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Anchorage Mechanical Characteristics of Newly Designed Rebar Bolt and Optimization of its Support Scheme

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Abstract

In Shendong coalfield, large cross-section underground gateways are often excavated for large machine transportation. It causes large deformation of the surrounding rock and the phenomenon of rib spalling. In this study, taking Xiaobaodang coal mine as the engineering background, a newly designed rebar bolt for large deformational roadway support was introduced to control large deformation. Results that the peak anchoring force of the new bolt increased by 20-30%, the total energy absorption of the system is increased by 35-50%, the post-peak displacement increases by 4.5mm comparing with traditional left-spiral non-longitudinal rebar bolt. The support schemes were analyzed by using FLAC3D, the newly bolting effect was better than the original scheme when the new rebar bolt was used in full-length anchorage and the increased bolting interval. This study provides a referencr for the similar roadway support.

Keywords: Roadway, Large deformation, Support scheme, Rebar bolt, Numerical simulation

1. Introduction

Safety and efficient production of coal is an important aspect for the sustainable development of the economy. Rock bolting support technology has been widely used in underground coal mines for its advantages of strong adaptability to engineering geological conditions, high excavation rate, low labor intensity, high support strength and low support cost. It is the main support technology for underground roadway in coal mines worldwide [1-4].

In recent years, with the increase of mining intensity and the increase of mining equipment in underground coal mines, the number of high-rib and large-cross section underground roadways has gradually increased. Largecross-section roadway is also beneficial to ventilation, transportation and reserve space for surrounding rock deformation, which isconducive to installation of large equipment and safe production [5]. However, the increase of roadway cross-section has a significant impact on the stability of the tunnel ribs, the large deformation of the coal ribs affects the stability of the whole roadway, which brings great difficulties on roadway support [6].

Large deformation roadway support has been studied in literature. Zhang et al. suggestedthat the traditional I-beam support cannot meet the large deformation of surrounding rock caused by large cross-section mining roadway under fully mechanized top coal caving mining method. Through an industrial test, a staggered support method for large cross-section roadway is developed [7]. Meng et al. have studied the large cross-section roadway developed in weak and fractured surrounding rock, and developed full cross-section bolt-mesh and shotcrete primary support, high-prestressing cable bolt and cement grouting secondary reinforcement support scheme. Through numerical simulation, similarity material experiment and industrial experiment, it is proved that the scheme can effectively control the large deformation and floor heave of large cross-section roadway excavated in weak and fractured surrounding rock [8]. Liu et al. studied the floor heave of large cross-section mining roadway, and considered that the floor heave increased linearly with the increase of roadway width. It was proposed that the floor heave could be better prevented by strengthening the corner of the roadway and installing the floor bolt [9].

At present, the conventional rebar bolt is often used as support material, or the high-strength bolt or yieldable bolt is introduced to cooperate with secondary support to improve the safety, however, these measures often increase the installation difficulty, technical difficulty and construction cost, and often reduces the development rate due to the increase of support density [10-14]. Therefore, increasing the surrounding rock controlling ability of the primary support by improving the rebar bolting capability without increasing the support cost, is of great practical significance for rebar bolt support in the large cross-section mining roadway.

Based on the engineering background of rockbolting of large cross-section mining roadway in Xiaobaodang Coal Mine, the authorsdevelop a new type of fully grouted rock bolt without increasing development cost. Through laboratory and field tests, the bolting performance of left-screw steel bolt and the new bolt are compared. The supporting effect of two bolts is numerically studied using

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FLAC3D software. Finally, the support design for Xiaobaodang mining roadway was optimized, which provides a reference for similar large cross-section coal mine roadway support design.

The rest of this study is organized as follows. Section 2 gives the design of the rebar bolt. Section 3 presents the laboratory pullout tests and its results. Section 4 describes the experimental studies in the field, Section 5 conducts the optimization analysis of the support schemes by using FLAC3D and finally, the conclusions are summarized in Section 6.

2. Rebar bolt design

The rebar bolt profile has great influence on the bolting performance. Based on the previous research results of bolt profile optimisation, this paper proposes a trapezoidal large rib spacing left spiral bolt, namely C1 bolt, as shown in Fig. 1.

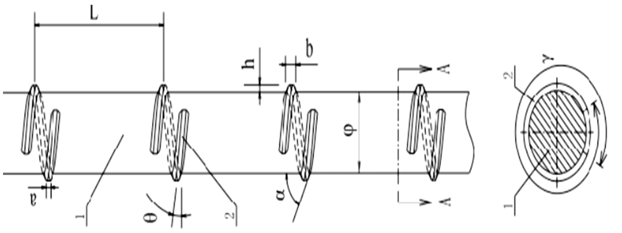
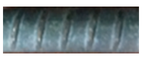


Fig. 1. Design of the new bolt (C1 bolt)

The diameter of the proposedrebar bolt in this paper is 20 mm, the transverse rib spacing is of 50 mm, the rib height is 2 mm. The cross-section of the transverse rib is trapezoidal, with top width 1.5 mm and bottom width 3.6 mm.The helix angle of the transverse rib is of 80°, and the one transverse rib spirals 405° around the anchor body. The overlaid spiral section is of 45° designed for resin flowing during the anchoring installation.The profile parameter of C1 bolt is shown in Table 1. C2 bolt is left-handed non-longitudinal rebar bolt commonly used in underground coal mine industry in China. The profile parameters of C2 bolt is also shown in Table 1.

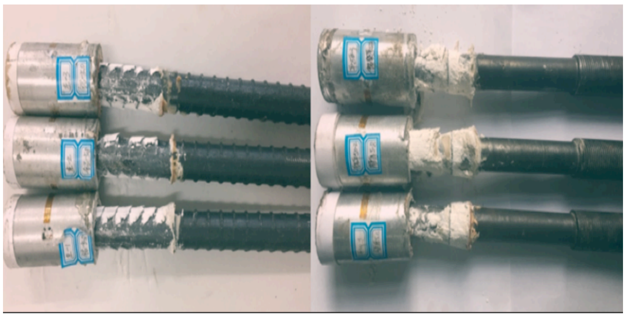
Table 1. Geometric parameters of two kinds of bolts

Rebar Bolt		Diameter (mm)	Rib spacing (mm)	Rib height (mm)
C1		21	13	1.2
C2		20	50	1.8

3. Laboratory pullout tests

3.1 Pullout test of steel sleeve

In laboratory pullout tests, steel sleeve was selected as confining material. The length of the tube is100 mm; its inner diameter is 30 mm and wall thickness is 5.5 mm, respectively. To prevent slip at resin-sleeve interface, the sleeve was threaded with thread pitch of 1.0 mm. Two kinds of the rebar bolts were cut into 280 mm length and anchored into the steel sleeve using resin grout. The average uniaxial compressive strength and shear strength of the resin are measured as 60.9 MPa and19.5 MPa, respectively. The measured Young's modulus is 12.6 GPa and Poisson's ratio is of 0.26.In the preparation, efforts had been made to ensure the bolt to be centered and parallel to the sleeve axis, so that the resin thickness is uniform, as shown in Fig. 2.



(a) Left spiral bolt (b) Newly design bolt

Fig. 2. Test bolting samples

WAW-600C electro-hydraulic servo universal testing machine controlled by microcomputer with a maximum test force of 600 kN was used, as shown in Fig. 3. The prepared specimens are placed in a frame and clipped by the testing machine, and the testing was displacement control with loading rate of 1.0 mm/min.

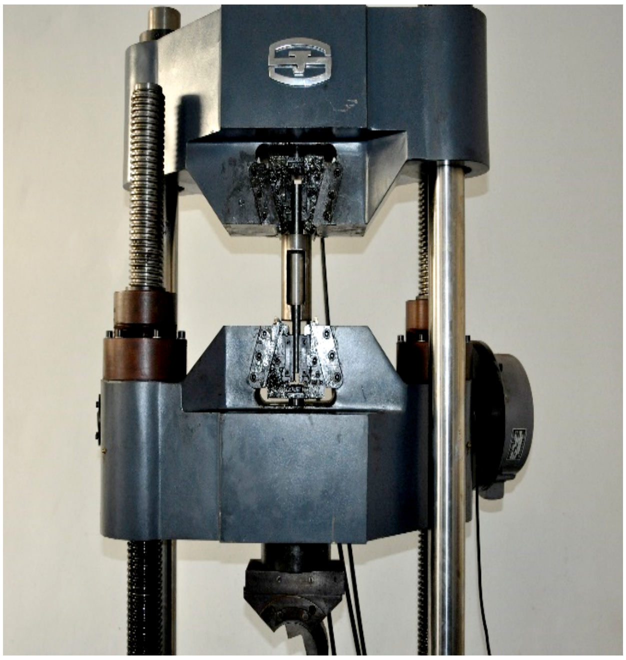


Fig. 3. Testing machine

The pullout curve is shown in Fig. 4. It can be seen that the average peak load of commonly used rebar bolt is 106.2 kN; and the average peak axial load of the newly design rebar bolt is 128.1 kN, which is 20.6% higher than former's. From a viewpoint of energy absorption (area under the pullout curve), the average energy absorption of C1 and C2 bolts are 2.90 kJ and 4.46 kJ, respectively.

Fig. 5 shows the displacements of the two kinds of anchors while the pulling force is greater than 90 kN. The average axial displacement of the new bolts with a pulling force of 90 kN or higher is 25.9 mm, and the axial displacement of the left spiral rebar bolts is 4.6 mm. The peak pulling force of the new anchor reaches to a displacement of about 26 mm, and the peak pulling force of the left spiral rebar bolt corresponds to a displacement of about 6 mm, which indicates an offset displacement up to 20 mm.

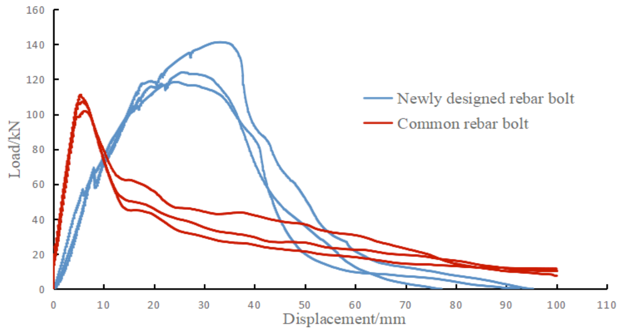


Fig. 4. Load-displacement curves of two kinds of anchor sleeves

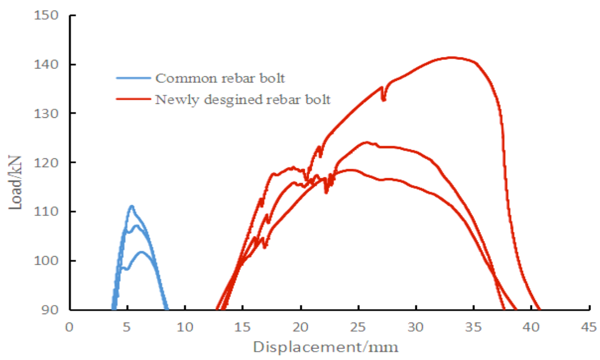


Fig. 5. Pulling force and displacement when drawing force is greater than 90 kN

It can be seen that the C1 anchor reaches its peak pulling force when the bolt deformation is about 6 mm, and the axial displacement is only 4.6 mm for anchor resistance greater than 90 kN. The new anchor reaches peak pulling force at bolt deformation of 26 mm with a axial displacement of 25.9 mm. Compared with the left spiral bolt, the anchorage performance of the new bolt is preferred for large deformation of the surrounding rock.

3.2 Pullout test of concrete block

The height of the roadway is 4.2 m, roof pull-out test does not carry out for safety reason. In the laboratory, a cubic 1 m^3 concrete pier made of fine sand and cement is used to simulate the roof sandstone conditions. Pullout test was carried out using the concrete block, as shown in Fig. 6.

The result of concrete pullout is shown in Fig. 7. The average peak load of the C1 bolt (114.9 kN) is 21.6% higher than that of C2 bolt (94.24 kN). The axial displacement at the peak load of C1 bolt is 12.6 mm, is 8.6 mm for C2 bolt.It indicates a shift of 4.5 mm. The average total energy absorption of the C1 bolting specimen (5321 J) is 36.2% higher than that of C2 (4275 J).


Fig. 6. Pullout test using concrete block.

4. Field pullout test

Considering the reliability of field application of the experimental data, field pullout experiments were carried out at 630 m and 2430 m of the roadway of 112201 longwall panel of Xiaobaodang Coal Mine. The anchoragelength is 150 mm, and the grouting agent is MSK2335 resin grout. Entangle with Tape was used to entangle the bolt at 150 mm end of bolt to avoid overflow of anchoring agent, as shown in Fig. 8.

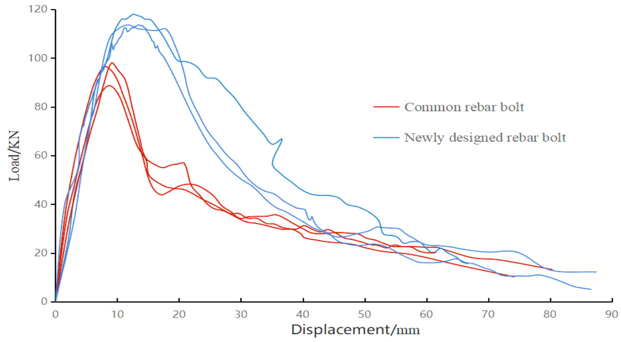


Fig. 7. Pullout curves of concrete block

The result of rib pullout is shown in Fig. 9. The average peak pull-out load of new bolt is 99.2 kN, the average peakpull-out load of commonly used left spiral bolt is 73.9 kN, and the peak load displacement of C1 bolt is 12.2 mm, C2 bolt is 7.7 mm, offset is 4.5 mm.

The area under the pullout curve is the total energy absorbed by the anchorage system, that is, the required energy for the failure of the anchorage.It is an important index of the anchorage effect. The higher the requiredtotal energy, the better the anchorage performance. At present, there are several kinds of specially designed bolt to improve the total energy absorption [15-17]. The average total energy absorption of C1 system is 4901J, and that of C2 system is 3267 J. The average total energy absorption of C1 system is 50% higher than that of C2 system.

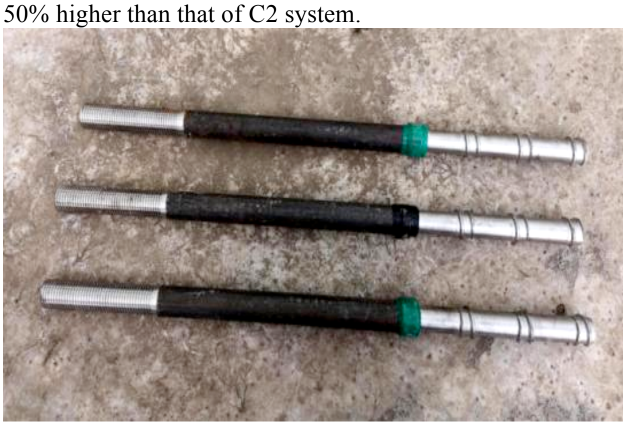


Fig. 8. C1 bolt used for field test

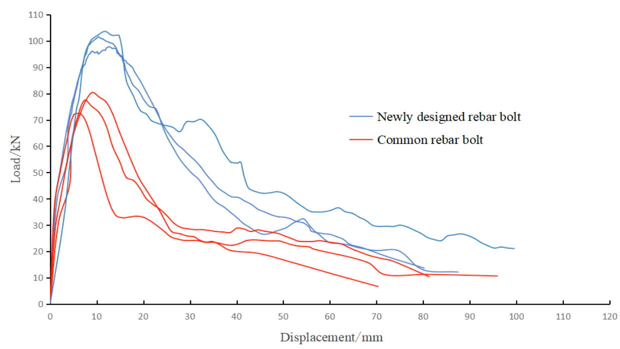


Fig. 9. Pullout curves from the roadway rib

The peak pull-out force and energy absorption of the bolt control the bolting effect of surrounding rock. The average peak pullout force of the new bolt is 20-30% higher than that of the commonly used rebar bolt;thedisplacementat peak load is 4.5 mm larger, and the total energy absorption of the system increases by 35-50% on average. It shows that the new bolt maintains a high strength in the case of large deformation, and can be used for large deformation of surrounding rock.

5. Numerical study of support design

5.1 Support design

The original support scheme of Xiaobaodang large cross-section roadway is, the roof and the pillar rib adopt ordinary rebar bolts with ϕ20 mm × 2400 mm, the spacing of roof bolt is 850 mm × 900 mm, 7 per row; spacing in the pillar rib is of 900 mm × 900 mm, 5 in a row, and the anchoring length is 1300 mm. Pre-tightening torque of the bolts is 60 N·m in pillar rib, roof bolt pre-tightening torque is 120 N·m. Roof cable specification is 17.8 mm × 6300 mm, anchorage length 1700 mm. The cable is arranged between the two rows of rebar bolt anchors. The panel ribadopts ϕ22 mm × 2400 mm glass fiber reinforced polymer (FRP) bolt to prevent the shearer from rubbing with the steel anchor during the mining process to ensure the safe production of the mine. The spacing at the panel rib is 900 mm × 900 mm.

An optimization scheme has been developed, roof bolt and pillar bolt are replaced by the new rebar bolt. Original ϕ22 mm FRP anchors are replaced by ϕ27 mm FRP bolt. The spacing becomes 900 mm × 1000 mm, the anchoring method is changed from the end anchoring to the full-length anchoring.The pre-tightening torque of the roof and the pillar rib bolts are 150 N·m, and the anchor cable support scheme is unchanged.

5.2 Numerical simulation

The deformation of the roadway is studied under the existing support scheme of the mining roadway, the full-length anchoring of the existing supporting scheme, and the full-length anchoring of the new bolt scheme by using FLAC3D. Tables 2 and 3 show the physical and mechanical parameters of the coal and rock and mechanical parameters of anchors.

Table. 2. Mechanics parameters of coal and rock

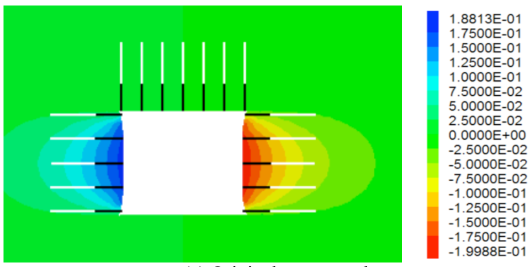
Lithology	Bulk Weight (g/cm^3)	Tensile strength (MPa)	Cohesion strength (MPa)	Friction angle φ (°)	Elastic Modulus (MPa)	Poisson's ratio ν
Siltstone	2.37	1.03	5.82	37	1.95E4	0.21
Sandy mudstone	2.36	1.44	5.12	35	2.7E4	0.19
Medium sandstone	2.30	1.32	6.09	32	2.4E4	0.18
Fine sandstone	2.33	1.59	9.42	34	2.96E4	0.18
Coal seam	1.33	0.44	4.40	34	0.88E4	0.21

Table. 3. Parameters of cable structural element

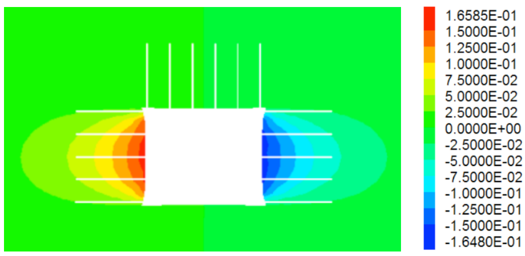
Material	Density (kg/m^3)	Elastic Modulus (GPa)	k_g (GN·m)	c_g (MN·m^2)	Out perimeter (m)	Cross-sectional area (m^2)	Maximum breaking force (kN)
Rebar bolt	7900	201	14	0.895	0.069	3.14×10^{-4}	174
FRP	2100	70	12	0.432	0.085	5.72×10^{-4}	280
New rebar bolt	7900	201	14	1.100	0.069	3.14×10^{-4}	174

Through borehole peeping and physical and mechanical properties testing of rock samples, it is found that the roof is hardrock, there are no obvious cracks, and the roof condition is good. The simulation results show that although the roof subsidence has been reduced, it is not very obvious. The displacement nephogram of the roof subsidence is not given here.

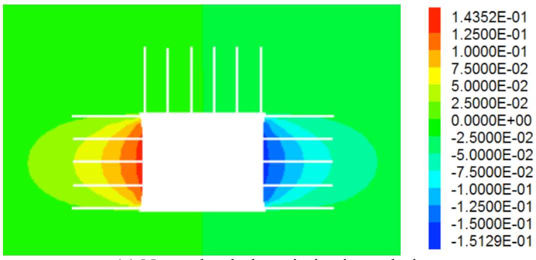
Through the numerical calculation of the existing support scheme, the present support parameter full-length anchorage scheme and the new bolt scheme, it can be seen (Fig. 10) that the pillar rib deformation of the full-length anchorage of the original support parameter has been reduced from 188 mm to 165 mm, with a reduction of 12%. The deformation of the pillar rib the new bolt scheme is 143 mm, with a reduction of 24%. The simulation results are limited to anchoring force of the new bolt, but the advantages such as strong energy absorption and large displacement of peak load retention, are not reflected. It can be seen that the new type bolt has the advantage of controlling the large deformation of roadway.



(a) Original support scheme



(b) Full length anchoring of original support parameters



(c) New rebar bolt optimization solution

Fig. 10. Horizontal displacements fields of different schemes

6. Conclusions

To realize rock bolting optimization of large cross-section roadway support with respects to strata controlling and development economy, a newly designed rebar bolt was introduced to control large deformation, the laboratory and field pullout tests were conducted, the mainly conclusions are as follows:

(1) A new rebar bolthas been designed with diameter 20 mm, the transverse rib spacing 50 mm, the rib height 1.8 mm. The transverse rib shape is trapezoidal, and the rib top width is 1.5 mm and the rib bottom width is 3.6 mm. The transverse rib has a helix angle of 80° on the outer surface of the rod, and the same transverse rib spirals 405° around the anchor body.

(2) In terms of anchoring performance, in the laboratory test, the new anchor bolting force is increased by 20% on average, and the load peak displacement is shifted by up to 20 mm. In field tests, the new rebar bolt has an average anchorage force of 20-30% higher than that of the common rebar bolt, the total energy absorption of the system is increased by 35-50%, and the peak displacement of the load is greatly offset by 4.5 mm.

(3) The new bolt full-length anchoring optimization scheme is effective than the original scheme support under the field condition.

Although the optimized design of this study has achieved good results in the practice, with the development of mining engineering, the advanced bolting support that meets the requirements of large deformation control and low cost needs to be further researched.

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