Mechanical Properties of Resin-grouted Bolting under Thermodynamic Effect

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1. INTRODUCTION

The boom of high-rise and super-high-rise buildings has increased the risks of tunnel construction (e.g. ground collapse), which raises the requirements and cost of the support to foundation pit and the tunnel. The traditional support system of steel brackets cannot satisfy the latest demand for tunnel support. In tunnel construction, the surrounding rock can be reinforced and maintained through anchoring, that is, placing anchors in the boreholes on the surrounding rock. The rock bolting is an important anchoring approach. The bolts are inserted to modify the surrounding rock, forming an overall stable rock system. The bolts work together with the surrounding rock to ensure the tunnel stability [1-4].

In China, rock bolting was first applied to coal mine tunnels, and entered the fast lane of development in the early 1990s. So far, three rock bolting methods have been developed, namely, end-anchored bolting, fully-grouted bolting and resin-grouted bolting [5]. The resin-grouted bolts are extremely easy to install. Once installed, the bolts will exert a high anchoring force, which limits the displacement of the surrounding rock [6]. However, most of resin-grouted bolts are designed based on simplified calculations. The design parameters often deviate greatly from the actual conditions, weakening the effect of rock bolting in actual projects [7-8].

In a real tunnel, the resin-grouted bolts in the surrounding rock face complex thermodynamic conditions, which arise from the internal ventilation and geothermal gradient through the tunnel. The thermodynamic effect is often so strong as to affect the anchor material (resin), thus dampening the bolting effect [9]. Under the pulling load, the bolt displacement varies with temperature, force and time. Thus, it is necessary to explore the bolt failure mechanism under thermodynamic effect [10].

In this paper, the mechanical properties and failure mechanism of resin-grouted bolts are examined, and the bolt-rock interaction mechanism was investigated under thermodynamic effect. On this basis, the anchoring parameters were designed under the thermodynamic effect. On this basis, the anchoring parameters were designed under the thermodynamic effect.

2. ANCHORING MECHANISM AND FAILURE TYPE

2.1 Anchoring mechanism

There are many types of resin-grouted bolts. Some bolts are grouted at the end and some are grouted fully in the borehole; some are prestressed and some are not; some are made of steel, some are made of wood and some are made of glass [11].

During installation, the bolt eye at the head of each bolt is bonded with resin. The commonly used steel bolts and their properties are stated in Table 1 below.

The bolts form an integrated mechanical structure with the surrounding rock. After resin-grouted bolting, the shearing or expansion of the rock mass is obstructed by the bolts when the surrounding rock faces the maximum stress. If the bolting is adopted after the breakage of the rock mass, the bolts will also withstand the pressure from the rock fragments [12, 13].

The existing theories on bolting support mainly include the suspension theory, the composite beam theory, the compound arch theory, and the loosing-circle theory of the surrounding rock [14]. There are also some less popular theories like the reduction span theory, the three-hinge arch theory, and the deformation control theory of the surrounding rock [15].
### Table 1. The commonly used steel bolts and their properties

<table>
<thead>
<tr>
<th>Level</th>
<th>Materials</th>
<th>Diameter</th>
<th>Yield Strength/MPa</th>
<th>Ultimate Strength/MPa</th>
<th>Elongation/%</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Q235</td>
<td>6mm~40mm</td>
<td>260</td>
<td>400</td>
<td>85</td>
</tr>
<tr>
<td>II</td>
<td>16Mn</td>
<td>6mm~25mm</td>
<td>340</td>
<td>540</td>
<td>17</td>
</tr>
<tr>
<td>III</td>
<td>25MnSi</td>
<td>6mm~40mm</td>
<td>420</td>
<td>600</td>
<td>1430</td>
</tr>
<tr>
<td></td>
<td>A5</td>
<td>6mm~40mm</td>
<td>300</td>
<td>520</td>
<td>—</td>
</tr>
</tbody>
</table>

### 2.2 Failure types

The resin-grouted bolting can enhance the lateral compressive strength, overall flexural strength and deformation modulus of the surrounding rock. Overall, three types of failure may occur to the bolting mechanism, namely, anchorage failure, long-term creep failure and tensile shear failure. The last type of failure is resulted from thermodynamic effect.

![Figure 1. The shape of the failure surface of the shearing cone](image)

The shear cone of the failure surface of a bolt is presented in Figure 1. As shown in Figures 1(a) and 1(b), the failure surface is either made of logarithmic spirals or straight lines. Thus, the bolting system is generally considered as an inverted cone to examine the shear failure. In this way, the pulling load can be derived from the shear strength of the cone.

### 3. MECHANICAL PROPERTIES

#### 3.1 Thermodynamic constitutive model

Our mechanical test aims to disclose the uniaxial compressive strength, yield stress and deformation properties of the bolts grouted with unsaturated polyester resin. The parameters of the resin are listed in Table 2 below.

During the mechanical test, the temperature in the environmental chamber was increased gradually at the rate of 0.5~0.8 °C/min, and maintain constant at 20 °C, 40 °C, 60 °C and 80 °C, respectively. Each of the temperatures was kept for 1h before the start of loading. The compressive strength and yield stress of the bolting system were measured at each temperature (Table 3).

Obviously, the compressive strength and yield stress of the bolting system both decreased with the growth of temperature. The compressive strength declined by 28.42%, 50.07% and 54.0%, respectively, at 40 °C, 60 °C and 80 °C.

Figures 2 and 3 respectively show the deformation parameters and the thermal expansion coefficients of the bolting system at different temperatures.

As shown in Figures 2 and 3, the Poisson’s ratio of the bolting system is positively correlated with temperature, while the elastic modulus is negatively correlated with temperature; the thermal expansion coefficient grew almost linearly with the temperature.

The structural analysis on the test results show that, due to material isotropy, the bolting system underwent viscous-elastic-plastic deformation under thermodynamic actions. The stress-strain relationship can be expressed as:

\[
\sigma = \sigma_1 = \sigma_2 = \sigma_3
\]

\[
\varepsilon = \varepsilon_1 + \varepsilon_2 + \varepsilon_3
\]

#### Table 2. Parameters of the bolting system

<table>
<thead>
<tr>
<th>Model</th>
<th>Gel time/s</th>
<th>Carrying Time/Min</th>
<th>Elastic Modulus/MPa</th>
<th>Compressive Strength/MPa</th>
<th>Shear Strength/MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z</td>
<td>90-200</td>
<td>50</td>
<td>1.2×10^4</td>
<td>≥40MPa</td>
<td>≥35MPa</td>
</tr>
</tbody>
</table>

#### Table 3. Compressive strength and yield stress of the bolting system/Mpa.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>20 °C</th>
<th>40 °C</th>
<th>60 °C</th>
<th>80 °C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>σ₁</td>
<td>σ₂</td>
<td>σ₃</td>
<td>σ₁</td>
</tr>
<tr>
<td>Specimen 1</td>
<td>55.7</td>
<td>62.9</td>
<td>43.2</td>
<td>55.0</td>
</tr>
<tr>
<td>Specimen 2</td>
<td>56.3</td>
<td>71.2</td>
<td>39.4</td>
<td>47.5</td>
</tr>
<tr>
<td>Specimen 3</td>
<td>69.8</td>
<td>82.3</td>
<td>49.5</td>
<td>60.1</td>
</tr>
<tr>
<td>Specimen 4</td>
<td>70.5</td>
<td>79.2</td>
<td>37.7</td>
<td>48.9</td>
</tr>
<tr>
<td>Specimen 5</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Mean value</td>
<td>63.1</td>
<td>73.9</td>
<td>42.5</td>
<td>52.9</td>
</tr>
</tbody>
</table>
3.2 Tensile shear test

Under the surrounding rock stress, the tensile shear properties of the bolting system depend on the anchor length and bolt diameter. In this sub-section, a steel drum is used to simulate the surrounding rock stress, and a Φ28mm steel cylinder was adopted to simulate the drilling into the surrounding rock. On this basis, a tensile shear test was performed on the bolting system in an environmental chamber. The outer diameter of the bolting system was 14.6mm, and each bolt was grouted to a length of 60mm. The test was carried out at four temperatures (20°C, 40°C, 60°C and 80°C), and the loading rate of 0.05 mm/s. Figure 4 shows the load-displacement curves at different temperatures.

The curves can be divided into three segments: the initial loading, the peak intensity and the residual strength, which correspond to the elastic phase, the plastic phase and the residual strength phase of shear failure.

Under the pulling stress, the displacement is positively correlated with the temperature. The load-displacement relationship can be described as:

$$\tau = K \cdot d + \zeta$$  \hspace{1cm} (3)

where \(\tau\) is the shear stress; \(d\) is the shear displacement; \(K\) is the shear stiffness; \(\zeta\) is a constant

Elastic phase:

$$K_1 = \tau_1 / d_a, \quad \zeta = 0$$  \hspace{1cm} (4)

where \(\tau_1\) is the ultimate tensile shear strength; \(d_a\) is the displacement under the ultimate tensile shear strength.

Plastic phase:

$$K_2 = (\tau_1 - \tau_2) / (d_a - d_b), \quad \zeta = (\tau_2 / d_a - \tau_1 / d_b) / (d_a - d_b)$$  \hspace{1cm} (5)

where \(\tau_2\) is the residual bonding strength; \(d_b\) is the displacement under the residual bonding strength.

Residual strength phase:

$$K_3 = 0, \quad \zeta = \tau_2$$  \hspace{1cm} (6)
Figure 5 shows the relationship between tensile shear stiffness and the temperature. It can be seen from Figure 5 that the tensile shear stiffness was negatively linear with the temperature in both the elastic phase and the plastic phase.

4. BOLTING EFFECT UNDER THERMODYNAMICS

4.1 Parameter design

The bolting system is usually analyzed by engineering analogy, theoretical calculation and numerical simulation. The resin-grouted area may deform under elastic and plastic mechanics. With the increase of temperature, the drawing load of the bolts in the elastic limit state decreases.

The share stress distributions of the bolts at different loads are presented in Figure 6, and the axial force distributions of the bolts at different loads are given in Figure 7.

![Figure 6. Shear stress distributions of the bolts at different loads](image)

![Figure 7. Axial force distributions of the bolts at different loads](image)

As shown in Figure 6, the shear stress of the bolts gradually decreased along the axial direction, as the load climbed up to 25 kN. As the load increased to 32, 34 and 36 kN, the maximum shear stress of the bolts transferred to the farthest end of bolt. The higher the load, the longer the transfer distance.

Figure 7 shows that the axial force of the bolts decreased along the axial direction, which is different from the trend of shear stress. In addition, the axial force is positively correlated with the load.

4.2 Bolt-rock interaction

The displacement of the bolting system mainly consists of the tensile displacement of the bolts and the deformation of the surrounding rock. In the shallow rock mass, the bolting system can restrain the broken surrounding rock effectively. In the deep rock mass, however, the bolting system may deform at a different rate with the surrounding rock, due to the high temperature gradient and high prestress of the bolts. Thus, the bolt-rock interaction mechanism should be fully explored under the thermodynamic effect. In addition, the rock mass carries different ductility and rheological properties in the shallow and deep parts under the high stress, and its Young’s modulus, Poisson’s ratio and tensile strength change inconsistently due to temperature variation.

In this subsection, the coring sample of surrounding rock is obtained to investigate the rheological mechanics of the rock mass under thermodynamic effect. Under the constant load of 30MPa, the yield stress of the sample was measured at 20 °C, 40 °C, 60 °C and 80 °C, respectively. The yield stresses of the sample under different temperatures are shown in Figure 8.

![Figure 8. Yield stresses of the sample at different temperatures (Load: 30MPa)](image)
It can be seen from Figure 8 that the yield stress of the sample increased rapidly and then slowly, and reached about 87με after 120 min under the constant temperature of 20 °C; the yield stress surged up early and reached 95με as the temperature rose to 40 °C; the yield stress changed similarly when the temperature increased to 60 and 80 °C, and stood at 105με and 133με, respectively, under the two temperatures.

Once the bolting system is installed, both the bolts and the surrounding rock will still deform at the tunnel excavation. Since the bolts were prestressed, the bolting system will deform less than the rock. In ideal conditions, the bolt prestress can offset the rock deformation, forming a flexible support. Meanwhile, the rheological displacement of the rock at the bolt end will increase with the temperature. The sandstone has a weaker thermal effect than the mudstone. Thus, the resin-grouted bolting will have a better effect on the sandstone.

5. CONCLUSIONS

Based on the thermodynamics theory, this paper examines the mechanical properties of resin-grouted bolting system, analyses the bolt-rock interaction mechanism, and determined the anchoring parameters of the system under thermodynamic effect. The main conclusions are drawn as follows:

(1) The resin-grouted bolts are extremely easy to install. Once installed, the bolts will exert a high anchoring force, which limits the displacement of the surrounding rock. With strong anti-impact and anti-vibration effects, the resin-grouted bolting system can be applied effectively in areas under strong blasting and vibration.

(2) The resin-grouted bolting system saw a reduction in compressive strength and yield stress with the growth of temperature. For the system, the elastic modulus is negatively linear with the temperature, while the Poisson’s ratio is positively linear with the temperature; the thermal expansion factor has a positive linear relationship with the temperature.

(3) The tensile shear failure of the system can be divided into the elastic phase, the plastic phase and the residual strength phase. In the first two phases, the tensile shear stiffness is negatively linear with temperature.

(4) The rock mass carries different ductility and rheological properties in the shallow and deep parts under the high stress, and its Young’s modulus, Poisson’s ratio and tensile strength change inconsistently due to temperature variation. The deformation of the surrounding rock can be offset by the prestress of the resin-grouted bolting system under the ideal conditions.

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