Theoretical Analysis of Bearing Capacity for Shield Tunnel Reinforcement Structure

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Abstract: Aimed at the bearing capacity of shield tunnel reinforcement structure, this paper conducts a series of research and theoretical derivations. First of all, the reinforced composite structure must meet some basic assumptions before any theoretical analyses. With the secondary stress analyses of the structure, the calculation method of the lag strain is derived. Adding this lag strain to the overall reinforced structure can make the strain of the whole section meet the plane hypothesis, and the overall structure can be analyzed from the strain diagram considering the lag strain. And then whether the steel bar and reinforced structure yield or not and their yielding sequence can give the shield tunnel reinforcement structure four typical failure modes under the ultimate limit state, according to which theoretical formula of the ultimate bearing capacity of various reinforced composite structure in different failure modes can be derived. At last, the result can be used to analyze the structure’s ultimate bearing capacity and convergence deformation.

Keywords: Secondary loading, the lag strain, shield tunnel reinforcement structure.

1. Introduction

As the operational mileage of China’s subway continues to increase, the total operational mileage has reached 4598.3 kilometers up to now. Therefore, the shield tunnel structure during the construction and operation will have some diseases such as the excessive opening of the longitudinal joints, segments cracking and water leakage caused by its own construction and external factors, which will pose a major threat to the structural safety of the tunnel and the normal running of the metro. Common structural diseases are shown in figure 1.

Therefore, the shield tunnel structure needs to be repaired and reinforced to improve the structural performance [1-4], so that the structure can meet the specified bearing capacity and the using function. Aimed at the above series of diseases of the shield tunnel structure, some common reinforcement methods can be used, including CFRP [5-7], full-ring steel plate reinforcement method, composite cavity reinforcement method and comprehensive reinforcement method.

Nowadays, the theory of reinforcement technology has been studied in many aspects at home and abroad. Bi et al. carried out a full-scale test to study the ultimate bearing capacity of the shield tunnel reinforced by full-ring steel plate [8-9]. The results showed that the strength and stiffness of the shield tunnel structure had been enhanced greatly in the condition of full-ring reinforcement compared with the pre-reinforcement tunnel before the bond between the steel plate and concrete failed, which is a reliable reinforcement method. Gu analyzed the causes of the tunnel damage and its failure modes, elaborating a new type of installation equipment for steel ring support inside the tunnel and its technological process [10]. Based on the ultimate bearing capacity full-scale test of the composite cavity reinforcement, Liu et al. presented a nonlinear model used to simulate the composite cavity
reinforcement for shield tunnel structure, and obtained its overall failure mechanism [11]. Although the structural model test can have a better verification of various performances of the shield tunnel structure, it costs a lot and is a time-consuming process, which is difficult to repeat in large quantities and multiple times.

![Images of tunnel structure issues: (a) Water leakage. (b) Structural damage. (c) Joint faulting. (d) Ballast disengaging.](image)

**Figure 1.** The diseases of tunnel structure.

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Unlike the costly structural test method, the method of numerical simulation can remedy the difficulty of large-scale implementation of structural test to a large extent. So a number of people have
made use of the finite element model to study and analyze the reinforced structure. By establishing a 3-dimensional finite element segment model considering the depth of cracks, Pan carried out numerical analysis on bearing behavior of tunnel structure reinforced by AFRP. It was concluded that the AFRP reinforcement can effectively reduce the tunnel deformation [12]. Liang et al. used the numerical simulation method to obtain the causes of damaged segment and cracking of the metro tunnel. The main reason is that when segments twists between each other, the stress concentration caused by the mutual extrusion between the segments and the extrusion from the bolt to the bolt hole will happen [13]. Taking the lateral deformation and the opening of longitudinal joints of the tunnel as the evaluation index, Liu et al. established a 3-dimensional finite element model of a metro shield tunnel in Shanghai, and studied the mechanism and effect of AFRP to restrain the lateral deformation of the tunnel [14]. Furthermore, the effect of various factors on the reinforcement was also discussed. Aimed at the tunnel lining structure reinforced by TRC, Liu conducted interface bond tests and numerical tests, and discussed the interface stress distribution law of tunnel lining strengthened by TRC [15]. A 3-dimensional finite element model containing two segments connected by a curved bolt was established by Zhai et al., and then a numerical test is designed to study the shearing performance of circumferential joints of segmental linings, which showed the interaction mechanism between the steel plate and the linings [16]. However, the finite element method needs a high computing power of the computer, and it also required the establishment of a refined model, which takes a lot of time and is less efficient.

The shield tunnel reinforced structure model based on the analysis method of secondary loading can calculate the bearing capacity and subsequent structural deformation of the reinforced shield tunnel structure quickly and succinctly, which can make preliminary judgement of the effect of reinforcement. Nowadays, the theoretical derivation and research of the bearing capacity of the shield tunnel reinforcement structure, which use the analysis method of secondary loading, are deficient in the field of the shield tunnel reinforcement. Therefore, through the theoretical derivation of the bearing capacity of the section of the reinforced shield tunnel and using 2-dimensional analysis method, a calculating method for the ultimate bearing capacity and subsequent deformation of the shield tunnel reinforcement structure is proposed in this paper. At last, this method is used to do the reinforcement calculation of a metro shield tunnel structure of the Hexi region in Nanjing.

2. A calculation Model Based on the Structural Secondary Loading of the Shield Tunnel Reinforcement Structure

2.1. The Bearing Capacity Analysis of the Secondary Loading in the Reinforced Composite Structure
Most of the reinforcement of the shield tunnel structure is carried out under the condition that the structure is already under a large external loading and unloads nothing. Under these circumstances, the original structure is under the loading, but the reinforcement structure is not under the loading, so it belongs to the secondary loading problem of the reinforced composite structure. The bearing capacity analysis of the shield tunnel reinforcement structure includes three parts: firstly, the calculation of the lag strain $\varepsilon_{\text{lag}}$ of the reinforced structure; secondly, the judgement of the yield condition and the failure mode of the reinforced composite structure; finally, the calculation of the ultimate bearing capacity of the section based on the failure mode of the reinforced composite structure.

2.1.1. Basic Assumption. Based on the stress and deformation characteristics of the reinforced composite structure, four basic assumption are proposed, which can simplify the process of the derivation:

- The plane hypothesis is conformed to by the reinforced composite structure until its failure under the loading;
- It’s assumed that the deformation of various materials is coordinated, and the bonding between the reinforced structure and the original structure is reliable, and there is no relative slip, and only the case of no interface peeling is considered.
- The tensile strength of concrete is not considered, and the reinforced structure is mainly used for its tensile properties.
During the calculation of the internal force of the shield tunnel, the tunnel structure is simplified to a freely deformed ring, and the effect of the thickness of the reinforced structure on the thickness of the ring is ignored, which means that the geometry of the ring is invariant before and after the reinforcement.

2.1.2. The Calculation of the Lag Strain of the Reinforced Composite Structure. After the shield tunnel structure is reinforced, the section of the whole reinforced composite structure is supposed to meet the plane hypothesis, but the stress and strain state of the reinforced structure at the beginning of the reinforcement is 0, so it’s necessary to virtualize a lag strain $\varepsilon_{sp0}$, which is extended from the pre-reinforced strain of the original structure in the same proportion to the reinforced place based on the plane hypothesis, so that the section of the reinforced composite structure after the reinforcement can meet the plane hypothesis. When calculating the lag strain, the reinforced composite structure is subjected to an initial bending moment $M_0$, at which time the original structure has produced the stress and strain, but the reinforced structure hasn’t been subjected to the force. When the reinforcement is completed, the stress and stress of the section are shown in figure 2.

![Figure 2. The graphic illustration of calculation under secondary loading.](image)

The relevant calculation method of the lag strain of the shield tunnel reinforced structure under the condition of the secondary loading is not determined by the specification. Based on the plane hypothesis, the formula of the lag strain is derived considering the stress characteristics of the reinforced concrete structure at the same time in this paper. According to the section analysis method of the reinforced concrete, the initial bending moment $M_0$ of the original structure before the reinforcement is relatively small, so the edge of the section under the compression is still in an elastic state. At this time, the tensile steel bar does not reach the yield limit. Obtained from the plane hypothesis:

$$\varepsilon_{sp0} = \varepsilon_{c0} \left( \frac{h - x_c}{x_c} \right)$$

In the equation:
- $\varepsilon_{c0}$——Initial compressive strain of concrete when the reinforcement is completed;
- $\varepsilon_{c0}$——Peak strain of steel;
- $f_c$——Axial compressive strength of concrete;
- $x_c$——The stress block depth of concrete when reinforcement is completed;
- $h_0$——The effective depth of the section;
- $h$——The depth from the point of resulting force of the reinforced structure to the edge of the section under the compression when reinforcement is completed;
The elastic modulus of steel bar

The resulting force of concrete in the compression zone can be obtained by the integration:

\[ C = \int_0^y b_f \left[ 2x - \frac{y}{x} \frac{e_{cm}}{e_0} - \left( \frac{y}{x} \right)^2 \frac{e_{cm}}{e_0} \right] dx = f_b x \frac{e_{cm}}{e_0} (1 - \frac{e_{cm}}{3e_0}) \] (2)

The distance from the point of the resulting force to the edge of compression zone of concrete is:

\[ y_c = x_c - \frac{1}{C} \int_0^x b_f x \left[ 2x - \frac{y}{x} \frac{e_{cm}}{e_0} - \left( \frac{y}{x} \right)^2 \frac{e_{cm}}{e_0} \right] dx = x_c \left( \frac{1 - \frac{e_{cm}}{4e_0}}{3 - \frac{e_{cm}}{e_0}} \right) \] (3)

From the equilibrium of force \( \Sigma X = 0 \), \( C = T_s \), that is

\[ f_b x_c \frac{e_{cm}}{e_0} (1 - \frac{e_{cm}}{3e_0}) = E_s e_{cm} A_s \]

When transformed further, an equation can be rewritten:

\[ f_b x_c \frac{e_{cm}}{e_0} (1 - \frac{e_{cm}}{3e_0}) = E_s e_{cm} (\frac{h_0}{x_c} - y_c) A_s \] (4)

Solve the moment at the position of the tensile steel bar. That is \( \sum M = 0 \):

\[ f_b x_c \frac{e_{cm}}{e_0} (1 - \frac{e_{cm}}{3e_0}) (\frac{1 - \frac{e_{cm}}{4e_0}}{3 - \frac{e_{cm}}{e_0}}) = M_0 \] (5)

\( e_{cm} \) and \( x_c \) can be solved form the equation (4) and (5), and then by substituting \( e_{cm} \) and \( x_c \) into the equation (1), the lag strain \( \varepsilon_{sp0} \) generated by the initial bending moment of the reinforced structure can be obtained.

2.1.3. The Judgement of the Failure Mode of the Shield Tunnel Reinforced Structure. Firstly, the yield strain of the reinforced structure can be determined by the lag strain \( \varepsilon_{sp0} \) obtained before, and then compare the yield strain of the reinforced structure and steel bar with the yield limit of each other to determine whether or not to yield and the sequence of its yielding. Therefore, the typical failure mode of the shield tunnel reinforced structure under the ultimate limit state may exist in the following four states:

- While the reinforced structure hasn’t yet reached the yield point, the steel bar yields first, and then the concrete in the compression zone reached the limit state;
- While the steel bar hasn’t reached the yield point, the reinforced structure yields first, and then the concrete reached the limit state;
- The concrete is crushed when it reaches the limit state, and neither the tensile steel bar nor reinforced structure yields, which belongs to over-reinforced failure. Under the circumstances, there is no obvious sign of the failure, and it happens by accident, which is a typical brittle failure;
- The steel bar yields, and as the load increases, the reinforced structure also reaches the yield limit with the concrete in the compression zone reaching the limit state. In this failure mode, the function of each part of the structure after the reinforcement is fully utilized, which is the most ideal state of the failure mode.

The judgement of the specific failure mode of the structure after the reinforcement depends on whether the steel bars and reinforced structures have reached the yield state. The strain relationship of the section under the ultimate limit states is shown as follows figure 3.
When the steel bar is yielding, the tensile strain $\varepsilon_s$ of the tensile steel bar is greater than its yielding strain $\varepsilon_y$, that is $\varepsilon_s \geq \varepsilon_y$. At this time, the stress block depth $x$ of the section in the equivalent rectangular stress diagram must meet:

$$x = 0.8 \varepsilon_c \leq \frac{0.8h_0}{1 + \frac{\varepsilon_s}{\varepsilon_{cu}}}$$

(6)

Where $\xi_b$ is the relative stress block depth of the balanced failure for the section of the ordinary reinforced concrete.

Similarly, when the reinforced structure yields, it should be satisfied that the tensile strain of the reinforced structure $\varepsilon_{sp}$ is greater than its yielding strain $\varepsilon_{spy}$, that is $\varepsilon_{sp} \geq \varepsilon_{spy}$. At this time, the stress block depth $x$ of the section in the equivalent rectangular stress diagram must meet:

$$x = 0.8 \varepsilon_c \leq \frac{0.8h}{1 + \frac{\varepsilon_{spy}^2 + \varepsilon_{sp}}{\varepsilon_{cu}^2}}$$

(7)

Where $\xi_{b1}$ is the relative stress block depth of the balanced failure for the section of the structure after the reinforcement.

2.1.4. The Calculation of the Bearing Capacity of the Section in the Shield Tunnel Reinforced Structure.

According to the sequence of the yielding of steel bars and reinforced structure, each ultimate bearing capacity of the section of four failure modes in the reinforced composite structure can be solved:

(1) When $\xi_{b1}h < x < \xi_b h_0$, the tensile steel bar yields and the reinforced structure doesn’t yield yet, which satisfies the first failure mode. The formula of the ultimate bearing capacity of the section of the shield tunnel reinforced structure is:

$$M_{u1} = f_c bx \left( h - \frac{x}{2} \right) - f_y A \Delta h$$

(8)

(2) When $\xi_b h_0 < x < \xi_{b1} h$, the reinforced structure yields and the tensile steel bar doesn’t yield yet, which satisfies the second failure mode. The formula of the ultimate bearing capacity of the section of the shield tunnel reinforced structure is:

$$M_{u2} = f_c bx \left( h_0 - \frac{x}{2} \right) + f_y A_p \Delta h$$

(9)

(3) When $x > \xi_{b1} h$ and $x > \xi_b h_0$, neither the tensile steel bar nor the reinforced structure yields yet, which satisfies the third failure mode. The formula of the ultimate bearing capacity of the section of the shield tunnel reinforced structure is:
\[ M_{u3} = f_yb(h - \frac{x}{2}) - \frac{0.8h_b - x}{x}E_A\Delta h \]  

(10)

(4) When \( x<\xi_bh \) and \( x<\xi_bh_0 \), both the tensile steel bar and the reinforced structure yield, and the concrete of the compression zone also reaches the limit state, which satisfies the fourth failure mode. The formula of the ultimate bearing capacity of the section of the shield tunnel reinforced structure is:

\[ M_{u4} = f_yb(h - \frac{x}{2}) - f_yA\Delta h \]  

(11)

In the equation:

\( \Delta h \) —— The depth from the tensile steel bar to the reinforced structure;

\( E_{sp} \) —— The modulus of elasticity of the reinforced structure;

\( T_s \), \( T_{sp} \) —— The tensile stress of the tensile steel bar and reinforced structure;

\( f_y \), \( f_{yp} \) —— The tensile strength of the tensile steel bar and reinforced structure;

\( A_{sp} \) —— The cross-sectional area of the reinforced structure;

\( A_s \) —— The cross-sectional area of the steel bar.

2.2. The Calculation of Subsequent Deformation of the Reinforced Composite Structure

The curvature of the reinforced section can be obtained from the geometric relationship of the section:

\[ \phi = \frac{\epsilon_c + \epsilon_s + \epsilon_{sp} + \epsilon_{sp0}}{h} \]  

(12)

According to the physical relationship, the stress-strain relationship of each material in the normal using phase is:

\[ \epsilon_c = \frac{\sigma_c}{E_c}, \epsilon_s = \frac{\sigma_s}{E_s}, \epsilon_{sp} = \frac{\sigma_{sp}}{E_{sp}} \]  

(13)

According to the equilibrium conditions, the equation (12) is transformed into the form as follows ignoring the tensile capacity of the concrete:

\[ \phi = \frac{M_0Ax_{sp}E_{sp}h_0 + bx_{s}E_s - A_sE_s(h_0 - x_0)}{A_{sp}x^2hE_{sp}E_c} + \epsilon_{sp0} \]  

(14)

At the same time, the relationship between the stiffness and curvature of the section is also satisfied as follows:

\[ B = \frac{M}{\phi} \]  

(15)

Where \( B \) is the section stiffness, \( \phi \) is the section curvature, and \( M \) is the bending moment to which the section is subjected. The bending rigidity of the section of the reinforced composite structure can be obtained from equation (15). Here, the calculation of the displacement of the horizontal diameter point of the shield tunnel under the vertical overload is taken as an example to illustrate the calculation principle.

Since the axial force and shear force have little effect on the deformation, the displacement is mainly caused by the bending:

\[ M = \frac{1}{4}qR^2(1 - 2\sin^2 \theta)h \]  

(16)

It is assumed that the bending moment caused by the horizontal unit load of the horizontal diameter point of the lining ring is:

\[ \bar{M} = R\cos \theta \]  

(17)

Therefore, the horizontal displacement of the horizontal diameter point of the lining ring under the overload is:
3. The Calculation Example of Reinforcement

Taking a section of a metro shield tunnel in Hexi region of Nanjing as a typical section for reinforcement calculation. The strata that the shield tunnel crossed can be roughly divided into the Yangtze River floodplain, the old clay, and Qinghuai River floodplain. Among them, the Yangtze River floodplain has the worst geological conditions. Based on the current service status of the Nanjing Metro shield tunnel, the typical strata that the shield tunnel crossed in the floodplain area of the Yangtze River are selected. The typical strata is shown in figure 4, and the shield tunnel is located in the muddy-silty clay stratum. The physical and mechanical parameters are shown in table 1.

![Figure 4. Typical strata crossed by Nanjing Metro shield tunnel.](image)

| The name of stratum   | Volumetric weight $\gamma$ (kN/m$^3$) | Layer thickness (m) | Coefficient of lateral pressure ($\lambda$) | Coefficient of the elastic resistance of ground (MPa/m) |
|-----------------------|----------------------------------------|---------------------|------------------------------------------|-----------------------------------------------------|
| Miscellaneous fill    | 18.1                                   | 1.94                | 0.42                                     | -                                                   |
| Muddy-silty clay       | 17.5                                   | 16.66               | 0.70                                     | 10                                                  |
| Silt                  | 18.2                                   | 12.2                | 0.53                                     | 15                                                  |
| Silty soil             | 18.8                                   | 13.4                | 0.33                                     | 30                                                  |

The staggered joint segment of Nanjing Metro shield tunnel is 6.2 m in outer diameter, 0.35m in thickness and 1.2m in width; the segment is made of C50 concrete, the diameter of the main reinforcement is 16mm, and the single row is equipped with 8 main reinforcements. The density of the reinforced concrete is about 2500 kg/m$^3$, and the reinforced structures are steel plates with a thickness of 20mm and a width of 900mm, and the material is NO.3 steel. The buried depth at the top of the tunnel is 12m. The segment is reinforced when it reaches the normal design load, and the vertical force under the normal design load condition increases by 1.5 times when it comes to the subsequent overload condition. The bending moment and axial forces at various sections of the lining ring are calculated through the modified routine method, as shown in figure 5.

In this example, the reinforcement is carried out when the load reaches the normal design load. At this time, the bending moment $M_0$ at the section of the lining ring arch is 69.8 kN·m. Substituting $M_0$ into the equation (1), (4) and (5) to obtain the lag strain $\varepsilon_{sp0}$=0.00167, and then substituting it into the equation (10), the bearing capacity of the reinforced section under the secondary loading is 132.35kN·m. At last, substituting $M_0$ and $\varepsilon_{sp0}$ into the equation (14), (15), and (18) can obtain the horizontal displacement of the horizontal diameter point of the lining ring under the overload after the reinforcement, that is, the lateral convergence deformation. The calculation result is shown in figure 6 and figure 7.
Using the formulas derived earlier, the ultimate bearing capacity and subsequent deformation of the shield tunnel structure can be calculated separately considering the secondary loading. By comparing the unreinforced and reinforced calculation results in figure 6 and figure 7, it can be found that the ultimate bearing capacity of the reinforced section was increased by nearly 20% compared with the unreinforced one, which increases the structural safety greatly. As for the subsequent deformation, the amount of deformation of the reinforced composite was reduced by nearly 15% compared to the unreinforced one no matter the lateral or vertical deformation, enabling the structure to meet its applicability. Therefore, the performance of the reinforced shield tunnel structure has been greatly improved and the service life of the structure will also be greatly increased.

Therefore, the reinforcement of the shield tunnel can effectively improve the bearing capacity of the structure. In addition, as the thickness and strength of the reinforced structure increase, the ultimate bearing capacity will also increase. As shown in figure 8, the thickness of the reinforced structure gradually increases from 20mm to 50mm, the ultimate bearing capacity of the reinforced composite structure basically increases linearly by 46.24%; as shown in figure 9, the strength of the material of reinforced structure increases from 235MPa to 500MPa, the ultimate bearing capacity of the reinforced composite structure also increases to a large scale by more than 100%. So, when the cost factors of the project are not considered, the effect of strengthening the shield tunnel reinforced structure by increasing the thickness and strength of the reinforced structure is significant.
4. Conclusion

Based on the research on the joint bearing performance of shield tunnel structure and reinforced structure together with the theoretical analysis of the bearing capacity of shield tunnel reinforcement structure, the following conclusions can be obtained:

(1) Firstly, the theoretical analysis of the secondary loading bearing capacity of the reinforced composite structure is carried out, and the calculation method of the lag strain of the reinforced composite structure is obtained. And then according to whether the steel bar and the reinforced structure yield and the subsequent of the yielding, the judgement of the failure stage of the shield tunnel reinforced structure can be obtained. Followed by the failure stage, the formulas for calculating the ultimate bearing capacity of sections of composite structures under different failure modes are derived. Finally, taking the displacement of the horizontal diameter point of the shield tunnel under vertical overload as an example in the calculation of the subsequent deformation of the reinforced composite structure, the formula of the horizontal displacement of the horizontal diameter point is derived.

(2) In the secondary loading analysis of the reinforced structure of the shield tunnel, it’s concluded that the bearing capacity of the reinforced composite structure was increased by 19.1% compared with the unreinforced one. Additionally, in the lateral deformation of the shield tunnel, the deformation of the reinforced composite structure is reduced by 13.8% compared with the unreinforced one; in the vertical deformation of the shield tunnel, the deformation of the reinforced composite structure is reduced by 16.1% compared with the unreinforced one. And as the thickness and strength of the reinforced structure increase, the ultimate bearing capacity will also increase.

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