33rd International Conference on Ground Control in Mining

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Chinese Mining Practices and Solutions

Development of the 3D Numerical Modeling of Roof Bolts for Studying the Bolt/Rock Interaction

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ABSTRACT

A 3D roof bolt model with the consideration of rebar, resin, bearing plate, and resin/rock interface was developed for studying the bolt/rock interactions of the tensioned and fully-grouted resin bolts. For the tensioned bolts, 2 ft compressive zone above the roofline is generated by the 10 tons pretension. Since the free portion of the tensioned bolts displays a higher vertical stress, the increase of the bearing capacity of the rocks in such range is much larger. For the fully grouted resin bolts, despite no pretension is generated during installation, the roof sag can indirectly generate a compressive zone near the roof line. In addition, the analysis on the differences in bolt/rock interactions when employing the tensioned or fully-grouted resin bolts indicates that the fully-grouted resin bolts are preferred as the primary support when weak and thinly-bedded immediate-roof is present. Meanwhile, it is found that both the tensioned and fully-grouted resin bolts may have very limited effect in preventing and/or control the cutter roof.

INTRODUCTION

The U.S. coal industry consumes hundreds of thousands of roof bolts every year for the past four decades (Peng 2008). Several researches have been done on the roof bolt design using various approaches such as analytical method, field measurement, statistical method, and numerical modeling (Yassien et al., 2002; Zhang and Peng, 2002; Mark et al., 2000; Stankus and Peng, 1994; Maleki, 1992). These researches have all contributed toward the development of the roof bolt design criteria. However, there is no widely-accepted criteria for roof bolt design up to now (Tadolini and Mazzoni, 2006) since the bolt/rock interaction has not been understood completely. The bolt/rock interaction involves how much the strength of the roof strata can be increased by the roof bolts.

Existing analytical tools are not sufficient to analyze the complex bolt/rock interaction; therefore, numerical models are very essential to investigating its behavior. Many previous roof bolt models employed mathematical models to represent bolts and simulate roof bolt behavior (Itasca, 2007a and 2007b). None of them considered the effects of the bolt installation procedure and in case of tensioned roof bolting, the effect of pretension and bolt accessories, for instance the bearing plate.

By using the finite element program ABAQUS, realistic numerical simulation models for the tensioned and fully-grouted resin bolts have been developed by Yassien et al., (2002) and Zhang and Peng (2002). The detailed bolt/rock interactions for both types of bolts were studied. However, they did not quantitatively discuss how much the strength of the roof strata in the bolting range was increased during or after the mining activities. Additionally, since the Itasca programs, such as FLAC^{3D} and 3DEC, have gained widely acceptance in the field of coal mine ground control, it is necessary to develop a 3D numerical model of roof bolts employing FLAC^{3D} for studying the bolt/rock interaction. Meanwhile, the stress and strength change of the host rocks during underground mining operations will be quantitatively discussed in the present study.

NUMERICAL MODELING

Global model

A typical longwall panel layout in southern Appalachia (see Figure 1) with overburden depth of 1,300 ft was used to model the effect of roof bolting. The panels were 1,200 ft wide, and the chain pillars in the gateroads and bleeder system were all 90 ft wide by 90 ft long. All the entries were 20 ft wide. A global model representing the cross-section R-R' in Figure 1 was generated, as shown in Figure 2. The size of the global model was 1,440×245.2×4 ft with half of each panel and the gateroad system between them. All the boundaries were roller-constrained except for the top of the global model. The upper boundary was subjected to a vertical stress of 1,312 psi. The horizontal stress was assumed as 1.2 times of the vertical stress.

The calibrated inputs for the coal and rock layers in the global model are shown in Table 1.The Mohr-Coulomb failure criterion was used to simulate the coal and rock strata except for the gob, which was assumed to behave as a strain-hardening material following the Salamon's theoretical gob-model (Salamon, 1990;Pappas and Mark, 1993). Table 2and Table 3 show the mechanical properties and ‹cap pressure› of the numerical gob material, respectively. The double-yield model was used to simulate the gob material in FLAC^{3D}. The approaches forcalibrating the inputs for coal, rock, and gob materials can be found in Li et al., (2013).

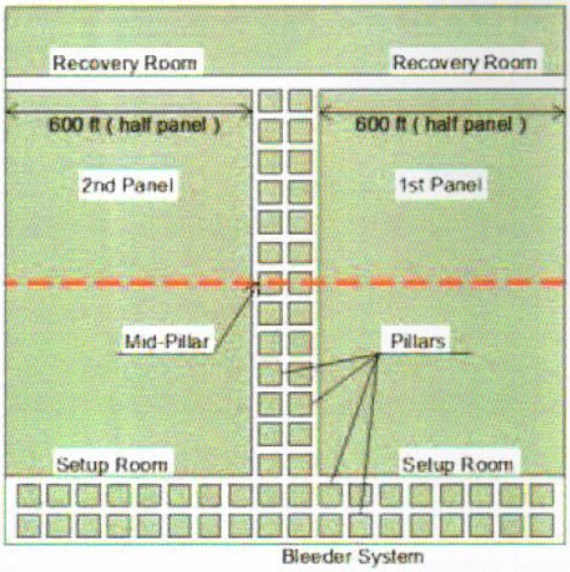

Figure 1. A typical longwall panel layout in southern Appalachia.

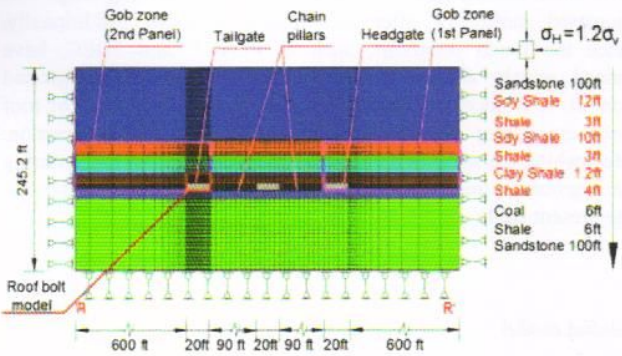

Figure 2. Global model along cross-section R-R'.

was assumed as 33.2 ft high above the coal seam of interest and consisted of shale, clay shale, shale, sandy shale, shale, and sandy shale in the ascending order (see the rock layers in red color in Figure 2). The cutting height was 6 ft.

There are two types of roof bolts that are mainly used for roof control in modern underground mines: tensioned and fully-grouted resin bolts. Both of them will be discussed in this paper.

Tensioned bolt model

The tensioned bolts are modeled by a three-dimensional beam with 1.5 ft long resin anchor on the upper end and a 6×6×1/4-in bearing plate on the lower end (see Figure 3a). The bolts are 8-ft long and 3/4-in in diameter, while the borehole for bolt installation is 1-in in diameter. The bearing plate is subjected to a uniformly distributed stress (556 psi) to represent the 10 tons pretension. The contact surfaces between the resin anchor and the host rocks and between the bearing plate and the roof surface are modeled as a contact interface, i.e. slippage occurs once its shear strength is exceeded.

Giraldo et al., (2005) conducted plenty of pull out tests on the tensioned and fully-grouted resin bolts and concluded that the average «Grip Factor» for the tensioned bolts is 0.66 ton/in. The «Grip Factor» is defined as the bolt›s resistance to pull out per inch of resin annulus length. Based on their conclusions, a pull out model (see Figure 4) was developed to calibrate the inputs for the bolt rebar and the interface between the resin anchor and the host rocks. In the pull out test model, a single tensioned-bolt was installed in a rock block, the left, right, and bottom boundaries of the model were roller-constrained. The resin anchor was 1.5 ft long. A constant-velocity displacement (1×10^{-5}) was applied to the end of the bolt, and the load and displacement of the bolt were recorded (see the curve in Figure 4). The predicted maximum load of the tensioned bolt is 11.88 tons that equals to the theoretical result of the bolt load. The corresponding or the validated inputs for the bolt rebar and the resin/rock interface are shown in Table 1 and Table 4, respectively.

Table 1. Rock and coal properties used in the global model.

Rock Strata	Density, lb/in^3	Shear Modulus, 10^6psi	Bulk Modulus, 10^6psi	Friction Angle, degree	Cohesion, psi	Tensile Strength, psi
Sandstone	0.0939	1.495	1.745	44	1319	236
Sdy shale	0.0939	1.35	1.6	41	1029	207
Shale	0.0906	1.19	1.49	39	920	181
Clay shale	0.0901	1.17	1.47	38	900	179
Coal	0.0505	0.249	0.448	34	436	116
Rebar/Resin	3.28	1.38	1.31	70	222,605	60,002

The global model was solved in three steps following the operations of underground mining activities. The global model was generated and the geostatic stress condition was applied in the first step. In the second step, all the entries were developed and the roof bolts were installed in the tailgate. Thereafter, the first panel was retreated in the third step by assigning the gob model into the caving zone (i.e. the gob zone of the first panel in Figure 2). It should be pointed out that in this case, the caving zone

Fully-grouted resin bolt model

As describing for the tensioned bolts, the fully-grouted resin bolts are also modeled by a three-dimensional beam with a 6×6×1/2-in bearing plate on the lower end (see Figure 3b). The parameters for the bolt length and diameter and the borehole diameter are the same as those of the tensioned bolts. There is no pretension for the fully-grouted resin bolt model since no pretension is applied

Table 2. Mechanical properties for the gob material.

Property	Density, lb/in^3	Bulk modulus, 10^6psi	Shear modulus, 10^6psi	Friction angle, degree	Dilation angle, degree
Value	0.036	1.26	0.92	20	5

Table 3. "Cap pressure" for the gob material.

Strain, in/in	0.0	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08
Stress, psi	0	35	73	117	167	224	289	365	455
Strain, in/in	0.09	0.1	0.11	0.12	0.13	0.14	0.15	0.16	
Stress, psi	564	696	856	1073	1357	1755	2350	3341	

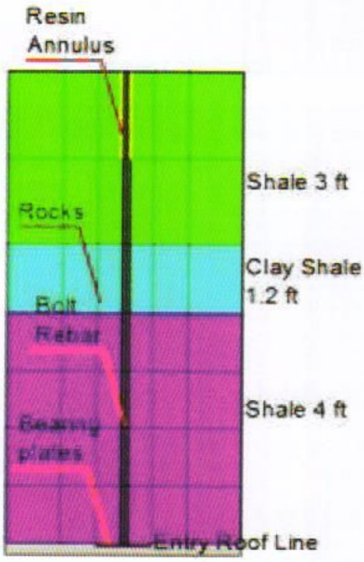

Figure 3a. Tensioned bolt.

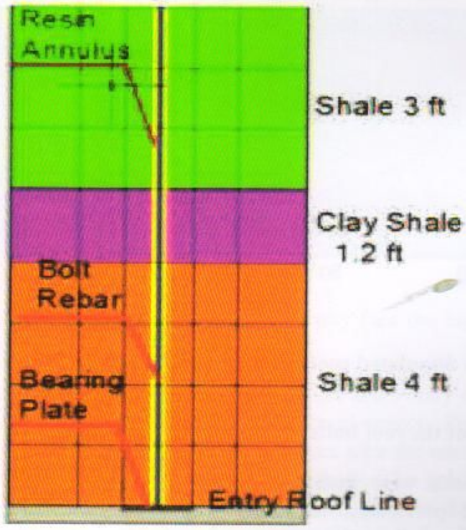

Figure 3b. Fully grouted resin bolt.

Table 4. Input properties for the resin/rock interface.

Property	Normal stiffness,	Shear stiffness,	Cohesion, psi	Friction angle, degree
Value	1.225×'08	1.146×10^8	3748	34

during the installation of fully-grouted resin bolts in practice. The inputs for the interfaces between the resin anchor and the host rocks and between the bearing plate and the roof surface are the same as those used for the tensioned bolts (see Table 4).

When to install roof bolts

Another important question that needs to be addressed for roof bolt simulation is that when to install or activate the roof bolt model? Zhang and Peng (2002) believed that more than 80% of the roof deformation has already developed when the bolts are installed in practice. However, Esterhuizen et al., (2013) installed the support units in their model after 30% of the roof deformation had taken place. Several published in-mine instrumentation data (Stankus et al., 2001; Li et al., 2013) indicates that the roof sag after bolt installation may have reached up to 4in, depending on the geological and stress conditions. In this respect, it seems more reasonable to activate the roof bolt model when 30% of the roof deformation has occurred. In fact, the less time dependent deformation involves after the bolt installation, the less amount of load is induced in the bolts. Figure 5 shows the roof deformation after entry development in the present numerical model. Each colored line represents the deformation curve of the relative colored point or points in the roofline. Note that the bolt was installed after 30% of the elastic roof deformation has occurred.

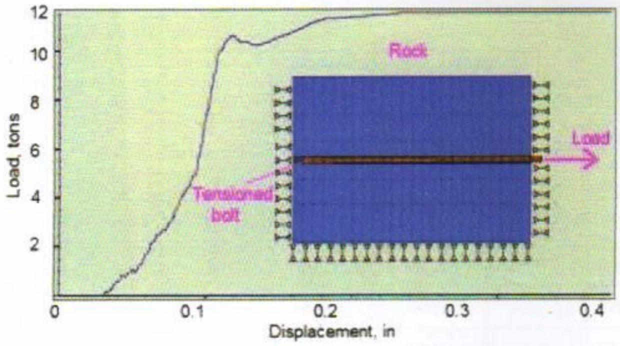

Figure 4. Pull out test for determining the strength of the resin/ rock interface.

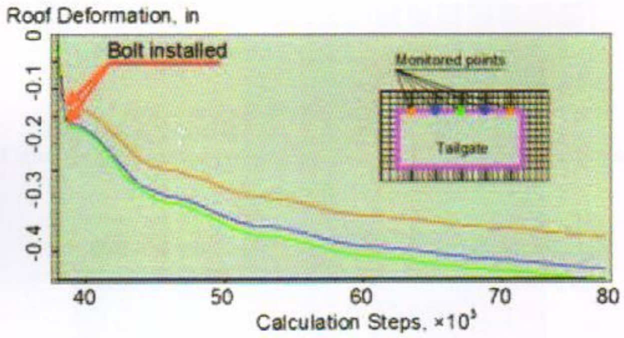

Figure 5. Simulated roof deformation after entry development.

Spacing of the roof bolts

The bolts were installed in the tailgate (see Figure 2). As discussed previously, the entry was 20 ft wide. Hence, the simulated spacing of the tensioned and fully-grouted resin bolts were 4 ft×4 ft, as shown in Figure 6.

BOLT/ROCK INTERACTION OF TENSIONED BOLTS

The vertical stress distributions of the tensioned bolts after tailgate development is shown in Figure 7, while Figure 8 presents that after retreating of the first panel. In each figure, the upper part of the tensioned bolts is grouted by the resin and called the resin-grouted portion, while the lower part is highlighted as the free portion.

The maximum vertical stress in the tensioned bolts after entry development is located in the free portion, reaching to 7,130-7,160 psi (see Figure 7). It is slightly increased to 7,980-8,820 psi (see Figure 8) after the retreating operation of the first panel. It is noted that the vertical stresses in the free portion of the tensioned bolts are not uniformly distributed (see Figure 7 and Figure 8). The bearing plates will be inclined in certain degree due to the roof sag after entry development, resulting in the different vertical displacements occurring in the opposite sides of the bolt end (see Figure 9). Hence, the sectioned vertical stress distribution in the free portion can be found.

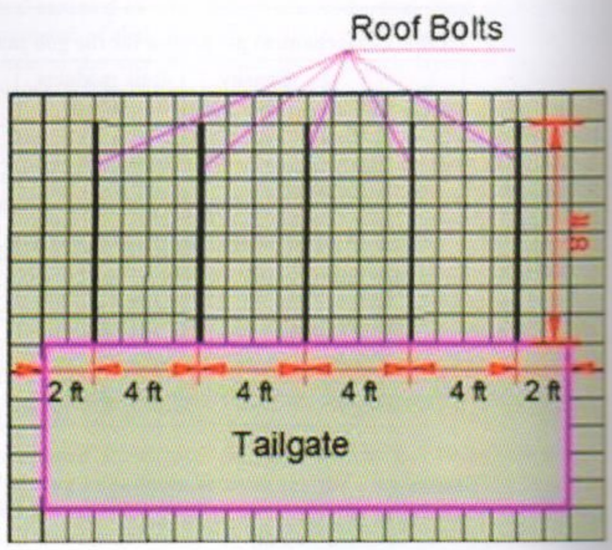

Figure 6. Spacing of the tensioned (or the fully-grouted) bolts in the model.

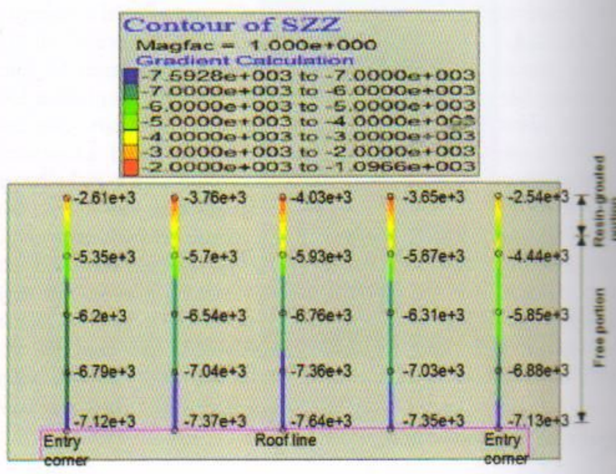

Figure 7. Vertical stress in the tensioned bolts after tailgate development, psi.

The vertical, horizontal, and shear stresses in the roof rocks after panel retreating are shown in Figs. 11a, 11b, and 11c, respectively. The yielding state of the roof rocks in the bolting range is shown in Figure 10. Note that points A and B in Figure 11a are located in the yield zone, while points C and D are located in the elastic zone.

For the three tensioned bolts installed near the middle of the roof span, 2 ft compressive zone above the roofline are generated by the pretension of 10 short tons. However there is no compressive zone for the two side bolts (see Figure 11a). Since the pretension of the roof bolt is much smaller than the vertical stresses concentrated in the entry corners, thus the compressive zone of the side bolt is invisible. In addition, it can be found in Figure 11a that the vertical stress at point B (in the middle between the adjacent bolts) is almost 0, while that at point A (close to the tensioned bolt) is much larger, reaching to 200 psi. On the other hand, The vertical stress in the rocks at point D is 440 psi (by prorata estimation), while that

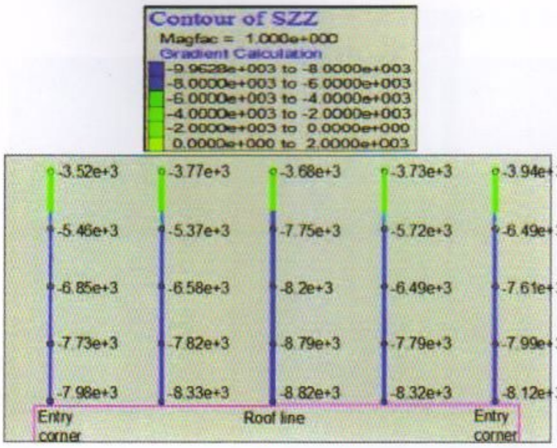

Figure 8. Vertical stress in the tensioned bolts after retreat of the first panel, psi.

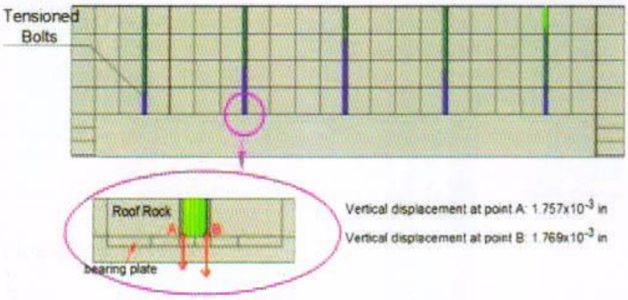

Figure 9. The effect of the inclined bearing plates on the sectioned vertical stress distribution in the tensioned bolts after tailgate development.

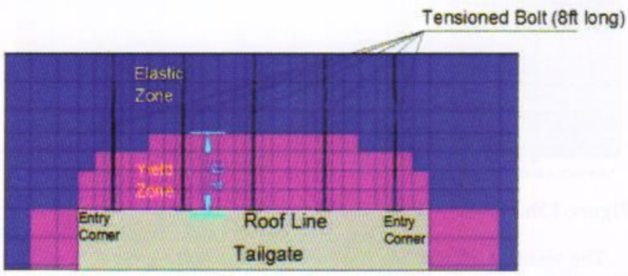

Figure 10. Yield zone around tailgate after retreat of the first panel (tensioned bolts).

at point C (close to the tensioned bolt) is slightly larger, reaching to 500 psi. If no roof bolt is installed, the vertical stress in points A and B (or C and D) should be close to one another since they are in the same elevation. However, the installed tensioned-bolts can significantly increase the bearing capacity of the rocks in the yield zone.

Figure 11b shows the horizontal stress of the roof rocks after the retreat of the first panel when employing the tensioned bolts. The gob (the first panel) is located at the right side of the entry, thus the horizontal stress at the right side is larger than that at the left side. It can be noted that the tensioned bolts can cut down the horizontal

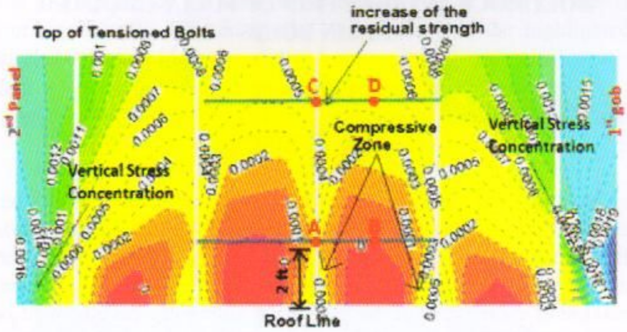

Figure 11a. Vertical stress, E+6 psi.

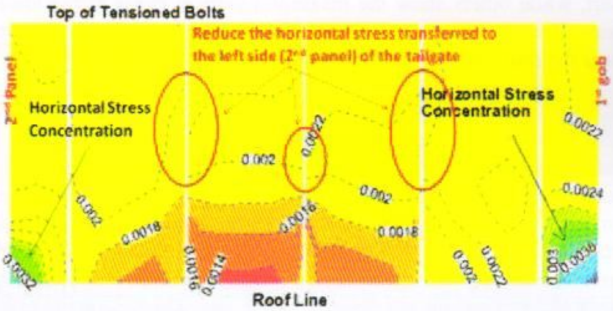

Figure 11b. Horizontal stress, E+6 psi.

stress transferred to the left side of the entry (see the highlighted circles in Figure 11b).

It is generally believed that the shear stress at the entry corners is a main contributor to the cutter roof development. Figure 11c shows the shear stress (σ_{xz}) of the roof rocks after the retreat of the first panel when employing the tensioned bolts. The gob (the first panel) is located at the right side of the entry, thus the shear stress at the right side is greatly larger than that at the left side. Meanwhile, it is noted that the shear stress distribution at entry corners was not affected effectively by the tensioned bolts (see the highlighted circles in Figure 11c). Hence the tensioned bolts may have limited effect on the cutter roof development.

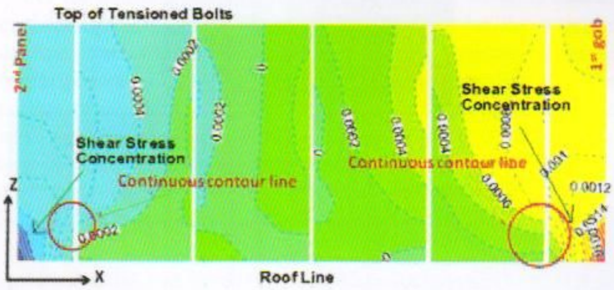

Figure 11c. Shear stress, E+6 psi.

BOLT/ROCK INTERACTION OF FULLY-GROUTED RESIN BOLTS

As analyzed in the last section, the stresses in the bolts and roof rocks will be discussed in detail to determine the bolt/rock interaction of the full-grouted resin bolts.

The maximum vertical stress of the full-grouted resin bolts after entry development ranges from 7,580-17,800 psi (see Figure 12a). It is greatly increased to 29,000-54,700 psi (see Figure 13a) after the retreating operation of the first panel. On the other hand, the maximum shear stress of the resin bolts after entry development is only 1,380-4,570 psi (see Figure 12b). However, it is increased to 2,620- 8,180 psi after panel retreat (see Figure 13b). Note that some of the resin bolts display the maximum vertical stress at the upper part, while others show the maximum vertical stress at the lower part. The maximum shear stress of the resin bolts always occurs near the roof line.

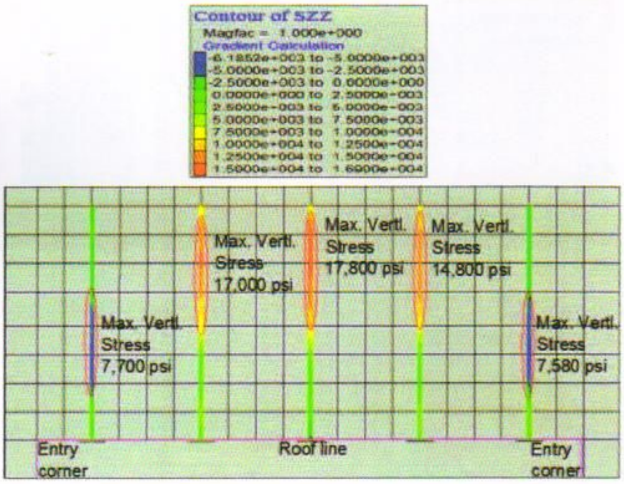

Figure 12a. Vertical stress.

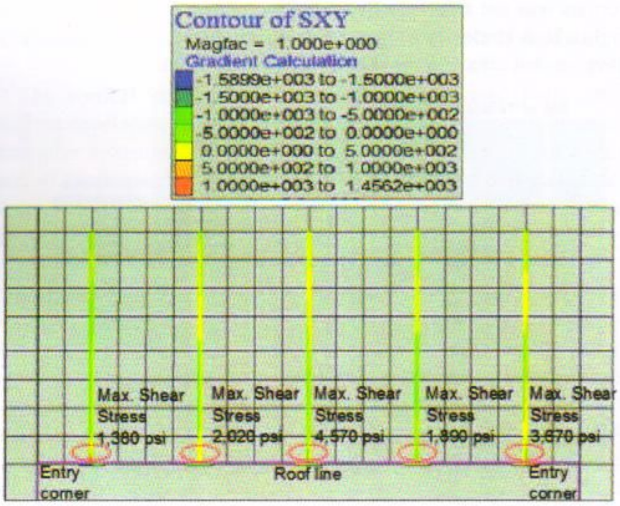

Figure 12b. Shear stress.

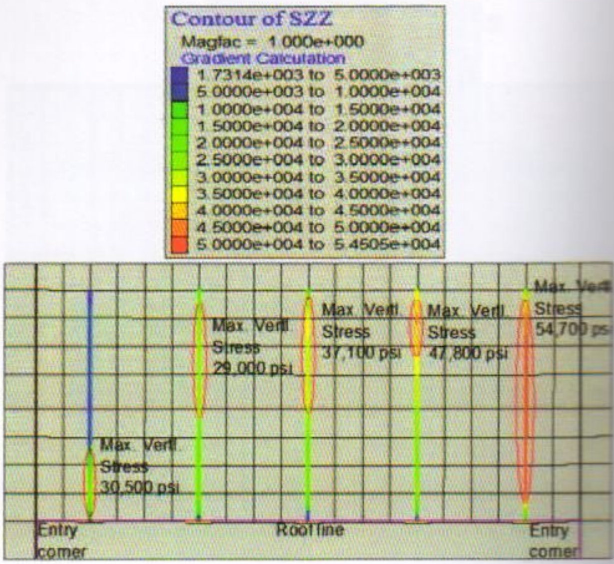

Figure 13a. Vertical stress.

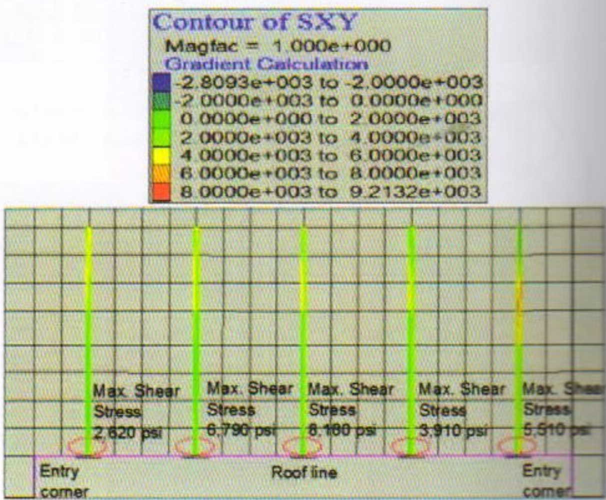

Figure 13b. Shear stress.

The yielding state of the roof rocks in the bolting range is shown in Figure 14. The vertical, horizontal, and shear stresses of the roof rocks after panel retreating are shown in Figs. 15a, 15b, and 15c, respectively. Note that points A, B, C, and D in Figure 15a are located in the yield zone.

Despite no pretension is generated during the resin bolt installation, a 2 ft compressive zone is developed near the roof line for the three bolts installed near the middle of the roof span (see Figure 15a). It is believed that the retreating-induced abutment load will cause the roof sag thus create the compressive zone. In addition, it can be found in Figure 15a that the vertical stress at point B (in the middle between the adjacent bolts) is almost 60 psi (by prorate estimation), while that at point A (close to resin bolt) is much larger, reaching to 400 psi. On the other hand, the vertical stress of the rocks at point D (in the middle between the adjacent bolts) is 340 psi, while that at point C (close to resin bolt) is only

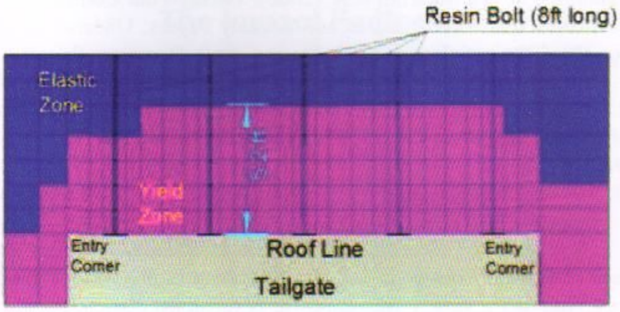

Figure 14. Yield zone around tailgate after retreat of the first panel (resin bolts).

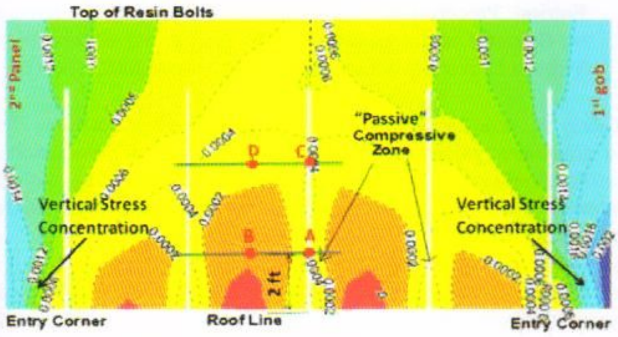

Figure 15a. Vertical stress, E+6 psi.

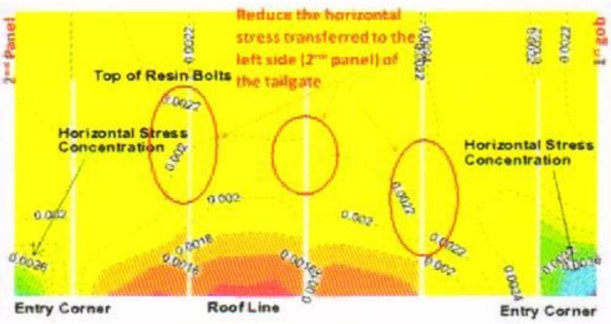

Figure 15b. Horizontal stress, E+6 psi.

slightly larger, reaching to 400 psi. Hence, the resin bolts can significantly increase the bearing capacity of the rocks in the lower part of roof yield zone, while they have limited effect on the rocks in the upper part of the roof yield zone.

Figure 15b shows the horizontal stress in the roof rocks after the retreat of the first panel when employing the resin bolts. The horizontal stress at the right corner is larger than that at the left corner since the right side is closer to the previous mine-out panel or gob. It has been noted that the resin bolts can cut down the horizontal stress transferred to the left side of the entry (see the highlighted circles in Figure 15b).

Figure 15c shows the shear stress (σ_{xz}) in roof rocks after the retreat of the first panel when employing the resin bolts. The resin bolts may have limited effect on the cutter roof development since the propagation of the shear stress contour line at entry corners is not significantly affected by the resin bolts (see the highlighted circles in Figure 15c).

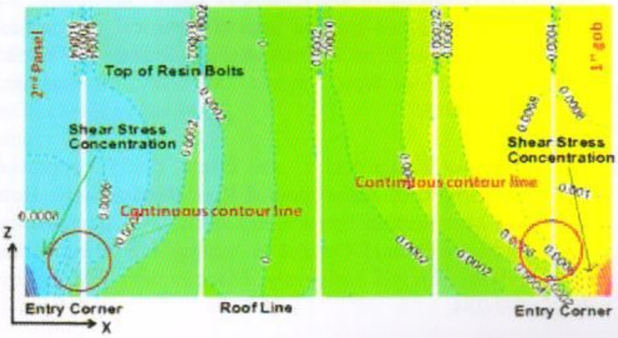

Figure 15c. Shear stress sxz, E+6 psi.

DISCUSSION

For the specified case with a weak and thinly-bedded immediate-roof in this study, the vertical stresses in the tensioned bolts are significantly smaller than that in the resin bolts after retreat of the adjacent panel. Hence, the fully-grouted resin bolts provide more loads for the supporting of the entry roof in this case. In addition, the bearing capacity of the rocks in the lower yield zone of the entry roof is increased more when the fully-grouted resin bolts are installed. The aim of the roof bolting is to increase the strength of the roof rocks thus reduce the potential roof instability. In this respect, the fully-grouted resin bolts are preferred as the primary supports when the weak and thinly-bedded immediate-roof presents. It agrees with the conclusions found by Unrug et al., (2004).

CONCLUSIONS

3D roof bolt models considering the rebar, resin, bearing plates, and resin/rock interface were developed for studying the complicated bolt/rock interaction during underground mining activities.

For the tensioned bolts, the vertical stresses in the bolts installed in the tailgate roof will be increased slightly after the retreat of the first panel. Meanwhile, a 2 ft compressive zone above the roof line is generated by the pretension of 10 short tons. Since the free portion of the tensioned bolts displays a higher vertical stress, the increase of the bearing capacity of the rocks in such range is much larger. In addition, it is found that the tensioned bolts may not be used to prevent the potential of cutter roof since they have very limited effect on the propagation of the shear stress at entry corners.

The similar conclusions can be obtained when employing the fully-grouted resin bolts in the specified tailgate. It should be emphasized that despite no pretension is generated during the installation of fully-grouted resin bolts, the roof sag can passively generate a compressive zone near the roof line. Comparing to the increase of the bearing capacity of the rocks in the lower yield zone of the roof when the tensioned bolts are used, bearing capacity of the rocks in lower roof is increased more when the fully-grouted resin bolts are installed. Hence, the fully-grouted resin bolts should be preferred as the primary supports when a weak and thinly-bedded immediate-roof exists.