Monitoring and correction of the stress in an anchor bolt based on Pulse Pre-Pumped Brillouin Optical Time Domain Analysis

Qi Liu | Jing Chai | Shaojie Chen | Dingding Zhang | Qiang Yuan | Shuai Wang

Abstract
Bolt is an important connection in underground construction and monitoring its stress characteristics is essential to evaluate the effectiveness of bolt. The strain information collected along a rock bolt reveals the long-term movement characteristics of rock mass, which greatly helps toward disaster prevention and risk warning. Grooving on the surface of a bolt and embedding an optical fiber is one of the main methods for monitoring the anchorage performance and stress distribution around the bolt in underground engineering. In this study, Pulse Pre-Pumped Brillouin Optical Time Domain Analysis (PPP-BOTDA) technology is used to evaluate the stress, axial force, and shear stress distribution of the bolt under tensile load for different types (grooved and nongrooved) of bolts embedded in concrete with resin as anchoring agent. The results show that the PPP-BOTDA sensor can be used to monitor the stress state of the bolt embedded in concrete with resin as anchoring agent when the bolt is subjected to a tensile force. However, the apparent stress value measured in this way is not the actual stress value of the bolt, but is an increased value caused due to the groove. The closer to the exposed end of the bolt, the greater is the deviation between the apparent stress value and the actual stress value of the bolt. Based on the monitoring results from this experimental study, a stress reduction calculation method is proposed, which can change the measured value into the actual stress of the bolt.

KEYWORDS
axial force, bolt, PPP-BOTDA technology, pullout test, shear stress
1 | INTRODUCTION

Bolts are vital to the advancement of underground excavation in engineering work, such as subway tunnels and coal mines, as they connect broken rock mass, enhance the stability of underground coal mine roads and surrounding rock, and reduce the occurrence of rock burst. In countries such as China where huge amount of coal is mined, the problems of roof falling (roof collapse), land subsidence, and collapse result in a series of secondary disasters, directly threatening production and life safety. Monitoring and evaluation of the anchoring performance is an important basis to judge the effectiveness of bolts, and hence, to ascertain the safety of the underground coal mine roadways. The stability of underground structures is closely related to the type and properties of rock. Rocks have complex mechanical properties, laboratory experiments alone are not adequate to study their properties and some in situ measurements are necessary. In particular, strain information along the rock bolts should be collected to reveal long-term movements of the rock mass and to allow an operator to take necessary precautions. With the development of optical fiber technology and its use in sensing and measurement, this technology is increasingly used in monitoring stress, overburden deformation, temperature, humidity, and moisture. Lately, optical fibers have been used in monitoring the stress of bolts. An optical fiber is embedded in a bolt for monitoring the corrosion of the bolt, the stability of the mine roadway, the deformation of landslide, and the strain of the surrounding rock mass. Monitoring by using an optical fiber can reveal the long-term stability or deformation of the rock mass and the three-dimensional deflection profile of the bolt.

In the early stage, the mechanism of grouted rock bolt is mainly to install some resistance strain gauges along the length of the bolt sample. Therefore, the coaxial strain distribution on the bolt can be determined by the difference between the discrete measurements provided by each strain gauge. However, the basic length of each strain gauge is very short, resulting in most of the anchor rods not being monitored. Therefore, the local load characteristics along the bolt are easy to be missed. It has been reported that electronic instruments have been used in underground engineering for bolt monitoring. However, due to their susceptibility to electromagnetic signal interference or deterioration due to moisture content in high humidity environment, their use in poor underground engineering conditions has been questioned. In recent years, due to the unique characteristics of high precision, excellent electromagnetic immunity, oil resistance, and distributed measurement, new sensors based on optical fiber sensing technology as sensing elements and transmission medium have been widely used in geotechnical infrastructure such as bridges, civil engineering, and railways.

In order to protect the integrity of the stress sensor and the sensing line and to minimize the impact on the mechanical strength of the bolt itself, it is common to construct a slot on the surface of the bolt and implant stress sensors (optical stress sensors and other types of stress sensors). The stress value measured in this way is regarded as the true stress on the bolt. Iten et al. compared three methods of integrating optical fibers into short rods, namely external longitudinal trench, internal integration, and helix integration. Laboratory strain testing was performed on these instrumented rods. Longitudinal trench method was found to be the best among the three methods to possess a good agreement between the optical fiber data and the data obtained from conventional measures. Frank et al. created a GFRP rock bolt with an FBG (fiber Bragg grating) sensor by inserting the FBG sensor into the GFRP rock bolt during the pultrusion process. Tensile test showed that the embedded FBG sensor can withstand 1.5% high strain. Based on this finding, GFRP rock bolts equipped with FBG sensors were installed in tunnels near Sargans, Switzerland for long-term load monitoring. Kou et al. proposed a new method based on FBG sensor and applied it to monitor the behavior of GFRP bolts. On this basis, different levels of axial force were determined during the pulling process and the shear stress distribution along the GFRP anchor was calculated. Zhang et al. conducted direct tension tests of rock bolts with different grooves and analyzed the full tensile load-displacement curves of rock bolts with different groove shapes. The influence of groove shape on bolt strength was discussed. The stress redistribution of different groove sections in the rock bolts was simulated by using a finite element analysis program ANSYS. Based on the simulation, the axial stress of grooved bolt as measured by using fiber optic stress sensor or any other stress sensor was not the average actual true stress value of the bolt, but was the increased local stress caused due to grooving. In field monitoring, people usually regard the stress measurements of grooved bolt as the true stress of the nongrooved bolt but the measured value is likely to overestimate the average actual stress in the bolt. Slotting on a complete and smooth anchor rod and implanting the optical fiber therein are used to measure the stress of the anchor rod, which is beneficial to protecting the integrity of the optical fiber, improving the service life and long-term stability of the fiber. Whether the strain and stress of the bolt measured by this method is consistent with that of the bolt without slotting, or whether it is feasible to characterize the stress characteristics and laws of the bolt without slotting with the measured values obtained by this method, is worth further study.

In this study, the Pulse Pre-Pumped Brillouin Optical Time Domain Analysis (PPP-BOTDA) technology is used to study the stress distribution, axial force, and shear stress characteristics of two (grooved and nongrooved) anchor rods embedded in concrete with resin as anchoring agent and subjected to tensile load. This study examines the feasibility of PPP-BOTDA...
technology for monitoring the stress state of bolt embedded in concrete with resin as anchorage agent during the drawing process and determines the effect of grooving on the stress distribution of bolt during drawing. Based on these studies, a method to calculate stress reduction is proposed to discount the stress values measured by optical fibers embedded in grooved bolts into the real stress values of bolts, so as to improve the accuracy of stress monitoring of bolts in underground engineering.

2 | ANCHOR SYSTEM BACKGROUND

At present, there are two main types of anchor structures: a mechanical anchor which transfers load through friction and mechanical interlocking, and a bond anchor which transfers load through the bonding force between anchor and bond. This paper mainly studies the bonding agent anchor. The anchor is embedded in the hole of the existing drilled concrete foundation. Load is transferred through the bonding effect of the bonding agent. The anchoring system consists of an anchor rod and binder. Common adhesives include organic and inorganic adhesives. Resin binders are prepackaged in plastic capsules or as separate chambers, requiring users to mix proportionally.

The bond between the anchor body and the surrounding body consists of three parts. The first part is the adhesive force that is the physical bond between the surface of steel bar and grouting body. When shearing occurs, the physical cohesion between the bolt and the anchor interface becomes the basic resistance, and this force disappears when a relative slip occurs between the bolt and the anchor interface. The second part is the mechanical embedding force that is formed due to the existence of ribs, threads and buckling on the surface of the anchor steel. Mechanical linkage between the anchor body and the grout body is formed, and this force plays a role together with the adhesive force. The third force is the surface friction, which forms a frictional force as a function of the clamping force and the roughness of the steel surface. The magnitude of the coefficient of friction also depends on whether the frictional force occurs before or after slipping along the contact surface. The greater the pressing force between the rod and the grout, and the greater the roughness of the contact surface, the greater is the friction.

3 | TEST SYSTEM

3.1 | Sensing principle and sensor arrangement

The working principle of PPP-BOTDA sensing is the stimulated Brillouin scattering effect, as shown in Figure 1. A pumping pulse light is emitted at one end of the sensing fiber, and the probe light is emitted at the other end of the sensing fiber to cause it to be transmitted in the opposite direction. Since the frequency difference between the pump light and the probe light is approximately the same as the Brillouin frequency (BF) of the optical fiber, the Brillouin scattering signal of a high amplitude is was amplified. The working principle of PPP-BOTDA sensing is the stimulated Brillouin scattering effect, as shown in Figure 1.

During the test process, the Brillouin optical analysis system is used to generate pumping pulse light and probe light, which are injected from both ends of the optical fiber to transmit in the opposite direction and to analyze the frequency characteristics of Brillouin scattered light. The relationship between Brillouin frequency shift and strain and temperature can be expressed as:

\[
v_B(\epsilon) = v_B(0)[1 + C_\epsilon \cdot \epsilon]
\]

\[
v_B(T) = v_B(T_0)[1 + C_T \cdot (T - T_0)]
\]

where \(v(\epsilon)\) and \(v(T)\) represent the Brillouin frequency shift for strain and temperature, respectively; variables \(v_B(0)\) and \(v_B(T_0)\) are the baseline (initial) frequencies; and variables \(C_T\) and \(C_\epsilon\) are the constant coefficients associated with temperature and strain, respectively.

In addition to the frequency domain characteristic analysis, the positions of strain and temperature are obtained by using the time domain analysis based on the following equation:

\[
L = \frac{c \Delta t}{2n}
\]

where \(c\) is the speed of the laser in the fiber, \(n\) is the index of refraction, and \(\Delta t\) is the time interval between the pulse signal and the received backscattered signal.
Two types of steel bars were used, namely grooved bolt and nongroove bolt. The bolt length was 1000 mm, and the diameter was 10 mm. The material parameters of the steel bolts are shown in Table 1. For grooved steel bolt, two diametrically opposite grooves were made along the axial direction of the bolt (for the entire length of the bolt) and the size of the rectangular groove was 2.5 mm × 2.5 mm. A single distributed optical fiber sensor was embedded in each groove after machining. For embedding, the fiber optic sensor was encapsulated in the groove with a special adhesive. The adhesive bound the sensor to the bolt and provided a protective barrier. The arrangement of the fiber optic sensor on the bolt is shown in Figure 2. For nongrooved bolts, the distributed fiber optic sensor was glued directly to the surface of the bolt with adhesive.

The experimental system consisted of a PPP-BOTDA, a loading apparatus and an end displacement measuring device, as shown in Figure 3. The bolt pullout device had an oil pressure of 100 MPa, a stroke of 120 mm and an oil cylinder area of 29.4 cm². The external load on the bolt was applied through the loading apparatus in the test. The pullout force was exerted on the bolt by increasing the oil pressure. The end displacement of the bolt was measured by a dial gauge with a range of 100 mm and an accuracy of 0.01 mm. Optical signals in the optical fibers were acquired and recorded by an NBX-6055 analyzer. Table 2 shows the basic parameters of the NBX-6055 analyzer.

Compared with the original BOTDA system, the PPP-BOTDA used pulsed pumping with leaking light to achieve higher spatial resolution. Leakage pump pulses were used to fully excite phonons, and detection pumps were used
to reduce spatial resolution. In this experimental study, the pulse width was set to 1 ns, and a spatial resolution of 50 mm was selected to achieve high spatial resolution sensing. Brillouin frequency shift had a good linear relationship with strain and temperature. By detecting the Brillouin frequency in real time, the strain and temperature distribution along the fiber were obtained. Since temperature variation was measured separately by the device itself, the temperature can be eliminated to achieve temperature compensation.

### 3.2 Sensor calibration

Two types of standard optical fibers are commonly used in engineering practice: (a) strain sensing fibers with a diameter of 0.9 mm and (b) armored cables with a diameter of 3.0 mm. The former is a single-mode fiber with excellent bending resistance. The maximum bending radius is between 8.5 mm and 15 mm, and the performance is good. The fiber is coated with double-layer UV curable acrylate to provide excellent environmental protection. In this study, this type of fiber was selected to embed in the bolt and to measure the stress distribution of the bolt. The composition of the fiber is shown in Figure 4A. The structure of the fiber was the core/coating layer/sheath, respectively, from the inside to the outside, and the thickness was 8.3/125/900 μm. The strain monitoring range of the fiber was $-2\%$ (compression) to $+5\%$ (stretching), the monitoring range was 200 m, and the tensile strength was 14.0 MPa.

For the accuracy of the test, the distributed fiber in the experiment was calibrated by an equal-strength beam experiment. The calibration arrangement is shown in Figure 4B. The distributed fiber with a diameter of 0.9 mm was placed on the equal-strength beam, and the fiber was glued on the upper surface of the beam by epoxy resin adhesive. To ensure the accuracy of the measurement, a certain amount of prestress was applied to both ends of the fiber. Figure 5 shows the relationship between the Brillouin frequency shift and the strain of the optical signal as obtained from the equal-strength beam experiment. The strain of PPP-BOTDA sensor showed a good fit with the coefficient of determination ($R^2$) greater than 0.99. The strain coefficient obtained from this calibration test was 0.05 MHz/με.

### 3.3 Experimental process

The concrete foundation for the experiment was made of ordinary concrete with a characteristic compressive strength of 35 MPa. The concrete block had length, width, and height of 5 * 2 * 0.8 m. The materials used were ordinary Portland cement, river sand, and water and were mixed with a ratio of 1:1:0.5. The properties of concrete are shown in Table 3. Natural sand was used with a maximum particle size of 4 mm and a minimum particle size of 0.1 mm. After casting the concrete block, it was cured for 40 days. A hole with a diameter of 15 mm was drilled in each concrete foundation. Bolts with two types of surfaces (grooved and nongrooved) were embedded into concrete foundations. The resin was used as a binder for which the physical and mechanical properties after curing are shown in Table 4.

**Table 2** Technical parameters of NBX-6055

<table>
<thead>
<tr>
<th>Attributes</th>
<th>NBX-6055</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spatial sampling interval (m)</td>
<td>0.05</td>
</tr>
<tr>
<td>Maximum spatial sampling point</td>
<td>20,000</td>
</tr>
<tr>
<td>Sampling frequency (GHz)</td>
<td>9-13</td>
</tr>
<tr>
<td>Frequency sampling interval (MHz)</td>
<td>1, 2, 5, 10, 20, 50</td>
</tr>
<tr>
<td>Strain measurement range</td>
<td>$-3%$-$+4%$</td>
</tr>
<tr>
<td>Pulse width (ns)</td>
<td>1/25/10</td>
</tr>
<tr>
<td>Spatial resolution (cm)</td>
<td>10/20/50/100</td>
</tr>
<tr>
<td>Dynamic range (dB)</td>
<td>1/2/3/6</td>
</tr>
<tr>
<td>Maximum measurement range (km)</td>
<td>1/5/10/20</td>
</tr>
<tr>
<td>Repeatability</td>
<td>$15\mu\varepsilon/\pm0.60$</td>
</tr>
<tr>
<td>Strain measurement accuracy (με)</td>
<td>±5</td>
</tr>
<tr>
<td>Temperature measurement accuracy (°)</td>
<td>±1</td>
</tr>
</tbody>
</table>

Installation process of bolt:

1. Drilling: The drill holes in each position were made by using twist drill rods and concave diamond compound drill bits. The diameter of the hole was 15 mm for inserting a bolt of 10 mm diameter.
2. Hole cleaning: In order to obtain accurate measurements, the dust in the holes and on the wall surface was cleaned. The reason for the cleaning was that dust affects the degree of bonding between the resin binder and the concrete. Before cleaning, the design depth, diameter, and verticality of the hole were ascertained. Pressure water was used to flush concrete debris and impurities from the hole. After the flushing was completed, the wall of the hole was cleaned with a rough cloth, and finally, the wall of the hole was dried.
3. Embedding the bolt: The epoxy adhesive was a two-component system stored in separate plastic cylinders with a certain amount of resin and catalyst, respectively. Firstly, the resin cylinder was placed in the drilled hole and then rotated into the drilled hole by the bolt. The rotation of the bolt destroyed the plastic sheath of the resin cylinder, and the resin and catalyst were mixed together. In contrast to cement binder, resin binder can be fully cured in 30 minutes. The rapid solidification of resin binder ensured rapid installation.

The pullout test was conducted to study the stress state of the anchor rod (grooved and nongrooved) by PPP-BOTDA.
technology. The effect of grooving on stress, axial force, and shear stress distribution of anchor rod was evaluated when the rod was subjected to the load.

Bolt drawing process:

1. For two different types of bolts (grooved and nongrooved), three pullout tests were conducted according to the following method. The Brillouin frequency shift of the optical fiber was recorded in each repeat, and an average value was taken as the measured value for each type of bolts.

2. Resin binder was fully cured after 2 hours of application. Thereafter, one end of the bolt was fixed and the specimen was pulled along the axial direction of the bolt by using the testing machine. The rate of the displacement-controlled loading was maintained at 30 mm/min.

3. The loading was divided into seven stages of tension, which were 12.9, 26.1, 39.2, 52.3, 65.3, 78.4, 91.4, and 105.3 kN, respectively. An equivalent gradient loading system was adopted in the test, and the load was kept stable for 5-10 minutes after each stage of tension was completed. When the load reached a stable state, the end displacement of the bolt and the Brillouin frequency shift signal of the optical fiber on the bolt were recorded in real time. This was also used to check whether there was creep between the BOTDA sensor and the bolt (ie, whether the bonding performance between the bolt and the concrete was weakened).

4. The loading was stopped and the experiment was terminated when one of the following three situations occurred: first, the bolt was pulled out and the end displacement increased continuously; second, the load ceased to increase, or the load could not be stabilized after being applied; and third, the bolt was pulled at the ultimate yield strength. In this way, the maximum drawing load was obtained for each test.

### 4 TEST RESULTS AND DISCUSSION

The axial strain along the bolt was calculated by using Equation (1), and the axial force was calculated using Equation (4) as follows:

\[ F = E \cdot A \cdot \varepsilon \]  

(4)

where \( F \) is the axial force, \( E \) is the Young's modulus of the bolt, \( A \) is the cross-sectional area defined by the diameter, and \( \varepsilon \) is the axial strain.

For the data analysis, the contact point of concrete and the exposed section of the anchor were taken as the origin, and the embedded part of the anchor was considered to lie in the x-axis positive direction. The relationship between the axial force of the bolt and the depth of embedment under different rated loads is shown in Figure 6. As shown in Figure 6A, the axial force distribution of the bolt presented a negative exponential distribution with the depth of embedment. In addition, with an increase in applied load, the axial force distribution curve corresponding to the location near the end of the bolt became concave, suggesting that decoupling occurred at the interface of the exposed end. In this case, the pullout force consisted of only the frictional force at the debonding interface and the mechanical interlocking force (but not the bonding force). The same phenomenon can be observed in Figure 6B for the nongrooved bolt. Until the embedment depth of 0.7 m, the axial force decreased with depth and then became stable when the depth was greater than 0.7 m. The portion of the anchor beyond 0.7 m depth did not contribute in sharing the axial load as no increase in axial force was observed even when the drawing force was increased. The role of the anchor system was primarily dependent on the stress transfer between the adhesive/concrete interface and the
steel/adhesive interface. Therefore, the distribution of axial force and the type of anchoring system were the main factors determining the anchoring effect.

The axial stresses of the two types of bolts monitored by PPP-BOTDA exhibited approximately negative exponential distribution, and the stress attenuation rate near the exposed end of the bolt was faster compared to the other positions of the bolt, and the stress mainly concentrated in the section less than 0.7 m away from the origin. Beyond 0.7 m, the axial force of the bolt basically remained unchanged and was close to 0. This is because the axial force of the bolt decreased gradually from the reinforcement head to the tail, caused by the adhesion of the anchor to the surrounding solidified anchoring agent and the friction. When

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**TABLE 3**  **Material properties of concrete**

<table>
<thead>
<tr>
<th>Model</th>
<th>Compressive strength [MPa]</th>
<th>Tensile strength [MPa]</th>
<th>Elastic modulus [GPa]</th>
<th>Poisson’s ratio</th>
<th>Density [kg/m³]</th>
</tr>
</thead>
<tbody>
<tr>
<td>C35</td>
<td>35</td>
<td>5.57</td>
<td>3.15</td>
<td>0.2</td>
<td>2.4E+03</td>
</tr>
</tbody>
</table>
the applied load was increased from 13.06 kN to 52.24 kN, the axial force was concentrated within 0.3 m from the orifice and the end of the anchor was basically unloaded. When the load increased from 65.3 kN to 104.48 kN, the axial force was gradually transferred to the end of the bolt, and the stressed range of the bolt extended from 0.3 m to 0.7 m. This phenomenon indicated that the bond stress between the bolt and the mortar was not evenly distributed under the pulling load, but was gradually shifting toward the end of the bolt as the tensile load increased. The relationships between the axial force and the pullout force

<table>
<thead>
<tr>
<th>Mechanical properties of resin binder after curing (based on the user guide from the manufacturer)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shear strength [MPa]</td>
</tr>
<tr>
<td>Tensile strength [MPa]</td>
</tr>
<tr>
<td>Bond strength [MPa]</td>
</tr>
<tr>
<td>Compression modulus [MPa]</td>
</tr>
<tr>
<td>Compressive strength [MPa]</td>
</tr>
<tr>
<td>Elongation at break</td>
</tr>
</tbody>
</table>

**FIGURE 6** Axial force distributions along the bolt at different load magnitudes

**FIGURE 7** Relationships of axial force with pullout force for the grooved and nongrooved bolts at different locations
The shear stress calculated using Equation (5) under different tensile forces is shown in Figure 8. It is obvious that the shear stress at lower tensile forces was less than the shear stress at higher tensile forces. The peak shear stresses of the grooved and ungrooved bolts were 9.2 and 7.08 MPa, respectively. These values are much smaller than the ultimate tensile strength of the bolt. Therefore, it can be inferred that the interface failure between the resin bonding layer and the concrete was caused mainly by the inter-laminar shear stress. Accordingly, the inter-laminar shear strength of anchor materials is an important parameter for evaluating the pullout resistance in steel anchoring systems.

At the positions of \( x = 0.05 \) m, \( x = 0.45 \) m, and \( x = 0.65 \) m, the peak shear stress of the grooved bolt was 8.5 MPa, 0.7 MPa, and 0.3 MPa respectively; and the peak shear stress of the nongrooved bolt is 6.4 MPa, 0.59 MPa, and 0.3 MPa respectively. The peak shear stress of the grooved bolt was 1.3 times, 1.2 times, and 1.1 times that of the nongrooved bolt at \( x = 0.05 \) m, \( x = 0.45 \) m, and \( x = 0.65 \) m, respectively. The experimental results demonstrated that the PPP-BOTDA technology was able to measure the difference between the stress distribution of the grooved bolt and that of the nongrooved bolt (usually considered to be the true stress value of the bolt). The difference between the two values was not fixed, however. The closer to the exposed end of the anchor, the greater was the difference in the shear stress ratio, indicating that the anchor slot would cause local stress concentration. The difference between the true value and the measured value was similar to the theoretical calculation result of Zhao. However, theoretical calculation shows that the ratio of the measured value of the stress distribution along the bolt to the true value is constant, which is inconsistent with the experimental result. This is possibly due to the difference in the deformation of the bolts at different embedment depths, which results in a change in the ratio of the measured value of the stress distribution along the bolt to the true value. Therefore, when the stress of the bolt is monitored by inserting the optical fiber sensor into the slot, it is necessary to apply a correction by considering this aspect in order to obtain the true stress distribution of the bolt.

A reduction coefficient \( \psi(x) \) was defined to transform the measured value (as monitored by means of a grooved surface implanted with a strain sensor) into the real strain value of the bolt. The strain values on grooved anchors and the strain values on nongrooved anchors can be converted by the following formula.

\[
\varepsilon_w(x) = \phi(x)\varepsilon(x), \quad \phi(x) = \begin{cases} 
1.3, & 0 < x \leq 0.3L \\
1.2, & 0.3L < x \leq 0.6L \\
1.1, & 0.6L < x \leq 1.0L 
\end{cases} \tag{6}
\]

where \( \varepsilon_w(x) \) is the cross-sectional area of the bolt; \( D \) is the diameter of the bolt; and \( \Delta x \) is the distance between two adjacent measuring points.

The average shear stress on the bolt was obtained from the following equation:

\[
\tau_i = \frac{(\varepsilon_j - \varepsilon_{j+1})EA}{\pi D \Delta x} \tag{5}
\]

where \( \tau_i \) is the shear stress at the midpoint of the \( j \)th and \( j + 1 \)th points; \( E \) is the elastic modulus of the bolt; \( \varepsilon_j \) is the strain value of the \( j \)th point; \( \varepsilon_{j+1} \) is the strain value of the \( j + 1 \)th point.
where $\varepsilon(x)$ is the axial strain of the slotted bolt at position $x$, $\varepsilon_{\text{n}}(x)$ is the axial strain of the nongrooved bolt at position $x$, $x$ is the position on the bolt, and $L$ is the length of the bolt.

It was verified by the experiments that the monitored stress values obtained by using the method of inserting PPP-BOTDA sensor into the groove of the bolt surface were not the real stress state in the bolt, but were the increased stress values caused by the groove. The closer to the pull end of the bolt, the greater was the deviation between the measured value of the stress and the true stress value of the bolt. It is suggested that in engineering applications, in order to monitor the stress by grooving the bolt and implanting optical fiber stress sensors (or other types of stress sensors), the in situ pullout test should be calibrated to obtain the reduction coefficients at different locations of the bolt. These coefficients can be used to convert the measured values into real stress values of the bolt. This will help improve the accuracy of bolt stress monitoring in underground engineering and provide an assessment of the effectiveness of the bolt more accurately. Such assessments can reveal the long-term movement characteristics of rock mass by using stress information collected along bolts and provide a basis for disaster prevention and control.

Some new phenomena are found through the experimental research, and the factors that are easy to produce errors are found in the common measurement methods of bolt stress, which are not noticed by the predecessors. The latest theoretical research is proved by the experimental way. The error value of bolt stress measurement under different conditions is obtained, and the maximum error reaches 30% of the real value. The method of eliminating the error is proposed. The error is eliminated by using the proposed conversion formula, and the strain reduction coefficient of different regions obtained from the experiment.

It is not accurate to directly convert the stress value of grooved bolt surface measured by optical fiber into the stress value of nongrooved bolt, which is quite different from the actual situation. It is very important to determine the conversion relationship between the two. Therefore, the corresponding experimental research has been carried out. According to the strain reduction coefficient of different areas of the bolt obtained in the experiment, the measured value can be converted into the actual strain/stress value of the slotted bolt.

Bolt is an important support tool for underground engineering, which is very necessary for the stress distribution and long-term characteristic monitoring of bolt. It is of great significance to improve the accuracy of bolt stress measurement, predict the possible dangers in advance, and propose solutions or remedial measures before the accident, so as to ensure the long-term stability of underground engineering and the safe and efficient exploitation of underground energy.

There are some limitations in this paper, including the influence of different bolt length, bolt diameter, bolt embedded depth, slotted groove type, and slotted size on the stress measurement of slotted bolt. In the follow-up research, through experimental research, we will carefully analyze the influence of slotted groove type, slotted size, embedded depth of anchor bolt and diameter of anchor bolt on the stress value of anchor bolt in different measurement methods, improve the accuracy of measurement results, and improve the accuracy of stress measurement of anchor bolt in underground engineering.

## 5 CONCLUSION

1. The axial stress and shear stress of the bolt are measured by the method of inserting the fiber optic sensor into the anchor rod. The measured value is higher than the actual value of the ungrooved anchor, and the deviation between the two is the largest at the position of the orifice. The deviation from the orifice to the depth is gradually reduced. According to the difference, the bolt can be divided into three parts. The difference between the first three parts is 1.3 times, the middle one is 1.2 times, and the rear one is 1.1 times.

2. The strain, axial stress, and shear stress of the bolt are measured by slotting the bolt and embedding the optical fiber sensor. The measured critical depth, the position of the maximum shear stress, and the position of the maximum axial stress are the same as those of the slotted bolt. The maximum axial stress position is at the position where the anchor is close to the orifice, and the maximum shear stress occurs at 0.15 m from the orifice on the anchor. These features are not affected by different types (grooved and nongrooved) of bolts. It is feasible to characterize the stress characteristics and law of nongrooved bolt by the stress measurement method of grooved bolt implanted with optical fiber sensor.

3. The stress/strain of the ungrooved anchor can be obtained indirectly by inserting the fiber optic sensor with the grooved anchor. According to the strain reduction coefficient of different regions on the bolt obtained in the experiment, the measured value can be converted into the actual strain/stress value of the nongrooved bolt.

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