**Effects of Shear Characteristics of Anchoring Interface on Bearing Performance of Fully Grouted Bolts Based on Variable Controlling Method**

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**Abstract:** The shear strength parameter of an anchoring interface is one of the key parameters affecting the design of bolt support. To better realize the design of bolt support, the pullout model of fully grouted bolts was established by FLAC3D numerical software. The commonly used tri-linear bond-slip model of the anchoring interface was selected. The variable controlling method was used to investigate the effects of the shear strength parameters of the anchoring interface on the bearing performance of fully grouted bolts. The results show that, with the increase in the displacement at the peak shear stress, the bearing capacity and the energy absorption of fully grouted bolts decrease and the ability of the fully grouted anchoring system to resist external loads weakens. Meanwhile, the deformation capacity of fully grouted bolts increases, and the durability of the fully grouted anchoring system is enhanced. With the increase in the residual shear stress and the displacement at the residual shear stress, the bearing capacity and deformation capacity of fully grouted bolts both increase, and the energy absorption also increases. Increasing the post-peak bearing properties of the anchoring interface can help improve the bearing performance of fully grouted bolts and enhance the ability of the fully grouted bolts to resist failure. The results may provide guidance for support design and performance enhancement of fully grouted bolts.

**Keywords:** fully grouted bolts; pullout test; shear characteristics; bearing performance; numerical model

1. Introduction

Coal resources are the stabilizer and ballast stone for China’s economic development, and roadway safety is the key to ensuring the safe and sustainable mining of coal resources [1]. A fully grouted bolt is an economical, fast and effective rock reinforcement technique, which has been widely used in coal mine roadway surrounding rock control [2]. Generally, the bolt is bonded to the rock by resin grout, and the bolt is usually under tension [3]. The pullout bearing performance of the bolt directly affects the supporting effect of the roadway [4]. Therefore, a better understanding of the pullout bearing performance of fully grouted bolts is critical for the design of bolt supports.

Fully grouted bolts are a typical Continuous Mechanically Coupled (CMC) system [5]. The pullout capacity of fully grouted bolts depends on the shear behavior of the an-
choring interface [6]. In recent years, many studies have been conducted to investigate
the pullout bearing performance of fully grouted bolts. Benmokrane et al. [7] proposed a
tri-linear bond-slip model by experiments to describe the shear behavior of the anchoring
interface. Wu et al. [8–11], Ren et al. [12], Martin et al. [13], Yan et al. [14,15], Cao et al. [16]
and Chen et al. [17] analyzed the pullout bearing capacity and force evolution character-
istics of fully grouted bolts using a tri-linear bond-slip model. Lu et al. [18,19] and Wu et
al. [20,21] analyzed the mechanical response of fully grouted bolts during the whole
pullout process by adopting an improved tri-linear bond-slip model. Chang et al. [22,23]
and Ma et al. [24] numerically realized the tri-linear bond-slip model of the anchoring
interface and studied the pullout bearing capacity and force characteristics of fully
grouted bolts. You et al. [25] established a shear lag-debonding mechanical model of the
anchoring interface, according to pullout tests. Cai et al. [26], He et al. [27], Xu et al. [28],
Zhao et al. [29] and Duan et al. [30] analyzed the pullout bearing capacity and force
characteristics of fully grouted bolts based on an improved shear lag-debonding model.
Zhang et al. [31] established a hyperbolic model for load transfer at the anchoring inter-
facing. Zhou et al. [32] and Ma et al. [33] analyzed the pullout bearing characteristics of
fully grouted bolts based on a hyperbolic model. Ma et al. [34,35] and Li et al. [36] real-
ized the hyperbolic bond-slip model of the anchoring interface using FLAC3D numerical
software and studied the pullout bearing characteristics of fully grouted bolts under
different composite rock strata conditions. Huang et al. [37–39], Li et al. [40] and Zhou et
al. [41,42] established a bi-exponential bond-slip model of the anchoring interface and
analyzed the evolution characteristics of the bolt axial force and shear stress at the an-
choring interface. Zou et al. [43] adopted a new dynamic bond-slip model to describe the
shear behavior of the anchoring interface and analyzed the pullout bearing performance
of fully grouted bolts. These studies provide beneficial results for understanding the
pullout bearing characteristics of fully grouted bolts. However, the above studies focused
more on exploring the pullout bearing performance of fully grouted bolts under different
bond-slip models of the anchoring interface and ignored the influence of the specific pa-
rameters of the bond-slip model of the anchoring interface on the pullout bearing perfor-
ance of fully grouted bolts.

In real engineering, determining the shear strength parameters of the anchoring in-
terface is the key to the design of bolt supports [44]. Pullout tests are usually used to ob-
tain the shear strength parameters of the anchoring interface [45], and the bearing capac-
ity \( P_m \) of fully grouted bolts can be expressed as follows [33]:

\[
P_m = \pi d L \tau_p
\]

where \( \tau_p \) is the peak shear stress of the anchoring interface, \( d \) is the bolt diameter and \( L \)
is the bolt bonding length. At present, the tri-linear bond-slip model of the anchoring
interface is widely used for the analysis of the bearing performance of fully grouted bolts
[7–16], as shown in Figure 1. It is not difficult to find that the indicators that determine
the shear strength parameters of the anchoring interface include peak shear stress \( \tau_p \),
displacement \( u_p \) at peak shear stress, residual shear stress \( \tau_f \) and displacement \( u_f \) at
residual shear stress. Therefore, it is unreasonable to only consider the peak shear stress
\( \tau_p \) of the anchoring interface when designing roadway bolt supports [46]. It is not con-
ductive to the reinforcement of the roadway surrounding rock. Previous studies have
shown that the intrinsic characteristics of the bond-slip model of the anchoring interface
can significantly affect the pullout bearing performance of fully grouted bolts [47,48].
However, there are limited studies on the influence of the specific parameters of the
bond-slip model of the anchoring interface on the pullout bearing capacity and the stress
characteristics of fully grouted bolts. Therefore, it is necessary to study the influence of
the specific parameters of the bond-slip model of the anchoring interface on the pullout
bearing performance of fully grouted bolts to better guide the design of roadway bolt
support.
The purpose of this paper is to investigate the influence of specific parameters of the bond-slip model of the anchoring interface on the pullout bearing performance of fully grouted bolts. Numerical simulation is an effective analysis method that is highly repeatable and can easily obtain “macro–micro” mechanical response characteristics. In this study, the commonly used tri-linear bond-slip model of the anchoring interface was adopted. A pullout mechanical model of fully grouted bolts was established using FLAC3D numerical software. According to the variable controlling method, the peak shear stress \( \tau_p \) of the anchoring interface was set as an invariant and the influence of the displacement \( u_p \) at the peak shear stress, the residual shear stress \( \tau_f \) and the displacement \( u_f \) at the residual shear stress on the pullout bearing properties, energy absorption characteristics and stress evolution laws of fully grouted bolts were thoroughly analyzed. It is hoped that this study can provide useful guidance to support the design of fully grouted bolts and ensure the safe and sustainable mining of coal resources.

Figure 1. Tri-linear bond-slip model of the anchoring interface.

2. Numerical Methodology
2.1. Realization of Mechanical Behavior of Anchorage Interface

FLAC3D is a commonly used numerical analysis software in mining engineering. In FLAC3D, the Cable and Pile structural elements can simulate bolts well. The Cable structural element uses a spring-slider to describe the mechanical behavior of the anchoring interface [49], where the spring assembly represents the bonding stiffness of the anchoring interface, and the slide assembly represents the bonding force of the anchoring interface, as shown in Figure 2. The Pile structural element is similar to the Cable structural element, and the parameters of the grout are replaced by the parameters of the coupling spring. The Pile structural element can describe the bond-slip relationship of the anchoring interface according to the user-defined FISH language, which can better realize the strain-softening behavior of the anchoring interface [50,51].

For the shear behavior of the anchoring interface, Figure 3 shows the mechanical behavior of the tangential coupling spring in the Pile structural element. The relationship between shear force and displacement of the anchoring interface can be expressed as follows:

\[
\frac{F_s}{L} = cs_sk \times u_s
\]  

(2)

where \( F_s \) is the shear force of the anchoring interface; \( L \) is the bonding length; \( cs_sk \) is the shear stiffness of the anchoring interface; and \( u_s \) is the displacement of the anchoring
interface. Assuming that the shear strength of the anchoring interface meets the Mohr-Coulomb strength criterion, it can be expressed as follows:

$$\frac{F_{s}^{\text{max}}}{L} = cs\_scoh + N \times \tan(cs\_sfric)$$

(3)

where $F_{s}^{\text{max}}$ is the peak shear force of the anchoring interface; $cs\_scoh$ is the bonding force of the anchoring interface; $cs\_sfric$ is the friction angle of the anchoring interface; and $N$ is the effective normal stress of the anchoring interface.

Figure 2. Spring-slider system of Pile structural element.

Figure 3. Mechanical behavior of shear coupling spring: (a) Shear force versus displacement; (b) Shear strength criterion.

2.2. Model Verification

In order to verify the accuracy of the selected bolt model, the numerical results of the pullout bearing performance of the fully grouted bolts were compared with the test results of Wang et al. [52]. In Wang’s pullout test, the bolt length was 12 m, the bolt diameter was 32 mm and the borehole diameter was 150 mm. The parameters of the tri-linear bond-slip model of the anchoring interface were $\tau_p = 1.19$ MPa, $\tau_f = 0.36$ MPa, $u_p = 2.19$ mm and $u_f = 9.58$ mm. Figure 4 shows the comparison between the numerical results and the experimental results of the pullout load–displacement curve of fully grouted bolts. The results indicate that the Pile structural element can better realize the mechanical behavior of the bolt; the tri-linear bond-slip model can also better describe the bearing
characteristics of the anchoring interface. The numerical results of the pullout load–displacement curve of fully grouted bolts are more consistent with the experimental results. Therefore, the method used in this study can better reflect the pullout bearing characteristics of fully grouted bolts.

Figure 4. Comparison of numerical and experimental results of pullout load–displacement curves for fully grouted bolts.

2.3. Pullout Calculation Model and Scheme Design

Figure 5 shows the numerical calculation model of fully grouted bolts established by FLAC3D. The numerical calculation model was a rectangular parallelepiped with a size of 2000 mm × 100 mm × 100 mm (length × width × height). The Pile structural element was used to simulate the bolt. The bolt diameter was 20 mm and the bolt bonding length was 2000 mm. The velocity in the y-direction of the model grid points on the y = 0 boundary was fixed, and other boundaries were free. The pullout velocity at the bolt loading end was set to 1 × 10⁻⁶ m/step.

Figure 5. Numerical calculation model.
Table 1 lists the values used in the numerical model. It should be noted that this study mainly focused on the shear mechanical behavior of the anchoring interface, so the following assumptions were made in the numerical modeling: (1) the tensile yield strength of the bolt was set to a very large value because the bolt was assumed to be elastic and will not yield; and (2) the isotropic elastic model was adopted to describe the mechanical behavior of the surrounding rock. In order to study the influence of specific parameters of the bond-slip model of the anchoring interface on the pullout bearing performance of fully grouted bolts, the variable controlling method was used in this study. The peak shear stress $\tau_p$ was set as an invariant, and the displacement $u_p$ at the peak shear stress, the residual shear stress $\tau_f$ and the displacement $u_f$ at the residual shear stress were set as variables. Table 2 lists the numerical experiment schemes of this study.

### Table 1. Input parameters required for the numerical model.

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<thead>
<tr>
<th>Type</th>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
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<td>Bolt</td>
<td>Perimeter (m)</td>
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</tr>
<tr>
<td></td>
<td>Cross-sectional area (m$^2$)</td>
<td>$3.14 \times 10^{-4}$</td>
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<tr>
<td></td>
<td>Elastic modulus (Pa)</td>
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<tr>
<td></td>
<td>Poisson’s ratio</td>
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<tr>
<td></td>
<td>Tensile yield strength (N)</td>
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<tr>
<td>Rock</td>
<td>Elastic bulk modulus (Pa)</td>
<td>$5.00 \times 10^9$</td>
</tr>
<tr>
<td></td>
<td>Elastic shear modulus (Pa)</td>
<td>$3.00 \times 10^9$</td>
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<tr>
<td></td>
<td>Density (kg/m$^3$)</td>
<td>$2.80 \times 10^3$</td>
</tr>
</tbody>
</table>

### Table 2. Numerical experiment scheme.

<table>
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<th>Variable</th>
<th>Number</th>
<th>Value</th>
<th>Image</th>
</tr>
</thead>
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<td><img src="image1.png" alt="Graph" /></td>
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<tr>
<td></td>
<td>A2</td>
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<td></td>
<td>A3</td>
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</tr>
<tr>
<td></td>
<td>A4</td>
<td>18.500</td>
<td></td>
</tr>
<tr>
<td></td>
<td>A5</td>
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<td></td>
</tr>
<tr>
<td>$\tau_f$ (MPa)</td>
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<td>2.0</td>
<td><img src="image2.png" alt="Graph" /></td>
</tr>
<tr>
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<td>B2</td>
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<tr>
<td></td>
<td>B3</td>
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</tr>
<tr>
<td></td>
<td>B4</td>
<td>8.0</td>
<td></td>
</tr>
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<td>B5</td>
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<td></td>
</tr>
<tr>
<td>$u_f$ (mm)</td>
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<td>20.0</td>
<td><img src="image3.png" alt="Graph" /></td>
</tr>
<tr>
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<td>C2</td>
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<td></td>
<td>C4</td>
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</table>
3. Parameters Analysis

3.1. Displacement \( u_p \) at Peak Bonding Stress

3.1.1. Bearing Properties Characteristic

Figure 6 shows the pullout load–displacement curve characteristics of fully grouted bolts when the displacement \( u_p \) at the peak shear stress is different. It can be seen that the displacement \( u_p \) at the peak shear stress will significantly affect the pullout load–displacement curve trend and pullout bearing process of the fully grouted bolts. With the increase in the displacement at the peak shear stress, the upward trend of the bearing curve before the peak pullout load gradually becomes flat, and the downward trend of the bearing curve after the peak pullout load gradually becomes steep. Obviously, the increase in displacement at the peak shear stress is not conducive to the timely response and timely support of the fully grouted anchoring system to the deformation of the roadway surrounding rock. Meanwhile, with the increase in the displacement at the peak shear stress, the pullout bearing process of fully grouted bolts gradually changes from one of the five stages (elastic stage, elastic-softening stage, softening stage, softening-friction stage and friction stage) to another of the five stages (elastic stage, elastic-softening stage, elastic-softening-friction stage, softening-friction stage and friction stage). It should be noted that the E stage, E-S stage, E-S-F stage, S-F stage and F stage in the figure represent the elastic stage, elastic-softening stage, elastic-softening-friction stage, softening-friction stage and friction stage, respectively.

![Figure 6. Pullout load–displacement curves of fully grouted bolts under different displacement \( u_p \) at peak shear stress.](image)

Figure 7 shows the pullout properties of fully grouted bolts when the displacement \( u_p \) at the peak shear stress is different. With the increase in the displacement at the peak shear stress, the peak load during the pullout process of fully grouted bolts gradually decreases, while the displacement at the peak load gradually increases. This indicates that the increase in displacement at the peak shear stress will weaken the bearing capacity of the fully grouted anchoring system, but will enhance the deformation capacity of the fully grouted anchoring system.

In order to better explain the influence of the displacement at the peak shear stress on the peak load of fully grouted bolts, the anchoring interface state characteristics cor-
responding to the peak load were analyzed, as shown in Figure 8. It should be noted that the E-length in the figure refers to the length of the elastic segment of the anchoring interface, the S-length refers to the length of the softening segment of the anchoring interface and the F-length refers to the length of the friction segment of the anchoring interface. With the increase in the displacement at the peak shear stress, the length of the elastic segment of the anchoring interface corresponding to the peak load gradually increases, the length of the softening segment gradually decreases and the length of the friction segment gradually increases. This is because the increase in displacement at the peak shear stress results in a decrease in the load growth rate in the elastic stage of the anchoring interface and an increase in the load reduction rate in the softening stage of the anchoring interface. During the pullout process of fully grouted bolts, the peak load occurrence stage gradually changes from the elastic-softening stage to the elastic-softening-friction stage. It can be seen that the increase in displacement at the peak shear stress will weaken the ability of the fully grouted anchoring system to resist external loads and reduce the bearing performance of fully grouted bolts.

**Figure 7.** Pullout properties of fully grouted bolts under different displacement $u_p$ at peak shear stress.
Figure 8. Characteristics of anchoring interface state corresponding to peak load under different displacement $u_p$ at peak shear stress.

3.1.2. Energy Absorption Characteristic

Figure 9 shows the energy absorption characteristics of fully grouted bolts during the bearing process under different displacement $u_p$ at peak shear stress. Obviously, the change in displacement at the peak shear stress will affect the energy absorption characteristics of fully grouted bolts during the bearing process. With the increase in the displacement at the peak shear stress, the energy absorption in the elastic stage increases, the energy absorption in the elastic-softening stage decreases, the energy absorption in the elastic-softening-friction stage increases, the energy absorption in the softening-friction stage decreases, and the energy absorption in the friction stage also decreases. Meanwhile, with the increase in the displacement at the peak shear stress, the total energy absorption of fully grouted bolts during the bearing process decreases. This indicates that the increase in displacement at the peak shear stress will reduce the durability of the fully grouted anchoring system and is detrimental to the support effect of fully grouted bolts.

Figure 9. Energy absorption characteristics of fully grouted bolts under different displacement $u_p$ at peak shear stress.

3.1.3. Stress Evolution Characteristic

Figure 10 shows the stress evolution characteristics of fully grouted bolts during the bearing process under different displacement $u_p$ at peak shear stress. It can be seen that the change in displacement at the peak shear stress will significantly affect the stress evolution characteristics of fully grouted bolts during the bearing process. When the pullout displacement is 5 mm, the shear stress and axial force during the bearing process of fully grouted bolts show a decreasing trend along the bolt length direction. With the increase in the displacement at the peak shear stress, the shear stress and axial force at the bolt loading end gradually decrease. When the pullout displacement is 15 mm, with the increase in the displacement at the peak shear stress, the shear stress gradually changes from a decreasing trend to first increasing and then decreasing during the bearing process of fully grouted bolts, and the axial force still shows a decreasing trend.

When the pullout displacement is 25 mm and with the increase in the displacement at the peak shear stress, the peak shear stress during the bearing process of fully grouted
builds gradually moves away from the bolt loading end; the shear stress shows two changing trends: decreasing trend and first increasing and then decreasing trend; the axial force shows a decreasing trend, but the change process of the axial force gradually changes from concave to convex. When the pullout displacement is 35 mm, the fully grouted bolt gradually loses the bearing performance. With the increase in the displacement at the peak shear stress, the shear stress shows two changing trends: unchanged-increasing trend and unchanged-increasing-decreasing trend; the axial force also gradually changes from a linear decreasing trend to a nonlinear decreasing trend. This indicates that the increase in displacement at the peak shear stress will reduce the response capabilities of fully grouted bolts to external loads and weaken the durability of the fully grouted anchoring system.

(a)  
(b)  
(c)
3.2. Residual Bonding Stress $\tau_f$

3.2.1. Bearing Properties Characteristic

Figure 11 shows the pullout load–displacement curve characteristic of fully grouted bolts under different residual shear stresses $\tau_f$. The bearing process of fully grouted bolts is divided into five stages: elastic stage (E stage), elastic-softening stage (E-S stage), elastic-softening-friction stage (E-S-F stage), softening-friction stage (S-F stage) and friction stage (F stage). With the increase in the residual shear stress, the growth rate of the pullout load before the peak load gradually increases, and the decrease rate of the pullout load after the peak load gradually decreases. Meanwhile, with the increase in the residual shear stress, the residual bearing capacity of fully grouted bolts also gradually increases.

Figure 12 shows the pullout properties of fully grouted bolts under different residual shear stresses $\tau_f$. With the increase in the residual shear stress, the peak load of fully grouted bolts during the pullout process gradually increases, and the displacement at the peak load also gradually increases. It can be seen that the increase in residual shear stress will improve the bearing performance of fully grouted bolts and strengthen the ability of the fully grouted anchoring system to resist failure.
Figure 11. Pullout load–displacement curves of fully grouted bolts under different residual shear stresses $\tau_f$.

![Graph showing pullout load-displacement curves](image)

**Figure 12.** Pullout properties of fully grouted bolts under different residual shear stresses $\tau_f$.

In order to better explain the influence of the residual shear stress on the pullout bearing performance of fully grouted bolts, the anchoring interface state characteristics corresponding to the peak load were analyzed, as shown in Figure 13. With the increase in the residual shear stress, the length of the elastic segment of the anchoring interface corresponding to the peak load gradually decreases, and the length of the softening segment and the friction segment gradually increases. This is due to the increase in residual shear stress, leading to a decrease in the load reduction rate in the softening stage of the anchoring interface. The peak load occurrence stage of fully grouted bolts during the pullout process gradually changes from the elastic-softening stage to the elastic-softening-friction stage. It can be seen that the increase in residual shear stress can fully mobilize the bearing performance of fully grouted bolts, improve the ability of the fully grouted anchoring system to withstand external loads and enhance the durability of the fully grouted anchoring system.
3.2.2. Energy Absorption Characteristic

Figure 14 shows the energy absorption characteristics of fully grouted bolts during the bearing process under different residual shear stresses $\tau_f$. It can be seen that the change in residual shear stress will significantly affect the energy absorption characteristics of fully grouted bolts. With the increase in the residual shear stress, the energy absorption in the elastic stage remains basically unchanged, the energy absorption in the elastic-softening stage, the elastic-softening-friction stage and the softening-friction stage gradually increases, and the energy absorption in the friction stage increases first and then decrease. Meanwhile, with the increase in the residual shear stress, the total energy absorption of fully grouted bolts during the bearing process increases. This indicates that the increase in residual shear stress can improve the bearing performance of fully grouted bolts, strengthen the interaction between the bolt and the surrounding rock, and improve the support effect of the fully grouted anchoring system.
3.2.3. Stress Evolution Characteristic

Figure 15 shows the stress evolution characteristics of fully grouted bolts during the bearing process under different residual shear stresses $\tau_f$. It can be seen that the residual shear stress $\tau_f$ has a great influence on the stress evolution characteristics of fully grouted bolts during the bearing process. When the pullout displacement is 5 mm, the change in residual shear stress has little influence on the stress characteristics of fully grouted bolts, and the shear stress and axial force both show a nonlinear decreasing trend along the bolt length direction. When the pullout displacement is 15 mm, the anchoring interface at the bolt loading end begins to soften, the shear stress first increases and then decreases, and the axial force shows a nonlinear decreasing trend. With the increase in the residual shear stress, the reduction amplitude and rate of the shear stress near the bolt loading end gradually decreases.

When the pullout displacement is 25 mm, the influence of changes in residual shear stress on the stress evolution characteristics of fully grouted bolts during the bearing process becomes gradually more significant, the shear stress shows an increasing-decreasing trend and the axial force shows a decreasing trend. With the increase in the residual shear stress, the shear stress near the bolt loading end gradually increases, the softening behavior of the anchoring interface gradually weakens and the axial force near the bolt loading end gradually increases. When the pullout displacement is 35 mm, the fully grouted bolt gradually loses its bearing capacity. When the residual shear stress is small, the shear stress remains unchanged; with the increase in the residual shear stress, the shear stress gradually changes from an unchanged-increasing trend to an unchanged-increasing-decreasing trend, and the shear stress value near the bolt loading end also gradually increases. With the increase in the residual shear stress, the axial force gradually changes from a linear decreasing trend to a nonlinear decreasing trend, and the axial force value near the bolt loading end gradually increases. This indicates that the increase in residual shear stress can effectively improve the bearing capacity of fully grouted bolts and strengthen the ability of the fully grouted anchoring system to resist failure.
Figure 15. Stress characteristics of fully grouted bolts under different residual shear stresses $\tau_f$. (a) $u = 5$ mm; (b) $u = 15$ mm; (c) $u = 25$ mm; (d) $u = 35$ mm.

3.3. Displacement $u_f$ at Residual Bonding Stress

3.3.1. Bearing Properties Characteristic

Figure 16 shows the pullout load–displacement curves characteristic of fully grouted bolts when the displacement $u_f$ at the residual shear stress is different. It can be seen that the displacement $u_f$ at the residual shear stress has a great influence on the pullout bearing performance of fully grouted bolts. The bearing process of fully grouted bolts is divided into five stages: elastic stage (E stage), elastic-softening stage (E-S stage), elastic-softening-friction stage (E-S-F stage), softening-friction stage (S-F stage) and friction stage (F stage). With the increase in the displacement at the residual shear stress, the load increase rate before the peak pullout load gradually increases, and the load decrease rate after the peak pullout load gradually decreases.

Figure 16. Pullout load–displacement curves of fully grouted bolts under different displacement $u_f$ at residual shear stress.
Figure 17 shows the pullout properties of fully grouted bolts when the displacement $u_f$ at the residual shear stress is different. With the increase in the displacement at the residual shear stress, the peak load during the pullout process of fully grouted bolts gradually increases, and the displacement at the peak load also gradually increases. It can be seen that the increase in displacement at the residual shear stress will improve the bearing capacity and deformation capacity of the fully grouted anchoring system and enhance the ability of the fully grouted anchoring system to resist failure.

Figure 17. Pullout properties of fully grouted bolts under different displacement $u_f$ at residual shear stress.

In order to better explain the influence of the displacement at the residual shear stress on the pullout bearing performance of fully grouted bolts, the anchoring interface state characteristics corresponding to the peak load were analyzed, as shown in Figure 18. With the increase in the displacement at the residual shear stress, the length of the elastic segment and the friction segment of the anchoring interface corresponding to the peak load gradually decrease, and the length of the softening segment gradually increases. This is due to the increase in displacement at the residual shear stress, leading to a decrease in the load reduction rate in the softening stage of the anchoring interface. The peak load occurrence stage of fully grouted bolts during the pullout process gradually changes from the elastic-softening-friction stage to the elastic-softening stage. It can be seen that the increase in displacement at the residual shear stress can better mobilize the softening performance of the anchoring interface and help the fully grouted anchoring system to better exert the bearing capacity. Therefore, the peak load of fully grouted bolts during the pullout process gradually increases.
Figure 18. Characteristics of the anchoring interface state corresponding to the peak load of fully grouted bolts under different displacement $u_f$ at residual shear stress.

3.3.2. Energy Absorption Characteristic

Figure 19 shows the energy absorption characteristics of fully grouted bolts during the pullout process when the displacement $u_f$ at the residual shear stress is different. During the bearing process of fully grouted bolts and with the increase in the displacement at the residual shear stress, the energy absorption in the elastic stage does not change, the energy absorption in the elastic-softening stage gradually increases, the energy absorption in the elastic-softening-friction stage gradually decreases, the energy absorption in the softening-friction stage gradually increases and the energy absorption in the friction stage gradually decreases. Meanwhile, with the increase in the displacement at the residual shear stress, the total energy absorption of fully grouted bolts during the bearing process gradually increases. It indicates that the increase in displacement at the residual shear stress is beneficial to the bearing performance of the fully grouted anchoring system and can better realize the deformation and damage control of the roadway surrounding rock.
3.3.3. Stress Evolution Characteristic

Figure 20 shows the stress characteristics of fully grouted bolts during the pullout process when the displacement $u_f$ at the residual shear stress is different. It can be seen that the displacement $u_f$ at the residual shear stress has a great influence on the stress characteristics of fully grouted bolts during the pullout process. When the pullout displacement is 5 mm, the displacement at the residual shear stress has no effect on the stress characteristics of fully grouted bolts during the bearing process, and the shear stress and axial force of fully grouted bolts show a nonlinear decreasing trend along the bolt length direction. When the pullout displacement is 15 mm, the anchoring interface of fully grouted bolts begins to soften, and the shear stress shows an increasing-decreasing trend. With the increase in the displacement at the residual shear stress, the reduction amplitude and rate of shear stress near the bolt loading end gradually decrease. The axial force still shows a decreasing trend and is not affected by the changes in displacement at the residual shear stress.

When the pullout displacement is 25 mm, the change in displacement at the residual shear stress has a more significant influence on the stress characteristics of fully grouted bolts. With the increase in the displacement at the residual shear stress, the shear stress gradually changes from the unchanged-increasing-decreasing trend to the increasing-decreasing trend, and the maximum value of the axial force near the bolt loading end gradually increases. When the pullout displacement is 35 mm, the fully grouted bolts corresponding to the smaller displacement at the residual shear stress almost completely lose the bearing capacity, the shear stress does not change and is constant and the axial force decreases linearly. With the increase in the displacement at the residual shear stress, the shear stress gradually changes from unchanged to unchanged-increasing trend, the axial force gradually changes from linear decrease to non-linear decrease and the maximum value of the axial force gradually increases. This indicates that the increase in displacement at the residual shear stress can slow down the progressive failure process of fully grouted bolts, improve the ability of the fully grouted anchoring system to resist failure and enhance the durability of the fully grouted anchoring system.
4. Discussion

4.1. Effects on Bearing Characteristics

Figure 21 shows the effects of the shear strength parameters of the anchoring interface on the pullout bearing performance of fully grouted bolts. For a better description, the relative coefficient \( \mu_i \) of the bearing performance of fully grouted bolts is defined, and the specific expression is as follows:

\[
\mu_i = \frac{(BP)_n}{(BP)_t}
\]  

(4)

where \((BP)_n\) refers to the bearing properties of fully grouted bolts when the shear strength parameters of the anchoring interface are fully considered; \((BP)_t\) refers to the bearing properties of fully grouted bolts when only the peak shear stress of the anchoring interface is considered. For the bearing capacity of fully grouted bolts, the relative coefficient is 0.80–0.90 when the displacement \( u_p \) at the peak shear stress changes, the relative coefficient is 0.71–0.95 when the residual shear stress \( \tau_f \) changes and the relative coefficient is 0.65–0.77 when the displacement \( u_f \) at the residual shear stress changes. It can be seen that the displacement at the residual shear stress has the greatest effect on the bearing capacity of fully grouted bolts, followed by the residual shear stress, and the displacement at the peak shear stress has the smallest effect.

For the deformation capacity of fully grouted bolts, the relative coefficient is 0.55–0.75 when the displacement \( u_p \) at the peak shear stress changes, the relative coefficient is 0.76–1.08 when the residual shear stress \( \tau_f \) changes and the relative coefficient is 0.71–0.81 when the displacement \( u_f \) at the residual shear stress changes. It can be seen that the displacement at the peak shear stress has the greatest effect on the deformation capacity of fully grouted bolts, followed by the displacement at the residual shear stress, and the residual shear stress has the smallest effect. For the energy absorption of fully grouted bolts, the relative coefficient is 0.67–0.77 when the displacement \( u_p \) at the peak shear stress changes, the relative coefficient is 0.66–1.23 when the residual shear stress \( \tau_f \) changes and the relative coefficient is 0.64–0.76 when the displacement \( u_f \) at the residual shear stress changes. It can be seen that the displacement at the residual shear stress has the greatest effect on the energy absorption of fully grouted bolts, followed by the residual shear stress, and the displacement at the peak shear stress has the smallest effect.
4.2. Thoughts on the Design of Bolt Support

In order to better realize roadway safety and ensure the sustainable development of coal mines, some thoughts for coal mine roadway bolt support are as follows, based on the above research:

1. The shear strength parameters of the anchoring interface have a great influence on the design of bolt support. It is inappropriate to only use the peak shear stress of the anchoring interface for bolt support design, which often overestimates the bearing performance of the anchoring system and brings hidden dangers to roadway safety. Therefore, the shear strength parameters of the anchoring interface must be fully considered when designing bolt support.

2. Improving the post-peak characteristics of the bond-slip model of the anchoring interface can significantly increase the bearing performance of the anchoring system. Therefore, when designing bolt supports, materials such as gravel or steel fibers can be added to the agent grout [53–55], or the roughness of the anchoring interface can be increased to strengthen the shear behavior of the anchoring interface and improve the shear strength parameters of the anchoring interface, thereby enhancing the durability of the anchoring system.

3. The bearing process of the anchoring system is the process of energy dissipation at the anchoring interface. Combined with the bond-slip model of the anchoring interface, the energy dissipation ratio of the anchoring interface is defined in this study. The energy dissipation ratio $\xi$ of the anchoring interface is the ratio of softening energy $E_s$ to elastic energy $E_e$ during the bearing process of the anchoring interface ($\xi = E_s / E_e$), as shown in Figure 22.
In this study, when the displacement $u_p$ at the peak shear stress increases, the energy dissipation ratio gradually decreases, and the bearing capacity of fully grouted bolts also gradually decreases; while when the residual shear stress $\tau_f$ and the displacement $u_f$ at the residual shear stress increase, the energy dissipation ratio gradually increases, and the bearing capacity of fully grouted bolts also gradually increases. It can be seen that increasing the energy dissipation ratio of the anchoring interface can improve the bearing performance of the anchoring system. Therefore, during the design process of bolt support, increasing the softening energy or reducing the elastic energy during the bearing process of the anchoring interface will help the anchoring system better withstand external loads. This also explains that strengthening the post-peak bearing characteristics of the anchoring interface is conducive to the fully grouted anchoring system to better exert the bearing performance.

5. Conclusions

This paper studies the effects of the shear strength parameters of the anchoring interface on the pullout bearing performance of fully grouted bolts. The pullout model of fully grouted bolts was established by FLAC3D. The commonly used tri-linear bond-slip model of the anchoring interface was selected to analyze the effects of the displacement at the peak shear stress, the residual shear stress and the displacement at the residual shear stress on the bearing properties, energy absorption characteristics and stress evolution laws of fully grouted bolts. The main conclusions are as follows:

(1) The displacement at the peak shear stress will significantly affect the pullout bearing process of fully grouted bolts. With the increase in the displacement at the peak shear stress, the bearing capacity of fully grouted bolts gradually decreases, the energy absorption also decreases and the response rate of the fully grouted anchoring system to external loads weakens. However, the ability of the fully grouted anchoring system to resist failure increases with the increase in the displacement at the peak shear stress, and the durability of the fully grouted anchoring system increases.

(2) The residual shear stress has a great influence on the pullout bearing performance of fully grouted bolts. With the increase in the residual shear stress, the bearing capacity and deformation capacity of fully grouted bolts increase, and the energy absorption also increases. Meanwhile, the increase in residual shear stress gives fully grouted bolts higher residual bearing capacity, which helps the fully grouted anchoring system to better withstand external loads.
(3) With the increase in the displacement at the residual shear stress, the bearing capacity and deformation capacity of fully grouted bolts show an increasing trend, and the energy absorption of fully grouted bolts also increases. The increase in displacement at the residual shear stress enhances the durability of the fully grouted anchoring system, which is beneficial to fully grouted bolts to better exert the support performance.

(4) The shear strength parameters of the anchoring interface will significantly affect the pullout bearing performance of fully grouted bolts. Therefore, when designing bolt support, in addition to considering the peak shear stress of the anchoring interface, it is also necessary to fully consider the post-peak shear strength parameters of the anchoring interface to avoid overestimating or underestimating the bearing capacity of the anchoring system. Meanwhile, measures can be taken to strengthen the post-peak bearing characteristics of the anchoring interface, which is beneficial to the bearing performance of the anchoring system.

The research results may provide guidance for the design and performance improvements of fully grouted bolts in coal mine roadways.

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References


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