Research on Mechanical Properties of U-Shaped Retractable Gangue Prevention Structure of Gob-Side Entry by Roof Cutting and Pressure Releasing in Deep Mining

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Received 19 November 2021; Accepted 4 January 2022; Published 29 January 2022

Academic Editor: Hao Xiong

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In recent years, as a new type of gob-side entry retaining method, roadway automatically formed by roof cutting and pressure releasing (RAFRCPR) has been widely used in China. Under the condition of deep mining, the deformation of the gangue rib of the automatically formed gob-side entry retaining is difficult to control, and it is difficult for the traditional I-shaped steel to provide the needed support. To effectively control the deformation of the gangue rib, a new type of U-shaped retractable gangue prevention structure (URGPS) with high lateral support strength and axial compressible dynamic absorption energy is proposed. Based on the geological conditions of the 21304-working face in the Chengjiao coal mine in Henan, the mechanical characteristics of URGPS and the causes of its local instability are analyzed in detail employing theoretical analysis, laboratory tests, and numerical simulation. A reasonable bolt tightening force, overlap length, and lap combination form of the URGPS are determined according to the actual situation of the project site. Engineering practice shows that a URGPS that was applied to control the deformation of the gangue rib in deep roof-cutting roadway was effective.

1. Introduction

Coal resources are one of the most important basic energy sources, accounting for about 30% of the world’s total energy consumption. China’s energy supply is dominated by coal, and the energy return on the investment in coal mining is and will continue to be higher than that in oil and gas mining, which indicates that coal is likely to continue to be China’s most important fossil fuel resource in the future [1–3]. However, with the decrease in coal resources and the increase in mining depths, the wastage of coal resources caused by traditional coal pillar mining is becoming increasingly prominent [4–7]. To effectively utilize the limited coal resources, improve the coal recovery rate, and enhance mining safety, He et al. first proposed the “cantilever beam cutting theory” in 2008 [8]. Based on this, a new goaf roadway retention method called roadways automatically formed by roof cutting and pressure releasing has been widely used in China. Compared with the traditional coal-pillar mining method, the technology of RAFRCPR mining has the advantages of simple process, high recovery rate, low tunneling volume, low accident rate, and high economic benefits [9–12].

RAFRCPR adopts bilateral cumulative tensile explosion technology [13] to directionally presplit and cut off the connection between the goaf side roof and the roadway roof in advance and reduce the influence of periodic pressure on the deformation of the roadway roof. It adopts constant resistance large deformation (CRLD) cables for the reinforcement of the roadway roof [14, 15]. After the coal seam is mined, the roof of the goaf falls along with the presplitting cutting slots under the action of mine pressure and the rock mass’s self-weight. Then, the collapsed gangue forms a gangue rib under the action of...
the retaining structure, and this gangue rib can support the roof of the goaf after being compacted. The schematic diagram and partial detail drawing of the RAFCPR method are shown in Figure 1.

In practice, deformation control of the gangue rib is a key factor for the success of RAFRCPR mining technology. The impact dynamic load formed in the process of roof collapse in the goaf and the squeezing effect between the...
collapsed gangue often have an adverse impact on the maintenance of the gangue rib [16–18]. Especially under the condition of deep high-stress mining, the traditional I-shaped steel retaining has a high failure rate, low recovery rate, and poor supporting effect [19–22].

Relevant scholars have done a lot of research on roadway U-steel support. Chunan [23, 24] conducted a mechanical analysis on the U-shaped steel bracket and pointed out that the load-bearing capacity of the U-shaped steel bracket mainly depends on the overall stability of the bracket itself.
and analyzed the force changes of the U-shaped steel before and after shrinking. Chunan [25] conducted a mechanical analysis on the U-shaped steel bracket and pointed out that the load-bearing capacity of the U-shaped steel bracket mainly depends on the overall stability of the bracket itself and analyzed the force changes of the U-shaped steel before and after shrinking. Li et al. [26] analyzed the mechanical properties and failure characteristics of U-shaped confined concrete arches in deep roadways. Although different scholars have conducted analysis and research on U-shaped steel support, there is little research on the U-shaped steel gangue retaining support of the gangue rib in RAFRCPR.

To further explore the mechanism of deformation and instability of the URGPS, in this study, based on the actual stress of gangue retaining in RAFRCPR, a mechanical model of the URGPS is established, and the factors influencing its deformation and instability are determined. At the same time, mechanical analysis, indoor experiments, and numerical simulation are used to determine the reasonable supporting parameters of the gangue retaining in the 21304-working face in the Chengjiao coal mine. A field test shows that the support structure significantly improves the deformation of the gangue retaining.

2. Deformation Characteristics of a Deep Gangue Retaining Wall

2.1. Engineering Geological Conditions. The Chengjiao coal mine is located in Yongcheng City, Henan Province, China. The 21304-working face of the Chengjiao coal mine is buried at a depth of 835-915 m; the width and height of the roadway are 4.2 m and 2.8 m, respectively; and the coal thickness is 2.6 m–4.3 m. The immediate roof of the coal seam is mudstone with a thickness of 1.5-5.0 m and an average thickness of 2.85 m. The main roof is composed of fine-grained sandstone with an average thickness of 3.76 m and siltstone with an average thickness of 5.23 m. The immediate bottom is sandy mudstone with a thickness of 0-0.86 m and an average thickness of 0.43 m. The main floor consists of siltstone with a thickness of 1.63 m and fine sandstone with a thickness of 11.22 m. The location of the mine and lithology of the rock layers are shown in Figure 2.

2.2. Deformation Characteristics of the Gangue Retaining Structure. In thin and medium-thick coal seams, the gangue retaining of RAFRCPR often employs I-shaped steel as the support structure, and the supporting effect meets the requirements of retaining roadways. However, as the mining depth increases, the ground stress and pressure on the supporting structure of the gangue retaining wall change accordingly, and it is difficult for the I-shaped steel's supporting effect to meet the engineering demand. Due to the unreasonable strength of the supporting structure, the unreasonable torque of the connection clamp, and the unreasonable length of the lap joint, heave failure, instability failure, and bending failure easily appear on the structure of the lever, as shown in Figure 3.

3. Mechanical Property Analysis of the URGPS

3.1. The URGPS Model. The URGPS structure is composed of two U-shaped steel joints with a certain length. The joints are connected by clamps and bolts, and the combination can undergo sliding contraction in the longitudinal direction. When the U-shaped retaining structure is used to support the roadway side, the lower part is buried into the floor to a certain depth, the upper end is inserted into the presplitting cutting slots, and the connecting parts of the clamps are connected with pull rods to prevent the clamps from moving up and down when the U-shaped steel is retracted. When the roof is displaced due to rotation and subsidence, the U-shaped steel has stronger lateral deformation resistance
than I-shaped steel. And it can bear a larger gangue extrusion load in the lateral direction when it has a certain length of lap combination, making it an ideal supporting structure for the roadway side. The gangue rib support form and the structure of URGPS are shown in Figure 4.

3.2. Stress Evolution Process of the URGPS. The formation of the gangue rib and the structural model of the surrounding rock of the gangue rib are shown in Figure 5. During the process of gangue rib formation, the stress evolution of the URGPS can be divided into three stages:

![Figure 5: Stress evolution process of the URGPS.](image-url)
Figure 10: Fitting curves of axial pressure and lateral pressure under different particle sizes and bending deformation diagram of the gangue retaining.

Figure 11: Main forms of unstable failure.

Figure 12: Roadway support form and URGPS numerical model.
Figure 13: Mechanical model of the U-shaped support.

Table 1: Numerical simulation program.

| Scheme | Bolt pretightening force | Axial pressure | Lateral pressure | Overlap length | Overlap position | Overlap form |
|--------|--------------------------|----------------|------------------|----------------|-----------------|-------------|
| 1      | 100 N·m                  | 0 MPa          | 32–44 kPa, 1.6–1.7 MPa | 1.00 m         | Middle          | Inside lap (Figure 14(a)) |
|        | 200 N·m                  | 0 MPa          | 32–44 kPa, 1.6–1.7 MPa | 1.00 m         | Middle          | Outside lap (Figure 14(a)) |
|        | 300 N·m                  | 0 MPa          | 32–44 kPa, 1.6–1.7 MPa | 1.00 m         | Middle          | Inside lap |
| 2      | 200 N·m                  | 0 MPa          | 32–44 kPa, 1.6–1.7 MPa | 0.50 m, 0.75 m | Middle          | Inside lap |
|        | 300 N·m                  | 0 MPa          | 32–44 kPa, 1.6–1.7 MPa | 1.25 m, 1.50 m | Middle          | Inside lap |
| 3      | 200 N·m                  | 1.6–1.7 MPa    | 1.00 m           | Middle          | Inside lap |
| 4      | 200 N·m                  | 1.6–1.7 MPa    | 1.00 m           | Middle          | Inside lap |

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(1) The first stage. The immediate roof does not collapse in the initial stage after the working face is advanced, the structures are mainly subjected to the axial pressure from the roof, and there is no lateral pressure, as shown in Figure 5(a).

(2) The second stage. With the increase in the mining distance, the direct roof gradually collapses to form gravel filling material. At this time, the gangue retaining is affected not only by the URGPS axial pressure but also by the lateral crushing force. However, since the immediate roof is not bent and fractured, the crushed rock only produces lateral pressure on the retaining structure under the action of gravity, and the lateral pressure is small, as shown in Figure 5(b).

(3) The third stage. When the main roof is fractured and acts on the gravel accumulation, the gravel gradually compacts to form the roadway side under the action of the overburden pressure. In the process of gravel compaction, the lateral pressure on the retaining increases rapidly, and after the overburden is stable, the lateral pressure tends to be stable, as shown in Figure 5(c).

3.3. Mechanical Analysis of the URGPS. The retractable resistance of the URGPS is the bearing capacity of the gangue retaining before shrinkage. Effective control of the gangue retaining structure’s bearing capacity is key to using it. If the retractable rejection capacity is too large, the gangue retaining structure fails to shrink and release pressure, which can cause structural damage. However, if the retractable rejection capacity is too small, the goal of ensuring roadway stability cannot be achieved.

The contact-interaction force \( F \) of a U-shaped gangue retaining can be decomposed into the normal contact force \( F_1 \), which is located between the ear edge or bottom of the U-shaped steel and clamps, and the normal contact force \( F_2 \), which is located between the U-steels and between the clamp and the U-shaped steel’s waist [23, 24].

\[
\begin{align*}
F_1 & = FA_0, \\
F_2 & = \frac{F}{\sin \alpha} (1 - A_0),
\end{align*}
\]

where \( \alpha \) is the angle between the cable, the U-shaped steel waist’s slope, and the axis of symmetry. \( A_0 \) is the contact distribution coefficient (\( A_0 = 1 \) for ear positioning and \( A_0 = 0 \) for waist positioning).

The main force behind the U-shaped steel’s sliding is the axial force \( N \) of the upper U-shaped steel, and the resistance is the contact force of the structure. The stress on the overlapping U-shaped steel part is shown in Figure 6. Considering formula (1), the yielding condition of the U-shaped steel is

\[
\left\{ \frac{TA + TC}{\sin \theta} [1 - A_1 (1 - \sin \theta)] + \frac{TE + TF}{\sin \theta} [1 - A_2 (1 - \sin \theta)] \right\} f \geq N_g.
\]

Using Figure 6(b) to establish the equilibrium relationship, we get

\[
\begin{align*}
\sum F &= T_A + T_C + Q - T_E - T_F = 0, \\
\sum M &= T_C l - M + T_F l = 0.
\end{align*}
\]

Substituting this into formula (2), we get

\[
\left\{ \frac{TA + TC}{\sin \theta} [1 - A_1 (1 - \sin \theta)] + \frac{TA + TC + Q}{\sin \theta} [1 - A_2 (1 - \sin \theta)] \right\} f \geq N_g,
\]

where \( f \) is the friction coefficient of steel, \( T_A, T_B, T_C \), and \( T_D \) are the normal contact force at the clamps; \( T_E \) and \( T_F \) are the normal contact force between the U-shaped steels; and \( A_1 \) and \( A_2 \) are the contact force partition coefficients of the U-steel and clamps. \( L \) is the distance from the positive pressure \( T_C \) to the upper-end section, and \( Q \) is the shear force.

3.4. Experimental Analysis of the URGPS

3.4.1. Experimental Research on Contractibility

(1) Experimental Scheme. In this experiment, two U29-shaped steels were used for the lapping combination. The total length was 3 m, the overlapping length was 1 m, and the lap joints were connected by clamps. During the experiment, the two ends of the gangue retaining structure were fixed on the support and the clamps were connected by bolts and nuts. Then, an axial load was gradually applied to one side of the U-shaped steel through the end hydraulic device to test the effect of different torques on the yield capacity of the U-shaped steel. The test device is shown in Figure 7.
The relationship between axial load and shrinkage under different torque conditions is shown in Figure 8. The following conclusions can be drawn from the test results.

The maximum bearing capacity of the URGPS under different torques is different. The slip resistance of the URGPS increases with the increase in the torque. The greater the torque, the greater the axial bearing capacity, and the more stable the structure.

It can be seen that the axial displacement curves of the URGPS under different torques are similar. The curve can be divided into three stages: small deformation stage of the retaining structure, constant resistance slip stage, and pressure unloading stage. When the axial pressure is less than the sliding resistance, the deformation of the structure is mainly caused by overcoming the deformation caused by the incomplete contact between the U-shaped steels and the elastic-plastic deformation of the material. When the axial pressure is greater than the sliding resistance, the axial displacement increases but there is a small change in the axial load, and the gangue retaining transitions to the stage of constant resistance sliding. This stage is the key stage to support the gangue and effectively release the roof pressure.

3.4.2. URGPS Model Experiment

(1) Experimental Scheme. Using a self-made crushed stone compression device and a gangue retaining device, a staged loading experiment was carried out on the roof sandstone. To negate the influence of gravel size on the experimental results, the lateral pressure and deformation of the gangue with different grain sizes on the URGPS were studied. The self-made experimental compression device, which has a size of 400 mm × 400 mm × 400 mm, is made of high-strength steel plates and steel ribs as shown in Figure 9(a). The structure of the device on three sides is a high-strength steel plate, and the other side is composed of steel ribs to simulate a URGPS. The experimental loading system is a 2000 kN servo loading system (MTS) as shown in Figure 9(b). The crushed stone was pressurized by compressing the top plate.

The URGPS model is made of Q345 stainless steel ribs in this experiment, and the length × width × height = 20 mm × 10 mm × 40 mm. The pressure on the side of the crushed stone was obtained using strain gauges and a static strain monitoring system as shown in Figures 9(a) and 9(c). The gravel particle size was 10-20 mm, 20-40 mm, 40-60 mm, and 60-80 mm. The experiment adopted the load stress control method, and the load rate was set to 1 kN/s. Taking into account the bearing capacity of the lateral gangue retaining, the maximum axial load was 2.0 MPa, and each level of load was 0.2 MPa, 0.4 MPa, 0.6 MPa, ..., 2.0 MPa. After loading to the specified load, the pressure was kept constant for 15 minutes, and then, the next level of load was applied.

(2) Test Result. From the fitting curve of the lateral stress under different axial forces as shown in Figure 10(a), it can be seen that the lateral pressure coefficients of the gangue rib at the particle size of 10-20 mm, 20-40 mm, 40-60 mm, and 60-80 mm are 0.77, 0.71, 0.66, and 0.55, respectively. Because the side of the crushed stone is only supported by the gangue retaining, its support resistance is smaller than that of the other three sides, and the crushed stone easily slides to the free support side, resulting in high pressure on the side of the crushed stone. Under the same axial pressure,
the lateral stress decreases with the increase in the gravel particle size, and the lateral pressure coefficient also decreases. This is due to the close contact and strong fluidity between the particles with smaller particle sizes, which makes crushed stone easier to slide and compress to the free side after the axial force is applied, and the gangue retaining also comes under greater stress.

The deformation of the steel ribs after compression is shown in Figure 10(b). With the increase in the axial compression amount of the crushed stone, the lateral pressure also increases, and the steel ribs produce bending deformation under the squeezing of the crushed stone, resulting in a bulging phenomenon. The maximum bending deformation is located in the middle and lower parts of steels. The diameter of the crushed stone has a certain effect on the lateral pressure of the steel rib, which shows that the diameters of the crushed stone are inversely proportional to the lateral pressure. Therefore, the URGPS must have a certain bending resistance to adapt to the impact of the crushed stone of different sizes during the collapse of roof in coal mines. Besides, this experiment did not take into account the top pressure and the scalability of the URGPS, which will be analyzed using a numerical calculation.

4. Analysis of the Instability Mechanism of the URGPS and Numerical Simulation

4.1. Analysis of the Instability Mechanism of the URGPS

4.1.1. The Influence of the Preload of Clamps. The retractable capacity of the URGPS is a key factor in controlling the deformation of the surrounding rock and ensuring the stability of the roadway [25, 26]. Although the bearing capacity and structural characteristics of U-shaped steel can better meet the actual requirements of projects, when the bolt is not tightened properly, it will be damaged. The damage forms are mainly divided into two types: the first type of U-shaped steel has an insufficient bearing capacity, and its strength is not fully exerted, resulting in a large relative displacement between the two U-shaped steels and the appearance of a tilting phenomenon. The main reason for this is that the torque applied by the nut is too small, resulting in less friction between the two U-shaped steels. The URGPS damage form is shown in Figure 11(a). The second failure mode is the bending instability of the U-shaped steel at the nonlap joint; the U-shaped steel’s bearing capacity after bending is significantly reduced. The main reason for this is that the torque applied by the bolt is too large, causing the friction between the U-shaped steel to become too large so that the gangue retaining loses its contraction characteristics. In the case of continuous deformation of the roof and crushed stone extrusion, failure to achieve the pressure releasing effect leads to the URGPS instability and failure as shown in Figure 11(b).

4.1.2. The Influence of External Load. The load on the URGPS is mainly from the bending and sinking of the roof and the collapse and extrusion of the crushed stone. As the mining depth increases, the vertical and horizontal stresses gradually increase. According to the monitoring data from the single pillar of the gravel side in the Chengjiao mine roadway at a depth of 835–915 meters, the axial pressure can reach up to 25 MPa. At the same time, due to the impact

![Figure 16: Stress diagram of the gangue retaining under different pretightening forces and force stages.](attachment:image.png)
of blasting operations and mining disturbance, the stress of
the surrounding rock of the gangue rib side increases, which
tends to cause instability and damage to the gangue retain-
ing’s supporting structure.

4.1.3. The Influence of Lap Length. Due to the different
heights of the roadways in different sections, the overlap
length of the U-shaped steel also needs to be changed. When
the lap length is too short, the lateral support stiffness is
insufficient and the U-shaped steel will easily produce large
bending deformation under the action of the roof and the
lateral pressure so that it cannot provide effective lateral sup-
port. When the lap length is too long, it does not meet the
economy of mine construction technology, and, therefore,
it is necessary to determine a reasonable lap length.

4.1.4. The Influence of Lap Combination Form. Because of
the difference in the lap position and the lap form of the

![Lateral displacement and stress diagrams under different overlap lengths.](http://pubs.geoscienceworld.org/gsa/lithosphere/article-pdf/doi/10.2113/2022/1288090/5521804/1288090.pdf)
U-shaped gangue retaining, the dangerous section and bearing capacity of the gangue retaining also change. Therefore, it is necessary to determine a reasonable lap form to ensure the stability of the gangue rib.

4.2. Numerical Simulation Analysis

4.2.1. Numerical Model. To further study the mechanical and deformation characteristics of the URGPS, a 3D 1:1 numerical model of the URGPS was established using the ANSYS software according to the support form of the 21304 panel in the Chengjiao coal mine. The roadway support form and the U-shaped retaining model are shown in Figure 12. In the test, the top of the U-shaped steel was pressed under the rigid plate to imitate the stress and deformation characteristics of the gangue retaining when subject to roof pressure. At the same time, side pressure was applied to simulate the extrusion effect of the falling gangue on the gangue retaining. The effective support length of the gangue retaining is 3 m, and the rigid plate is a square plate of 200 mm. The vertical compression of the rigid plate is 100 mm, the density of the U29 steel is 7800 kg/m³, the cross-sectional area is 36.92 cm², the modulus of elasticity is 210 GPa, the Poisson ratio is 0.3, the yield strength is 400 MPa, and the tensile strength is 575 MPa; surface contact was adopted between the U-shaped steels and between the U steel and clamp, and the friction coefficient was 0.3 [27, 28].

4.2.2. Simulation Schemes. During the formation of the gangue rib, the lateral force of the URGPS constantly changes. According to the three stages of roadway side formation, different distributions of lateral forces were selected to simulate the influence of lateral force on the compressibility of the gangue support structure.

In the first stage, there was no lateral pressure, and the stress model is shown in Figure 13(a). After the second stage was stable, the lateral pressure was approximately calculated according to the Rankine earth pressure. The stress model is shown in Figure 13(b).

\[ P = K_0 y Z, \]

where \( P \) is the strength of the earth pressure acting at any accumulation height \( Z \); \( K_0 \) is the static earth pressure coefficient, with the values for gravel and pebbles taken as 0.2 [29–31]; \( y \) is the average gravity of the gravel (20 kN/m³); and \( Z \) is the gravel stacking height (according to the cutting seam depth and support height on-site, a stack height of 11 m was chosen).

In the third stage, the side pressure is the field monitoring value whose maximum is 1.7 MPa at the bottom and 1.6 MPa at the top. The stress model is shown in Figure 13(c). The numerical simulation scheme is shown in Table 1.

4.2.3. Analysis of the Simulation Results

(1) The axial bearing capacity of the gangue retaining increases with the increase in the bolt preload, which is close to the result obtained from the indoor experiment. The axial bearing capacity of the U-shaped gangue retaining under different lap forms (shown in Figure 14), preload, and stress stages is shown in Figure 15.

When the upper U-shaped steel is overlapped inside, the axial bearing capacity of the gangue retaining is similar in the first and second load-bearing stages, which shows that the lateral pressure in the first collapse stage has little effect on the shrinkage of the gangue retaining. In the third stage, the axial bearing capacity of the gangue retaining increases sharply. Compared with the first stage, the axial bearing capacity of the gangue retaining under different preloads of 100 N·m, 200 N·m, and 300 N·m increases by 99.27%, 42.86%, and 25.47%, respectively. The larger the lateral force, the more difficult it is for the gangue retaining to shrink. The lateral force in the third stage significantly improves the bearing capacity of the gangue retaining, and, therefore, bending instability of the gangue retaining easily occurs in the third stage.

When the upper U-shaped steel overlaps outside, the axial bearing capacity of URGPS increases by 34.3% on average compared with when the U-shaped steel overlaps inside in the first and second stages when the lateral pressure is small. This is due to the lateral micro bending of the gangue retaining in the process of compression. If the upper U-shaped steel overlaps outside, the bending of the lower U-shaped steel will increase the sliding resistance of the upper U-shaped steel, while the overlapping of the upper U-shaped steel inside is conducive to the contraction of the URGPS. Therefore, the outer lap joint has a larger bearing capacity than the inner lap joint and is less likely to be retracted. When choosing the preload applied by the URGPS, the change in the stress stage and the change in the lapping form should be considered simultaneously.

The stress cloud at different stages during the compression process is shown in Figure 16. During the same stage, the greater the preload, the greater the stress when the structure shrinks. The stress is mainly concentrated in the
connection part of the clamp. The lateral forces in the first and second pressure stages are smaller than those in the third stage, and the stress distribution is similar. In the third stage, the large lateral pressure of the rock slope leads to the rapid increase in the shrinkage rejection capacity of the gangue retaining structure. The stress in the third stage is significantly higher than that in the first two stages, and the edge of the top and bottom of the U-shaped steel is prone to yield.

(2) The simulation results of the influence of lap length on the stability of the URGPS are shown in Figure 17.
The simulation results show that the change in the lap length has almost no effect on the bearing capacity of the gangue, all of which is about 196 kN. When the axial shrinkage is small, the lateral displacement of the URGPS gradually reduces with the increase in the lap length, and the greater the lap length, the stronger is the resistance to lateral bending. The maximum lateral displacement of the different lap lengths is shown in Figure 18.

Under the third stage of stress, the linear stress distribution curve of the upper and lower lap parts with different lap lengths is shown in Figure 19. The ear of the U-shaped structure’s top and bottom end is under large stress. Besides, the upper U-shaped steel has a large stress at the upper lap joint and the lower U-shaped steel has a large stress at the unapped portion, which is the weak surface prone to bending and similar to the site bending instability. The maximum stress of the weak surface is shown in Figure 20. The stress of the bending parts tends to decrease with the increase in the lap length, and, therefore, the increase in the lap length can effectively prevent the failure of the weak surface.

(3) The displacement and stress nephogram of different overlapping parts is shown in Figure 21. When the lap length is the same, the maximum lateral displacement of the upper, middle, and lower lap positions is 12.57 mm, 11.82 mm, and 12.78 mm, respectively, and the lateral displacement of the lap positions of the upper and lower lap positions is larger than that of the middle lap positions, as shown in Figure 21(a). The maximum stress of the weak surface at the upper, middle, and lower overlapping positions is 525.52 MPa, 291.15 MPa, and 232.95 MPa, respectively. It can be seen that the middle position should be selected as the overlapping position to avoid the instability of the gangue retaining under the condition that the lateral pressure difference between the upper and lower ends is not large enough, as shown in Figure 21(b).

5. Field Application

Due to the large depth in the Chengjiao coal mines, U-shaped shrinkage gangue retaining support is adopted for the side of the crushed stone in the 21304-working face. It can not only bear the large pressure of the roof but also maintain the stability of the side of the gravel and prevent the bulge phenomenon from occurring. According to the results of the experiment in this study, the URGPS is composed of U29 mining steel, the pretightening force of the cable is 200 N, the inner side of the active force-bearing end is overlapped, and the overlapping length is 1 m, overlapped position is the middle part, the lower end is under-cover, and the upper end is inserted into the presplitting seam. The field support effect is shown in Figure 22. The URGPS can well adapt to the surrounding rock’s deformation and achieve a good supporting effect.
6. Conclusions

(1) The mechanical properties of the new type of URGPS are mainly manifested in the following aspects: (1) the constant adjustable axial support resistance and the axial bearing capacity can be controlled by changing the pretightening force of the clamp; (2) the URGPS has strong lateral support rigidity, which can effectively prevent the extrusion deformation of the side of the crushed stone; and (3) the URGPS can undergo a large amount of shrinkage deformation caused by the axial shrinkage release pressure to adapt to the deformation of the surrounding rock and provide an effective supporting effect.

(2) Through analysis of a mechanical model and laboratory tests, the mechanical conditions and the law of shrinkage of the URGPS were analyzed. The pretightening force of the clamp has a direct impact on the shrinkage and stability of the URGPS. An unreasonable pretightening force of the URGPS easily leads to sliding instability and cannot achieve the pressure relief effect. At the same time, the lateral force of the gangue retaining is affected by the particle size of the crushed stone, which shows that the diameters of the crushed stone are inversely proportional to the lateral pressure.

(3) In the numerical simulation test, the pretightening force, lap length, lap form, and lap position all affect the stability of the retractable gangue retaining. The larger the preload, the larger is the bearing capacity of the gangue, and the more difficult it is for URGPS to shrink. The longer the lap length, the stronger is the lateral bending capacity. When the form of the lap joint is changed, the bearing capacity of the outer lap joint under active load is increased by 34.3% compared with that of the inner lap joint. The maximum stress of the weak surface in different overlapping positions is obviously different. When the lateral pressure at the top and bottom of the gangue is not very different, the middle position should be selected for overlapping.

(4) According to the specific engineering conditions of the 21304-working face in the Chengjiao coal mine and based on the results of laboratory and numerical simulation experiments, the bolt pretightening force of the shrinkable U-shaped shackle should be 200 N·m, the inner side of the upper compression part should overlap, and the length of the middle overlap should be 1.0 m; this was successfully implemented on-site and achieved an effective supporting effect.

Data Availability

The data are available and explained in this article; readers can access the data supporting the conclusions of this study.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

This work was supported by the National Natural Science Foundation of China (41941018).

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