Numerical study on mechanical properties of large diameter double-layer shield tunnels under the elevated temperatures in fire

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Abstract: As the development of underground engineering, shield tunnels in single-pipe and double-deck type have been widely used and promoted to improve the utilization rate of the effective space. For this complex structure, fire may trigger tunnel lining structure damage or even the failure of the structure. In this paper, the mechanical properties of a large diameter double-layer shield tunnel under elevated temperatures induced by fire were analyzed numerically. A thermo-mechanical coupling numerical approach was employed to implement the thermo-mechanical models in full size. Aiming at a large-diameter shield tunnel with the internal structure combining road and metro space in Jinan, China, the model is applied in a parametric study to verify the fire resistance of tunnel structures under different configurations and RABT fire exposure. The effects of the internal structure and fire location on the complicated mechanical properties of the tunnel were analyzed. Results from numerical analysis showed that the elevated temperatures have a significant impact on the mechanical properties of tunnel, and the structure subjected to elevated temperatures has obvious expansion deformation and stress change. The internal structure has a great influence on the mechanical properties of the tunnel under elevated temperatures, which is conducive to reducing the radial convergence deformation of the tunnel lining structure and improving the internal force state of the lining structure. The location of the fire in the tunnel has a major influence on the internal force and deformation of the tunnel structure. When the fire occurs in the lower space of the tunnel, the fire safety of the internal box culvert structure should be paid more attention. The key design considerations have been identified as the concrete deck slab and the tunnel lining segmental joints configuration.

1. Introduction

With the large-scale development of urban underground space, more and more cases of underground engineering construction under the complex environment with various facilities are densely distributed, which puts forward higher requirements for the spatial utilization of urban tunnel. Under this background, shield tunnels in single-pipe and double-deck type have been widely used and promoted [1]. This complex structure form also brings greater challenges to the fire safety of tunnel structure. The internal structure of the double-layer tunnel has a significant impact on the mechanical properties of the tunnel under elevated temperatures. The tunnel structure will also have different mechanical response when fire occurs in different layers of tunnel. However, there is little research on the
mechanical properties of the large diameter double-layer shield tunnel under high temperature in fire. When a fire occurs in the tunnel, the high temperature of the fire will not only affect the safety of the lining, but also affect the internal structure of the tunnel, and even lead to collapse of the tunnel structure [2]. In this paper, based on a large-diameter double-layer shield tunnel in Jinan, China, a thermo-mechanical model is established to analyze the mechanical properties of a large diameter double-layer shield tunnel under elevated temperatures induced by fire. The influence of the internal structure and the location of fire on the mechanical properties under elevated temperatures are studied in this paper. Through the research, some useful results are gained to deepen our understanding of the mechanical properties of a large diameter double-layer shield tunnel under elevated temperatures.

2. Thermo-mechanical coupling analysis method for large diameter double-layer shield tunnel

2.1. Basic information of model

This tunnel is the first large-diameter shield tunnel crossing the Yellow River in China, which is constructed with the internal structure combining road and metro space. The tunnel is divided into upper and lower layers. The outer diameter of the tunnel is 15.2 m. The thickness of lining segment is 650 mm. The whole ring is composed of 10 segments, which are connected by inclined bolts. According to the tunnel structure information, a numerical analysis model is established as shown in figure 1.

![Figure 1](image1.png)

**Figure 1.** Finite element model: (a) Tunnel structure model; (b) Mesh generation of box culvert in tunnel.

2.2. Analysis method

In order to obtain the temperature field of tunnel structure under elevated temperatures, the method of temperature rise curve is used to describe the fire scene of the tunnel in this paper. The RABT curve is adopted to obtain the mechanical properties of the tunnel structure during the fire [3,4]. The expression of the curve is as follows:

$$T = \begin{cases} 
20 + 236t & 0 \leq t < 5 \\
1200 & 5 \leq t < 130 \\
1200 - 10.727(t - 130) & 130 \leq t \leq 240 
\end{cases} \quad (1)$$

Where T is the temperature represented by the reference curve at time t; t is the duration of fire.

In this paper, the lining ring without considering the internal structure, the lining ring with considering the internal structure and the tunnel fire occurred in the upper layer of the tunnel, and the lining ring with considering the internal structure and the tunnel fire occurred in the lower layer of the tunnel were analyzed. According to the temperature of the tunnel under fire, the lining thermal boundary is divided into three zones shown in figure 2 (a), when a fire occurs in the upper layer of the tunnel [5].
When a fire occurs in the lower layer of the tunnel, the lining thermal boundary is divided as shown in figure 2 (b).

![Figure. 2 Temperature division: (a) Fire in the upper layer of the tunnel; (b) Fire in the lower layer of the tunnel.](image)

### 2.3. Parameters used in this paper
The mechanical properties of tunnel structure under elevated temperatures are quite different from those under normal temperature. The thermal parameters of concrete will directly affect the temperature field of the tunnel structure. Therefore, it is necessary to determine the thermal parameters of concrete before analyzing the temperature field of tunnel structure. The thermal parameters used in this paper are shown in Table 1 [6].

| The thermal parameters | The expression |
|------------------------|---------------|
| The thermal conductivity (W/m·°C) | $\lambda = 1.6 - 0.16 \times \left(\frac{T}{120}\right) + 0.008 \times \left(\frac{T}{120}\right)^2$ |
| The specific heat (J/kg·°C) | $c = 900 + 800 \times \left(\frac{T}{120}\right) - 4 \times \left(\frac{T}{120}\right)^2$ |
| The thermal expansion coefficient | $a_c = 6 \times 10^{-6} + 4.92 \times 10^{-9} \times T$ |

The research shows that the strength of concrete and steel will decrease with temperature increasing. When the temperature exceeds 400 °C, the mechanical properties of concrete decrease obviously with temperature increasing. When the temperature exceeds 1000 °C, the concrete is seriously damaged and almost loses its bearing capacity [7-10]. The strength reduction coefficient of concrete used in this paper is shown in Table 2.

| The strength reduction coefficient | The expression |
|-----------------------------------|---------------|
| The compression strength reduction coefficient | $\gamma_c = 0.00165 \times \left(\frac{T}{100}\right)^3 - 0.03 \times \left(\frac{T}{120}\right)^2 + 0.025 \times \left(\frac{T}{120}\right) + 1.002$ for $T \leq 100°C$ |
| $\gamma_c = \begin{cases} 1 & 100°C < T \leq 600°C \\ 0 & T > 600°C \end{cases}$ |

### 3. Analysis of numerical simulation results

#### 3.1. The temperature field of tunnel structure under fire
When a fire occurs in the tunnel, the heat is gradually transferred from the high-temperature zone to the low-temperature zone. The closer the distance from the fire surface is, the greater the influence of
the elevated temperatures is, and the higher the temperature is. The temperature of the heat conduction region is significantly different from that of the heat convection region, and the temperature rise in the heat convection region is significantly slower than that in the heat conduction region in the initial stage of fire. As the fire continues, the temperature of the two regions tends to be consistent. Due to the thermal insulation of the carriageway slab, the tunnel structure in the adiabatic area is not affected by the fire, and the temperature is basically unchanged.

When a fire occurs in the upper layer of the tunnel, the temperature distribution of the tunnel vault lining is shown as figure 3. It can be seen in figure 3 (a) that the temperature of the lining changes with time under the fire. In the stage of heating and stable combustion, the closer to the fire surface, the faster the temperature rise and the higher the temperature. In the cooling stage, the temperature of the concrete near the inner surface of the lining will decrease slowly. With the increase of the distance to the inner surface of the lining, the temperature of the lining will decrease less obviously, and even the temperature will increase. It can be seen in figure 3 (b) that the maximum temperature of tunnel lining structure is about 60 mm away from the inner surface after four hours of the fire. The inner surface of tunnel lining structure has experienced a long period of cooling stage, and the temperature has been significantly reduced. The concrete with a certain distance to the inner surface is blocked by the inner concrete, and the heat dissipation is difficult, so the temperature is higher. The temperature of the place far away from the inner surface of the tunnel lining is low due to the slow heating up in the heating stage. Therefore, in the cooling stage, the temperature in the high temperature zone of the lining will transfer to the inner surface and the outer surface of the lining, resulting in the temperature in the high temperature zone decreasing in the cooling stage, while the temperature in the low temperature zone increasing in the cooling stage.

![Figure 3. Temperature distribution of tunnel vault lining: (a) Temperature time curve at different positions of vault; (b) Temperature distribution at different positions of vault.](image)

3.2. The influence of internal structure on mechanical properties of tunnel structure

The basic deformation of tunnel lining structure is shown in figure 4. The tunnel lining structure has a trend of flattening under the action of ground pressure. The vault of the lining produces vertical downward deformation, and the waist of lining bulges out to both sides. With the increase of temperature under fire, the lining concrete expands and deforms, which leads to the decrease of vertical deformation of the vault and the increase of horizontal deformation of the waist. When the fire is controlled gradually, the temperature of the tunnel lining structure decreases slowly, the thermal expansion of the lining decreases gradually, and the vertical deformation of the vault increases gradually.

It is found that the internal structure of the tunnel has a significant impact on the deformation and internal force of the tunnel lining structure under elevated temperatures by comparing the deformation and internal force of the lining under condition 1 and condition 2.
When a fire occurs in the upper layer of the tunnel, the lining deformation of the tunnel with and without internal structure shows the same law. However, for the tunnel with internal structure, the internal structure increases the stiffness of the lining structure, resulting in a significantly smaller radial convergence deformation than that of the tunnel without internal structure. It can be seen in figure 4 that the maximum vertical deformation of the tunnel vault lining without internal structure reaches 11.26 mm in fire, and the maximum horizontal deformation of the waist is 11.47 mm. For the tunnel with internal structure, the maximum vertical deformation of the vault lining is 10.19 mm, which is reduced by 9.5 %, and the maximum horizontal deformation of the arch waist is 3.21 mm, which is reduced by 71.5 %. It shows that the internal structure of the tunnel has a great constraint on the deformation of the part below the arch waist of the tunnel lining ring, but has little effect on the deformation of the tunnel vault.

In order to measure the radial convergence of tunnel lining structure, the concept of convergence degree is proposed in this paper. The radial convergence deformation of several points on the tunnel lining structure is taken uniformly, and the convergence deformation is divided by the tunnel diameter, and then the mean value is taken to obtain the convergence degree of the tunnel lining structure. The curve of convergence degree of tunnel lining structure with time is shown in figure 4 (d). It can be seen from the figure that the convergence degree of tunnel lining structure gradually increases with temperature increasing. When the fire occurs in the upper layer of the tunnel, the variation of tunnel lining convergence degree under conditions 1 and 2 shows a similar law. However, the maximum convergence degree of the tunnel without internal structure reaches 0.046 %, while that of the tunnel with internal structure is only 0.028 %, which decreases by 38.38 %. It shows that the internal structure has a significant constraint effect on the radial convergence deformation of the tunnel.

The variation of internal force of tunnel lining structure with time is shown in figure 5. It can be seen from figure 5 that the internal force changes of the lining structure of the tunnel with and without internal structure show the same law when a fire occurs in the upper layer in the tunnel. The vault
lining expands and deforms under fire, the bending moment of the vault changes from positive to negative and increases gradually. With the decrease of the temperature of the lining, the negative bending moments of vault and waist gradually decrease, and finally become positive bending moments. The axial force of tunnel vault and waist lining has always been pressure under fire. And the axial force of vault lining and waist gradually decreases with the decrease of temperature. It is found that the maximum bending moment of tunnel vault lining without internal structure is 740.4 kN · m under fire, the corresponding axial force is 5010 kN, and the eccentric distance is 0.15. The maximum bending moment of tunnel vault lining with internal structure is 697.7 kN · m, the corresponding axial force is 5401 kN, and the eccentric distance is 0.13, which is 30.1 % lower than that of the tunnel vault lining without internal structure. We can be seen that the internal structure has little effect on the bending moment of tunnel lining structure. Thus we can see that the internal structure is conducive to improving the internal force state of tunnel lining structure.

![Figure 5](image)

**Figure 5.** Internal force of tunnel lining structure: (a) Bending moment of vault lining; (b) Axial force of vault lining; (c) Bending moment of waist lining; (d) Axial force of waist lining.

### 3.3. The influence of fire location on mechanical properties of tunnel structure

It can be seen from figure 4 and figure 5 that when a fire occurs in the lower layer of the tunnel, the heat is limited in the lower rail transit space, which has little effect on the tunnel lining structure. The internal force and deformation of the tunnel lining structure have almost no change in fire. When a fire occurs in the upper layer of the tunnel, the internal force and deformation of the tunnel lining structure have obvious changes with temperature. We can be seen that the location of the fire has a significant impact on the internal force and deformation of the tunnel lining structure. When the fire occurs in the upper layer of the tunnel, the safety of the tunnel lining structure will be more challenged. It can be seen from figure 6 and figure 7 that the deformation and internal force of the top of the box culvert do not change significantly in fire when a fire occurs in the upper layer of the tunnel. When the fire occurs in the lower layer of the tunnel, a large expansion deformation occurs at the top of the box culvert, and the axial force at the top of the box has experienced a process of increasing first and then decreasing. The bending moment at the top of the box increases gradually from the negative bending moment first, then gradually decreases, and finally becomes a positive bending moment. It shows that the position of the fire has a significant impact on the internal force and deformation of the box culvert.
structure in the tunnel. When the fire occurs in the lower layer of the tunnel, the fire safety of the box culvert structure in the tunnel needs more attention than that of the tunnel lining structure.

![Figure 6. Vertical deformation of the top of the box culvert.](image)

![Figure 7. Internal force of box culvert structure: (a) Bending moment of top of the box culvert; (b) Axial force of top of the box culvert.](image)

4. Conclusion

When a fire occurs in the tunnel, the temperature of the heat conduction region of the tunnel is significantly different from that of the heat convection region in the early stage of the fire. With the fire continuing, the temperature distribution in the two regions gradually tends to be consistent. The influence of the fire on the adiabatic region is very small, and the temperature is almost constant. The internal structure of the tunnel has a significant impact on the internal force and deformation of the tunnel lining structure under elevated temperatures. The internal structure increases the stiffness of the lining structure, reduces the convergence deformation of the tunnel, improves the internal force state of the lining, and improves the fire safety of the tunnel lining structure.

The location of the fire in the tunnel has a great influence on the internal force and deformation of the tunnel structure. When the fire occurs in the upper layer of the tunnel, the internal force and deformation of the tunnel lining structure will be significantly affected by the elevated temperatures. When the fire occurs in the lower layer of the tunnel, the fire safety of the tunnel box culvert structure should be paid more attention.

5. References
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