was pushed out of the grout into a hollow cylindrical base plate of the specimen holder (Figure 1). 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.

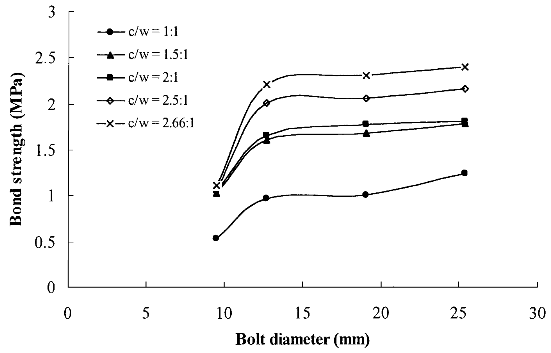

Figure 2. Variation of bond strength with bolt diameter.

4. Influence of diameter of the bolt on bond strength

The bond strength has been defined as the ratio of pull out load to the contact area of the bolt (Yazici and Kaiser, 1992). Figure 2 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 to 25.4 mm bolt diameter. With smaller diameter rock bolts (16 mm) 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 cement water ratio could not be increased beyond this ratio as it was difficult for the flow of grout into the bore hole.

5. Comparison of experimental and numerical load versus displacement curves

The load–displacement results from the pushout test along with the corresponding displacement values obtained from the numerical analysis are given in Table 3. In the laboratory pushout tests failure loads varied from 10 to 60 kN for L/D 4.25 to 17, respectively and it is essential due to increase in the length of the bolt (Table 3).

The bond strength values of both pullout (Table 2) and pushout tests for 19.05 mm bolt diameter embedded in grout concentration of 2.5:1 (cement:water) are very close and those obtained from pushout tests are 2.08, 2.90, 2.75 and 3.09 MPa for L/D 4.25, 8.5, 12.75 and 17, respectively.

In the numerical analysis the material properties assumed were elastic, homogeneous and isotropic and also the numerical analysis does not take into account the changes in the specimen at the time of failure and the failure condition and therefore the displacements obtained were linear. The load versus displacements curves were drawn for both the experimental and numerical results and are shown in Figure 3. The load–displacement curve obtained for the experimental work indicated higher displacement up to a load of 2 to 3 kN and thereafter followed a near linear

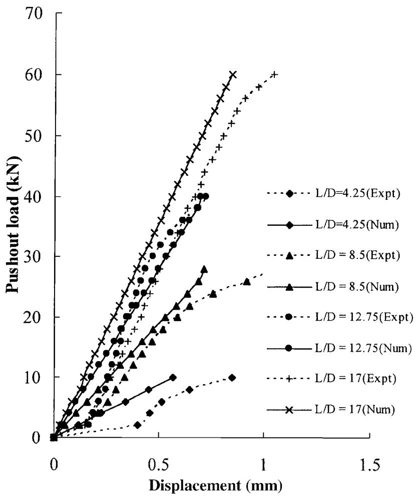

Figure 3. Load–displacement curves from pushout tests.

variation, which is in close confirmation with the numerical results. The difference in the displacement values obtained for pushout load and the corresponding numerical values are varying between a maximum of 30% for L/D 4.25 and 8.5 to a minimum of 4% for L/D 12.75 and 17.

A detailed finite element analysis was carried out to understand the state of stress developed at the bolt–grout interface for the pullout load as the input loads. The shear stress developed at bolt–grout interface for all the four L/D ratios was computed for the failure loads obtained from experimental pushout tests (Table 4). The magnitude of shear stress increased with the increase in the L/D ratio (Figure 4). The

Table 4. Shear stress distribution along the grout–bolt interface for various L/D ratios

Maximum shear stress values developed at grout–bolt interface (MPa)							
L/D = 4.25		L/D = 8.5		L/D = 12.75		L/D = 17	
Distance from Collar (mm)	Pullout load (10 kN)	Distance from collar(mm)	Pullout load (28 kN)	Distance from collar (mm)	Pullout load (40 kN)	Distance from collar (mm)	Pullout load (60 kN)
0	34	0	91	0	127	0	195
4.1	31	4.2	69	12.7	89	8.5	150
10	23.2	12.6	64	34	76	17	140
12.7	21	17	59	44.8	62	34	122
20	17	27.7	48	55.2	52	46	110
29.8	13	38	38	63.7	43	62	88
34	15	48	27	72.3	34	72	76
		52	23	82	26	80	67
		60	17	97.7	14	100	46
		63.7	13	102	16	112	32
		68	16			132	16.5

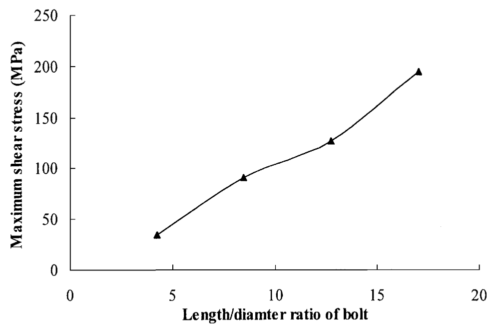

Figure 4. Maximum shear stress developed at grout–bolt interface at the collar of the borehole.

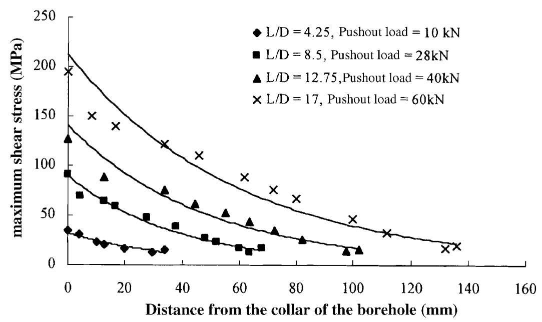

Figure 5. Shear stress distribution along the grout–bolt interface for various L/D ratios.

shear stress values obtained are highest at the point of application of pullout load and decreased exponentially (Figure 5). In the shorter bolts, the shear stress levels were lower compared to the bolts with longer anchorage, however the nature of shear stress decay remained exponential. From the laboratory pullout tests conducted by Benmokrane and Chekired (1995) have drawn a conclusion that the maximum pullout load increased with the anchorage length and further presented a shear stress–slip model which consists of three linear stages between the shear stress and slip of the bolt along the bolt–grout interface. The first stage represented the elastic behavior and the second defined the debonding characterized by decrease in shear stress while the third represented the residual resistance developed by friction. A similar observation was made earlier by Farmer (1975) who inferred that at higher stress levels, the greater movement allowed as the anchor restraint is overcome, reduced skin friction to residual levels over the top half of the anchor. However in the present numerical analysis it was observed that the shear stress decayed to residual levels at lengths less than half of the total anchored length (Figure 5). The lower residual strength values may be due to ignoring the effects of radial confining stresses. From the non linearity of shear stress curve it can be inferred that debonding at bolt–grout interface initiates from the point of application of load, which is, the collar of the borehole, and goes down in cycles of peak and residual shear stress until the bolt totally slips out of the hole.

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 20 mm diameter bolt for 1200, 1500 and 1800 mm long in a 28 mm diameter bore hole. The pullout loads of 20, 40, 60, 100 and 140 kN were applied and the corresponding shear stress 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 highest at the point of application of the pullout load that is at the collar zone of the fully grouted bolt and dropped exponentially until it is almost zero at a certain length into the borehole (Figure 6). The zero displacement was in general remained between 300 and 400 mm 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 pullout load and the increase in displacement was 0.0136, 0.0116, 0.01 and 0.0077 mm for every increment of 10 kN in pullout load in 16, 18, 20 and 24 mm diameter bolts. In a fully grouted bolt the influence of diameter was found to be effective only up to 250 mm 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

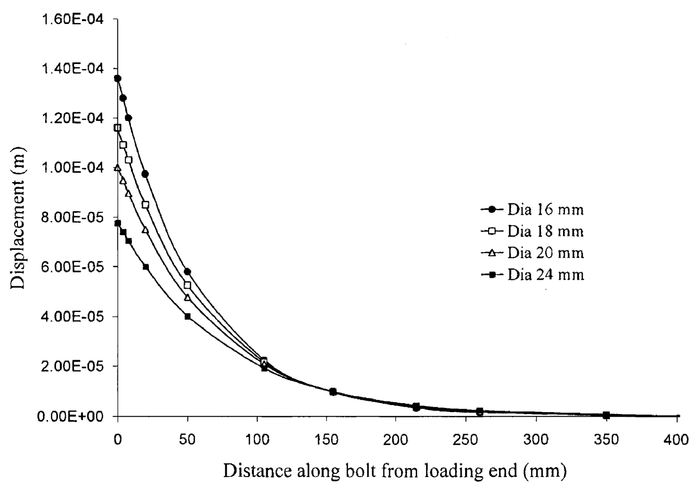

Figure 6. Displacement for various diameters (load = 100 kN, bolt length = 1500 mm).

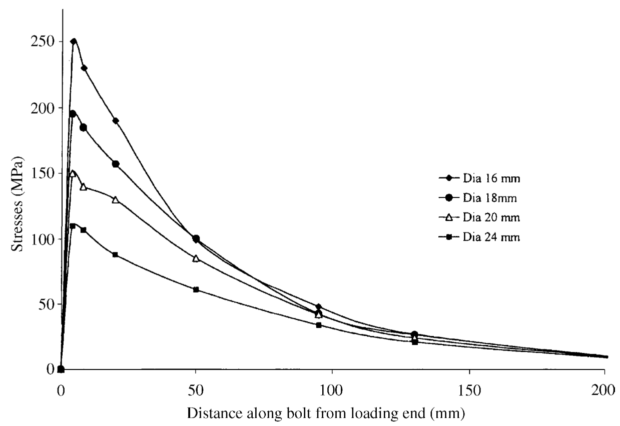

Figure 7. Shear stress for various bolt diameters (load = 100 kN, bolt length = 1500 mm).

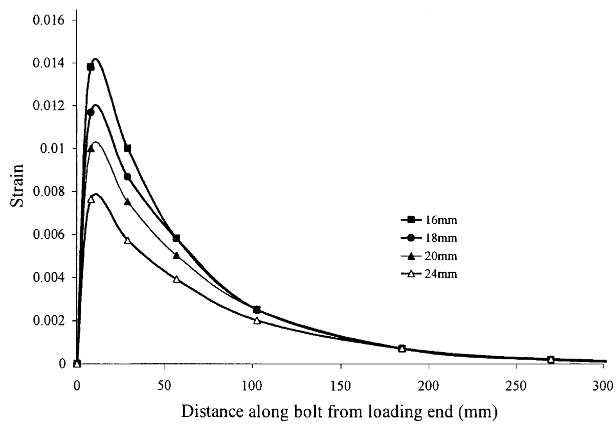

Figure 8. Strain along the length of the bolt (load = 100 kN, bolt length = 1500 mm).

occurs is 250 mm from the point of application of the load, that is the collar end of the bolt.

The shear stress and shear strain increased very steeply from the loading point 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 and 400 mm for all the diameters considered in the present investigation (Figures 7 and 8).

The maximum shear stress recorded was 250, 195, 150 and 110 MPa for 16, 18, 20 and 24 mm diameter bolts respectively and in these cases the bolt length was taken as 1500 mm. In fact in fully grouted bolt, the length of the bolt seems has little significance after 500 mm length from the loading point. A similar observation was reported by Aydan et al. (1995), Li and Stillborg (1999) and Farmer (1975).

7. Conclusions

The investigations undertaken had certain limitations, more importantly with respect to the numerical studies in which the analysis was confined to linear elastic limits, further the effects of changes in the radial stresses were ignored since it was beyond the scope of the ALGOR finite element package. In the experimental investigations the smoothed surfaced bolt were considered for both the pullout and pushout tests. Notwithstanding some of these limitations, the present investigations have indeed helped in understanding the effects of L/D ratio on the shear stress developed at the bolt–grout interface and helped in extending the stress analysis model to the hypothetical conditions of bolt length and diameter.

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 stress develops as shown in Figure 7, just before decoupling initiates at the loading point and propagates along the bolt to the far end 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 300 to 500 mm 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. Further on the basis of the observation made from the numerical analysis 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 300–500 mm. Since the pullout load continues to act along the axis of the bold 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 9.

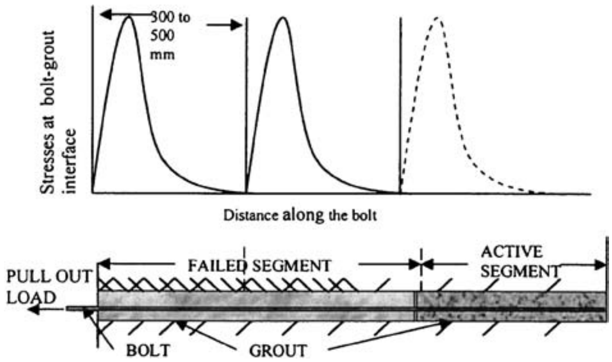

Figure 9. Conceptual shear stress model of fully grouted bolt.

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 from the bolt diameters considered in the present investigations, that 24 mm diameter bolts for borehole diameters between 28 and 34 mm would be a more appropriate selection, and longer bolts would play a greater role in increasing the bond strength of the fully grouted bolts.

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