Simulation and Analysis on the Mechanical Properties of a New Slide-in Joint for Shield Tunnel Segment

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Abstract. There are many joint forms of shield tunnel lining segments. The new types of joints mainly include plug-in type and slide-in type where few researches concerning whose mechanical properties. This paper aims to construct a full-size numerical simulation model of the selected slide-in quick coupling joint and accomplish a fine prefabricated model. Given the complexity of the mechanics on the joint, loading and constraints are designed into the simulation model which achieves a successful simulation on various working conditions. The numerical results show that joint deformation can be reduced by optimizing the connectors’ position; A strengthening on the structure of C-type embedded groove can improve the overall bearing capacity of segment joint; Axial force can significantly reduce the deformation of the joint. Therefore, this research will help facilitate the effective design of the new type of shield tunnel joint.

Keywords: Tunnel lining, Slide-in joint, Numerical model, Mechanical property, Load combination

1. Introduction

Shield tunneling method has been widely used in urban transport tunnel construction. Segments are assembled by joints to form the tunnel lining as a primary structure supporting for shield tunnel. However the joint is the weak part of shield lining, affecting the mechanical properties of segments and the bearing capacity of whole shield tunnel lining structure.

Current researches on mechanical properties of joint mainly focus on analytical solution (Zhang J G et al. 2019)¹, model test (Liu X et al. 2019; Zhang H M et al. 2002)²,³ and numerical simulation (Zhang H M et al. 2003; Zhang J et al. 2018)⁴,⁵. The analytical solution is mainly based on the equilibrium equation of the stress and deformation of the joint. The shape of concrete compression zone is considered as simple geometry and the joint is under the assumption of springs. By means of the model test, the deformation and crack of joint can be observed directly. However, large-scale model tests result in high cost with small quantity of data. Given a relatively low cost with a large data volume obtained, which is one of the main advantages, numerical simulation methods have been widely accepted.
Lining joints on shield tunnel are mainly connected by bolts (Zhu Y H et al. 2015)[6], which are mostly equivalent to springs in the numerical simulation. The discussions on their mechanical properties mainly focus on measuring the stiffness of springs (Zhang J et al. 2018)[5]. With the development of research, Zhang W J et al. 2018[7] takes the bolt as the entity to analyze the influence of the weak part through the displacement and internal force. It proved an intuitive method for the research of joint mechanical properties based on Zhang’s work. In this study, it is found that the stress distribution of the bolt is uneven, which leads to the crack of the joint.

Based on the rationalization trend of the structural forces at present, some new types of joints have been developed and applied. These joints adopt connectors of plug-in type (Liu X et al. 2018)[8], slide-in type (Yue S Q et al. 2010)[9] and other structures. Compared to the traditional bolts, the deformation is reduced and the construction work is simplified. However, the structure becomes more complex and the machining precision is more challenging. Zhu Y H et al. 2015[6] and Liu X et al. 2018[8] equivalent a new type of joint to the spring in the test, which provides the flexural rigidity of the joint in terms of theoretical design. Since the joint is not considered as a 3D entity, the mechanical response of the joint cannot be further studied.

This research selected a representative new slide-in type joint, which is regarded as a 3D entity to establish a finite element model. Considering the complex stress of the segment, combined loads consisting of axial force, shear force and bending moment are applied to the model to analyze the mechanical response, the stress trend, and the deformation trend of the joint.

2. Modeling approach

2.1. Segment joint modeling for shield tunnel lining

Shield tunnel lining is composed of several precast segments and their connectors. The connector prevents the relative displacement between the segments and is the main load-bearing structure at the segment joint. The bolt is a cylinder structure, the cross section area accounts for about 0.2% of the joint. When subjected to bending moment, the deflection is likely to occur. When bearing shear force, the stress is concentrated on joint cross sections. The C-T slide-in connector is a typical new type of connector, consisting of a connector C and a connector T (Figure 1). In a subway project, the two components are embedded in the middle line of segment joint and connected by transverse sliding (Liu X et al. 2018)[8], with the section area accounting for about 2% of the joint area. When bearing bending moment, the contact between two members can effectively prevent the bending deformation of the joint. When bearing shear force, the larger cross-sectional area makes connectors more capable of bearing. In addition, joint fastening operation can be completed by pushing the segment along axial direction of tunnel, which eliminates the need for bolt fastening operation and improves construction efficiency. There are many factors affecting mechanical properties of the joint, including the joint size (Zeng D Y et al. 2005)[10], joint material (Zhang W J et al. 2018)[7], position of connector (Zhang W J et al. 2017)[11], external load (Zhang H M et al. 2002)[3], waterproof gasket. Have considered the above factors, the finite element software ABAQUS is used in this study to establish a 3D solid model of C-T slide-in joint (Figure 2).

Figure 1. C-T slide-in joint of lining segment The model sets a fixed joint size, material parameters and layout of connectors to analyze the mechanical properties of joints under different combinations of external loads. The influence of flexible structures such as waterproof gaskets is ignored (Liu X et al. 2019; Zhang W J et al. 2017)[10]. Constructed by C3D8R unit, The model adopts straight segment structure (Zhang H M et al. 2002; Zhang H M et al. 2003)[3-4], and encrypts the mesh near the segment connector.
2.2. Material attribute

The C-T slide-in joint model established in this study mainly consists of two parts which are segment and connector respectively. The concrete grade C50 is used for the segment. In order to study the entire stress process of the segment joint (including the elastic stage and the local plastic stage), the elastoplastic constitutive is applied to the segment material. According to the Code for Design of Concrete Structures\cite{12}, the elastic modulus of segment is set as 34.5GPa and Poisson's ratio as 0.2. The constitutive equation is

\[
\frac{3}{2} \left( \frac{2}{2} \right) \leq \frac{1}{\alpha} - \frac{1}{\gamma} \leq \frac{1}{\alpha} \left( \frac{1}{\gamma^2} \right)
\]

where \(f^*\) is the compressive stress of concrete at any strain, \(\alpha\) and \(\gamma\) is the basic parameter values of the ascending and descending sections of the constitutive curve, which are 1.78 and 2.48 respectively, \(f_c^*\) is the ultimate compressive stress of concrete, 50N/mm\(^2\), \(c\) is the strain when \(f^*\) reaches 1.92×10\(^3\).

The connector is made of steel with yield strength of 480N/mm\(^2\), elastic modulus of 210GPa and Poisson's ratio of 0.3. The bilinear strengthening model (Zhang W J et al. 2018; Yang F et al. 2020)\cite{7}\cite{13} is adopted as the material constitutive (Equation 2). This constitutive model is idealized as a double straight line with the front line representing the elastic stage and the back line representing the yield hardening stage of the connector.

\[
E_b \frac{f_b}{E_b} \leq \frac{E_b}{b} \leq \frac{E_b}{b}
\]

Where \(f_b\) is the yield stress, \(E_b\) is the elastic modulus, \(E_b\) is the plastic modulus, 2.1GPa, \(f^*_b\) is the yield strain obtained by \(f_b / E_b\).

2.3. Contact Settings

According to the characteristics of C-T slide-in joint, the contacts of joint include the following three types:

1. the contacts between the connector and the segment;
① the contacts between the connectors;
② the contacts between the segments.
The connectors are embedded in the concrete segment. It is difficult for them to separate or stagger. Binding constraints can satisfy class ① contact requirements. In class ② contact, the connector C and connector T are connected by sliding. A relative slip is allowed between the two components. The penalty function friction model is set in the tangential direction of the contact surfaces, and the friction factor is 0.36. A hard contact model is set in the normal direction of the contact surface to prevent the two entities from embedding into each other. In class ③ contact, sliding may also occur between the segments. The tangential direction of contact surface adopts penalty function friction model, and the friction factor is 0.21. The normal direction adopts a hard contact model.

2.4. Simulated condition

This study selects the working conditions by analyzing the actual force of the joint to obtain the mechanical response of joints under different external loads. The load-bearing deformation of the shield lining ring is mainly made of the overall radial compression deformation and the "duck egg" shape deformation (Ge S P et al. 2013)[14], and the deformation of the joint is generally in the form of a staggered pattern (Zhang S R et al. 2018)[15] and an open pattern (Zhang J et al. 2018)[5]. The overall compression of the lining ring will lead to axial force at the joint, and the two deformation patterns of the joint are dominated by shear force and bending moment respectively. In actual engineering, segment joints are subjected to bending moment, shear force and axial force simultaneously. When shear force is relatively large, the joint shows a staggered pattern. When bending moment is relatively large, the joint shows an open pattern. Therefore, the external load condition can be determined as shear load condition and bending moment load condition. The shear conditions include pure shear and axial shear, the bending moment conditions include pure bending and axial bending. As for constraint conditions, the relative rotation of the joint should be limited when the shear force is applied, the translation and rotation of section A of segment #1 should be limited when applying the bending moment (Figure 3). Under pure bending and pure shear conditions, the upper limit of bending moment and shear load is determined according to the joint response. If the segment is close to yield or yields, loading will stop. Considering the influence of axial force on the mechanical properties of the joint, the values of bending moment and shear force under the axial bending and axial shear conditions are the same as those under the pure bending and pure shear conditions. The upper limit of axial force loading under working condition is determined by the absence of obvious joint extension. For the above reasons, this paper sets the numerical simulation condition as shown in Table 1.

![Figure 3. Boundary and loading](image)
Table 1. Numerical simulation condition Load (Fs: shear force, Fb: bending moment, Fa: axial force)

| No. | Condition       | Fs      | Fb      | Fa   |
|-----|----------------|---------|---------|------|
| 1   | Pure shear     | 500kN   |         |      |
| 2   | Pure bending   |         | 150kN·m | 1000kN, 500kN |
| 3   | Axial shear    |         | 350kN   | 4000kN, 500kN |
| 4   | Axial bending  | 2450N   | 150kN·m |      |

3. Simulation results and analysis

3.1. Analyze content

The mechanical response of joints includes joint opening, joint dislocation, high stress area and stress distribution of joints. The joints exhibit different mechanical responses under different loads. Taking the above parameters as the object to analyze the mechanical properties of the joint, the load forms of pure shear, pure bend, axial shear and axial bend are analyzed through working conditions 1, 2, 3, 4 respectively. In axial shear load, Fa=3500kN, in axial bending load, Fa=350kN. Shear force conditions 1, 3 and bending moment conditions 2, 4 are adopted to consider the influence of axial force. The joint rotation angle is used to analyze the joint opening. The calculation formula of rotation angle $i$ in a joint is

$$ \delta_i = \frac{n_1 - n_2}{h_i} (i=1,2,3,...) \tag{3} $$

where $n_1$ and $n_2$ are respectively the upper and lower edge opening of $i$, $h_i$ is the opening depth of $i$ (Figure 4).

3.2. Pure bending and pure shear

3.2.1. Opening of segment joint

Under the pure shear condition, the displacement at the joint is mainly radial dislocation, and the dislocation amount is the same in the whole joint plane, about 0.24mm. Under the pure bending condition, the displacement at the joint is mainly open, with the opening amount of about 0.78mm, which is about 3 times of the joint displacement under the pure shear condition. The joints under the two working conditions are in double-fold shape (Figure 5, 6), and the connectors are located at the

![Figure 4. Schematic view of the joint rotation angle.](image)
junction of the two joint rotation angles. Under the pure shear condition, segment #2 has the downward displacement trend, and the shear force is transferred to the connector. The downward deflection of the connector causes the joint to open. The opening of the joint is affected by the placement of the connectors. The overall deformation of the segment ring usually presents the shape of horizontal, vertical and oblique “duck eggs” (Cheng Q et al. 2018)\textsuperscript{[16]}. The joints near the short axis and the long axis of the ellipse have an opening tendency respectively in the inside and outside of the tunnel. The joint in other positions has the tendency of dislocation. It is suggested that at the design stage, the position of connectors should be shifted to the joint opening side to reduce the opening amount.

![Joint deformation](image)

(a) Pure shear  
(b) Pure bending

**Figure 5. Joint deformation**

![Joint rotation angle](image)

(a) Shear force versus rotation angle (Pure shear)  
(b) Bending moment versus rotation angle (Pure bending)

**Figure 6. Joint rotation angle**

### 3.2.2. Stress of segment and connector

The high stress area of segment is concentrated in the embedded groove, and there is stress concentration phenomenon in the embedded groove and connector (Figure 7). These stress concentration areas can be regarded as the weak part of each part of the joint, among which the weak part of the embedded groove can be enhanced by means of infilling reinforcement, and the weak part of the connector can be improved by adding gaskets.

The peak stress curves of the embedded groove and the connector are shown in Figure 8. It can be seen that the peak stress relationship between each connector and embedded groove is:

$$\sigma_{\text{Connector T}} > \sigma_{\text{Connector T}} > \sigma_{\text{Groove C}} > \sigma_{\text{Groove T}}.$$
The peak stress of connector T is less than the ultimate bearing capacity of the connector. The peak stress of groove C is close to the ultimate bearing capacity of the segment, and it is the first part of the joint to enter into the plastic yield stage. While designing, connectors with smaller ultimate bearing capacity can be selected, and attention should be paid to strengthening groove C at its high stress zone.

**Figure 7.** Stress of embedded groove and connector

**Figure 8.** Peak stress of embedded groove
3.3. Axial shear and axial bending

The stress distributions of each part under the two working conditions are shown in Table 2. Under the axial shear condition, the joint has almost no rotational displacement, and the offset is 0.052mm. The stress of the joint increases gradually during the bearing process. During the loading stage, the high stress area of connector C changes from the upper and lower jaws to the lower jaw solely. The high stress area of connector T changes from the rear to the front platform. The high stress area of the groove C changes from the back to the front and the bottom. The high stress area of groove T changes from the back to lower part of the rear. At all stages of the axial shear condition, high stress area exists in the sliding passage, in which concrete should be filled after the assembly is completed in real situation. Under the axial bending condition, the joint displacement is dominated by rotation, and the opening volume is 0.32mm. The stress of the joint increases gradually during the bearing process. The distribution of high stress zone is slightly different from that of axial shear. Under the two working conditions, the joint is at the elastic strain stage from beginning to end. The connector has no obvious deformation. The weak part of all parts of the joint is similar to the pure bending and pure shear conditions. It is suggested to improve the weak part of joint in the same way while designing.

Table 2. Stress distribution of connector and groove

| Condition       | Connector C | Connector T | Groove C | Groove T |
|-----------------|-------------|-------------|----------|----------|
| Axial shear     | 98N/mm²     | 80N/mm²     | 23N/mm²  | 19N/mm²  |
| Axial bending   | 100N/mm²    | 154N/mm²    | 17N/mm²  | 13N/mm²  |

3.4. Influence analysis of axial force

Under the axial shear conditions, with the increase of shear force, both displacement and stress of the joint show an approximate linear increase and increase slowly. With the increase of axial force, the parameters of the joint change significantly (Figure 9). The joint deformation is in the form of opening and dislocation under pure shear load. When Fa=1000kN, axial force is insufficient to limit joint opening, which causes bending moment additionally, leading to a large joint stress. With the increase of axial force, the joint opening decreases obviously. The displacement form of the joint is gradually dominated by the dislocation, which tends to 0 after the axial force reaches 3000kN. When the axial force stays between 1000kN and 3000kN, the stress of the embedded groove decreases with the increase of axial force. As the axial force continues to increase, the stress at the embedded groove begins to increase gradually. No obvious deformation occurs to the connectors in the axial shear load. When the axial force is between 1000kN and 3000kN, the stress presented the same trend as the embedded groove. After increasing axial force, the stress of connector has no obvious change. It can be concluded from the above analysis that under the axial shear condition, the axial force within a certain range is beneficial to the structure of joint, but excessive axial force will lead to the increase of stress in the weak part.
The influence of axial force on the joint parameters under bending moment condition is similar to that under shear condition. When the axial force reaches 1050kN, there is no obvious displacement of the joint. Under axial bending conditions with different axial forces, the parameters of the joint show nonlinear changes with the increase of bending moment (Figure 10). Under the pure bending condition, joint displacement, the peak stress of connector and embedded groove all increase linearly with the increase of bending moment. Under the axial shear condition, when the axial force is small, the parameters increase first slowly and then linearly with the increase of bending moment. After the axial force increases to 1400kN, the increase of bending moment basically does not affect the parameters which show 0 growth or a slow growth trend. According to the above analysis, the displacement and stress of the joint under the bending moment condition can be reduced effectively by axial force, which is beneficial to the joint structure.
4. Conclusion
A three-dimensional solid model of segments with C-T slide-in new joints was constructed. The joints’ deformation and mechanical response under pure shear, pure bending, axial shear and axial bending were analyzed. This study has extracted the corresponding stress distribution patterns of the joint under different load combinations, and analyzed the mechanical properties of the joint. However, the conditions set in this paper is too idealized to be verified and compared by actual cases. Conditions that are set close to actual cases will be discussed in further research. Some conclusions and suggestions are as follows:

(1) At the elastic stage, the joint can withstand 500kN of pure shear or 150kN·m of pure bending, and the displacement is 0.24mm (staggered) or 0.78mm (opening) respectively. The weak part of the joints under different load combinations are all located in the embedded groove and connector. The increase of load will lead to the yield of connector T and groove C. These two structures need to be strengthened while designing.

(2) The placement of C-T slide-in connectors does not affect the dislocation of the joint, but affects the opening deformation of the joint significantly. Arranging the position of connector towards the opening side can effectively reduce the opening amount of the joint.

(3) Under the bending moment condition and shear condition, the axial force can reduce the deformation and peak stress of the joint within a certain range. However, too much axial force will lead to the increase of stress in the joint's weak part. The most adverse conditions of the joint should be set as the minimum and maximum of the axial shear ratio and axial bending ratio while designing.

(4) The mechanical properties of bolt joints or other new joints can be analyzed under the same conditions, so as to compare the application range of different joints.

Acknowledgments
The work presented in this article was supported by the Science and Technology Commission of Shanghai Municipality (Grant No. 18DZ1205902)

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