Fire resistance characteristics of steel-concrete-steel structure and reinforced concrete structure in an eight-lane dual-directional super large-span immersed tunnel

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Abstract. In order to obtain the fire resistance of Steel-Concrete-Steel structure (SCS) and reinforced concrete structure (RC) in super-large span cross section immersed tunnel, fire numerical simulation calculation was conducted to analyze the temperature field of SCS and RC in an Eight-lane Dual-Directional immersed tunnel fire by the finite element method. Three-dimensional finite element models of steel and concrete composite structure under different tunnel fire scenarios in terms of reasonable thermal parameters, material model, and correct boundary conditions was established. On this basis, analysis for the mechanical properties of the composite steel-concrete structure under the ISO-834 standard fire was conducted. The results of the study indicate that temperature of RC slab near the fire surface is grew faster than SCS slab in the immersed tunnel fire, and the temperature inside the SCS slab is lower than that of RC slab in the immersed tunnel fire. The temperature at the nearest monitoring point by the fire surface of the SCS slab is 31.3% lower than that at the same position in the RC slab, which is 41% lower in the center of SCS slab. Research result provide a reference to the theoretical studies and practical engineering of SCS extra larger span immersed tunnel fire, and provide support for the fire protection design of SCS structures in practical engineering.

Keywords: Tunnel fire, large-span immersed tunnel, steel-concrete-steel structure, numerical simulation, characteristics of fire resistance

1. Introduction
The immersed tunnel is mainly divided into reinforced concrete immersed tunnel, single-layer steel immersed tunnel and double-layer steel reinforced concrete immersed tunnel. At present, apart from Hong Kong, the immersed tunnels built in China are all reinforced concrete structures, the most representative of which is the immersed tunnel of the Hong Kong-Zhuhai-Macao Bridge project. Although the structural type is low in cost, the design method and construction technology are relatively mature, but under the requirements of high water pressure, large section, high durability and uneven settlement, it is still necessary to focus on solving the cracking problem of the reinforced concrete structure, and there is a large limit on the limit net span of the immersed tunnel section.

The steel slab and concrete composite component originally originated in the United States. Compared with the traditional ordinary reinforced concrete technology, there are many advantages such
as high rigidity, shock resistance, vibration resistance and fatigue resistance of steel-concrete slab structure, and which is safer. The mechanical behavior of steel-concrete slab structure is more clearly, with better performance, better construction and operation, which is beneficial to shorten the construction period and achieve higher economic efficiency.

In 1976, Solomon proposed a new slab structure with concrete in a double-layer steel slab [1]. Tomlinson proposed to set up shear joints in a double-layer steel-concrete composite structure for the first time, and presented an SCS structural system using a superimposed stud connection [2, 3]. Zeng Jing (2007) of Tsinghua University analyzed the double-plate type composite structure. The research shows that the structure has the advantages of high strength, good ductility, strong impermeability and convenient construction [4]. Wei Fangfang (2012) of Hohai University carried out finite element numerical simulation on the double-steel concrete combined shear wall and proposed a simplified formula for calculating the shear capacity of the composite wall [5]. Yan Jiabao. (2016) of Tianjin University studied the ultimate strength behavior of steel-concrete-steel (SCS) composite plates under concentrated load [6].

Many researches and experiments on SCS composite structures were carried out in the UK, but they were mainly promoted in Japan. Many famous SCS structure tunnels have emerged in Japan, such as Osaka Port Sakishima Tunnel, Kobe Port Minatojima Tunnel, Osaka Port Yumeshima Tunnel and Okinawa Naha Port Tunnel. Fig. 1 illustrates the typical structure of SCS composite structure.

![Figure 1. Typical structure of SCS composite structure.](image1.png)

At present, the research on immersed tunnel fires mostly focuses on fires under the reinforced concrete structure. There are some research results in the fire in the steel immersed tunnel [7]. However, there are few studies on the fire in extra-large span eight-lane dual-directional immersed tunnel of SCS structure at home and abroad.

2. Project overview
This work is based on an immersed tunnel project of SCS structure. The tunnel is 6845 meters long, and the cross section is large-span adopting “two tunnels with one pipe gallery” design. The cross section of the whole tunnel is 46m wide and 10.6m high. The thickness of main structure slab is 1.5 m~1.7 m. Fig. 2 illustrates the cross section of the tunnel.

![Figure 2. Cross section of eight-lane dual-directional immersed tunnel(cm).](image2.png)
3. Thermal analysis model
The results of multiple researchers are comprehensively compared when selecting the thermal parameters of the material. The thermal parameters of concrete and steel are selected according to the actual design parameters [8]. The effect of water vapor in the concrete is considered when calculating the section temperature field, assuming that the mass percentage of moisture in the concrete is 5%. The specific heat calculation formula of the concrete used is as follows.

\[
\rho'_c c'_c = \begin{cases} 
0.95 \rho_c c_c + 0.55 \rho_w c_w & T \leq 100^\circ C \\
\rho_c c_c & T \geq 100^\circ C 
\end{cases}
\]

(1)

\[
\rho_w c_w = 4.2 \times 10^6 \text{ J/(m}^3\text{•C)}
\]

where \( \rho'_c \) is the mass density of concrete with considering the effect of water vapor; \( c'_c \) is the specific heat of concrete with considering the effect of water vapor; \( \rho_c \) is the mass density of core concrete without considering the effect of water vapor; \( c_c \) is the specific heat of core concrete without considering the effect of water vapor; \( \rho_w \) is the mass density of water; \( c_w \) is the specific heat of water.

4. Establishment of model
The numerical calculation model of bi-directional eight-lane immersed tunnel is established by fire calculating software. On condition that only a fire happens at the same time. Numerical simulation calculation model is established by actual size of the immersed tunnel of 1:1 along the tunnel cross section. Fig. 3 illustrates the calculation model of an Eight-lane Dual-Directional Immersed tunnel.

The grid size should be 10% of fire characteristic diameter in numerical simulation calculation. Because the area nearby the fire source is sensitive to grid density of numerical simulation, so the density of calculating grid in this area should be increased. The amount of grid in this model is 383,000. Fig. 4 illustrates the calculation model grid setting.

5. Parameters setting
Eight-node three-dimensional solid thermal analysis unit DC3D8 is used for steel plates, concrete, support plates and studs when performing finite element modeling, while DC1D2 is for reinforced steel. Temperature changes mainly consider the transfer along the cross-section of the tunnel structure. The transfer along the longitudinal direction of the tunnel is also need to be considered, but not the focus of this paper. Studs and concrete are joined to the steel plate by Tie, the same to steel and concrete. In this way, when the steel-concrete composite slab is fired, the heat can be transferred from the profiled steel to the concrete, the studs and the steel bars. It can effectively simulate the heat transfer inside the component when the actual fire occurs. The heating curve is based on the international standard heating curve ISO-834. Steel-concrete continuous composite floor surface is treated according to the third type of boundary conditions [9]. The boundary condition of fire numerical simulation calculation in immersed tunnel and other settings are depicted in Table 1.
Table 1. Boundary conditions and calculation parameters

| Specification                  | Value         | Specification        | Value                                      |
|-------------------------------|---------------|----------------------|--------------------------------------------|
| Heating curve                 | ISO-384       | Stefan-Boltzmann constant | $5.67 \times 10^{-8}$ $\text{(m}^2\text{K}^{-4})$ |
| Convection coefficient        | 25W/(m$^2$K)  | Material of immersed tunnel | SCS/RC                                    |
| The initial temperature       | 20 °C         | Width of tunnel single span | 18.3 m                                    |
| Thermal radiation coefficient | 0.5           | Height of tunnel      | 6.7 m                                      |

6. Result and analysis
Numerical simulation analysis of fire performance was carried out, include SCS immersed tunnel and RC immersed tunnel structure. Figure 5 is a schematic diagram of the arrangement of the temperature monitoring points of the tunnel top slab.

Figure 5. Layout of temperature measuring point of tunnel top slab (units: cm).

Before the numerical simulation calculation, a rectangular section reinforced concrete column model was established and calculated in order to verify the reliability of the calculation model, and compared with the test results obtained by Li [10]. Figure 6 shows the temperature versus time curve of reinforced concrete columns under fire, where $h$ is the distance from the outer surface of the reinforced concrete column to the inner center point parallel to the central axis of the short side of the rectangular section. It can be seen from the figure that the calculation results are in good agreement with the experimental results, indicating that the established model and the selected calculation method are reasonable and feasible. The temperature of each measuring point in the top slab of the RC immersed tunnel changes with time as shown in Fig. 7. The calculation results of the temperature field of the SCS immersed tunnel structure are shown in Figure 8.

Figure 6. Temperature distribution of reinforced concrete column under fire.

Figure 7. Temperature-time curves of RC immersed tunnel top slab.
Figure 8. Temperature-time curves of SCS immersed tunnel top slab.

According to the calculation results, temperature field differs greatly at individual points, which is result from the large discrete type of temperature field, and the temperature field heating trend is consistent. The temperature rise of the measuring point close to the fire surface is extremely fast, and the temperature rising speed decreases as the distance between the measuring points and the fire surface increases. At 120 min, the temperature at the measuring point 1 reached $755^\circ C$, while the temperature at the measuring point 5 was only $315^\circ C$.

It can be seen that the temperature field heating trend is basically the same as the RC structure. Due to the action of the steel plate near the fire surface, most of the heat is absorbed, resulting in a lower temperature in the concrete than in the RC structure. The temperature of RC slab near the fire surface is grew faster than SCS slab in the immersed tunnel fire, and the temperature inside the SCS slab is lower than that of RC slab in the immersed tunnel fire. The temperature at the nearest monitoring point by the fire surface of the SCS slab is 31.3% lower than that at the same position in the RC slab, which is 41% lower in the center of SCS slab.

7. Conclusions

Based on the project of Eight-lane Dual-Directional super-long span immersed tunnel, analysis of temperature field distribution of different material structures in immersed tunnel fire. Temperature field analysis of the SCS immersed tunnel and the RC immersed tunnel was carried out respectively, and the temperature field in the tunnel top slab was compared. The results are as follows:

(1) The calculation model can be used to simulate the temperature field and fire resistance of the steel-concrete composite structure under fire, and it is consistent with the test results. The established model and the calculation method adopted are reasonable and feasible;

(2) For SCS immersed tunnel structure, the temperature in the concrete is lower than that in the RC structure, due to the action of the steel slab near the fire surface, most of the heat is absorbed.

(3) The temperature at the nearest monitoring point by the fire surface of the SCS slab is 31.3% lower than that at the same position in the RC slab, which is 41% lower in the center of SCS slab.

8. References

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