Hydration Heat Analysis and Temperature Control on Steel Shell Concrete Immersed Tube during Precasting

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Abstract: In order to support the high-precision and high-quality prefabrication of steel shell concrete immersed tube for Shenzhen-Zhongshan Bridge, this paper analyzes the influence of temperature field produced by concrete hydration heat on the deformation and local stress of steel shell concrete immersed tube considering the influence of strength time-varying, autogenous shrinkage and creep of concrete and casting technology. Then, this paper puts forward the temperature control index of concrete molding based on the control requirements deformation and local stress of immersed tube. The results show that: the hydration heat of concrete is beneficial to the deformation control of steel shell concrete immersed tube, and it has little influence on the final deformation, the molding temperature of concrete should be controlled below 3°C of the ambient temperature to prevent the cracking of steel concrete interface of immersed tube. The research results of this paper have been applied to the control of concrete casting process of steel shell concrete immersed tube for Shenzhen-Zhongshan Bridge, which can make up for the domestic research blank and provide technical reference for similar projects.

1. Introduction
The reinforced concrete immersed tube has been extensively applied to river-crossing and sea-crossing traffic infrastructure construction engineering with the global scope [1-2], while the project cases of steel shell concrete immersed tube are relatively few. This type of tube is widely applied in Japan, but there are just six steel shell concrete immersed tube tunnels [3-4]. In China, the steel shell concrete composite structure has been initially applied to the final connection segment of immersed tube tunnel along the Hong Kong-Zhuhai-Macao Bridge, but the volume is small, and Shenzhen-Zhongshan Bridge is the first application project of steel shell concrete immersed tube in real sense in China.

The crack control in the prefabrication process is one of the construction difficulties of reinforced concrete immersed tube, and directly related to the long-term serviceability of structures. The studies carried out by domestic (Chinese) and foreign scholars show that the factors leading to the cracking of concrete immersed tube mainly include concrete mix proportion, hydration heat, concrete molding
temperature, concrete pouring process, curing process, dismantling time, etc. [5-6]. One of the key reasons for the cracking of concrete immersed tube is the secondary temperature stress generated by the temperature field, which is formed by the concrete hydration heat under the structural self-weight or external constraint. In comparison with reinforced concrete immersed tube, the steel shell concrete immersed tube has low crack control requirement for concrete, but high prefabrication accuracy control requirements, and it has a direct bearing on the sequential installation of immersed tube. At present, the prefabrication processes of steel shell concrete immersed tubes have been rarely investigated in China, not to mention the stress and deformation of immersed tubes generated under the joint action of concrete temperature and gravity, etc. during the concrete pouring process, and the relevant control technologies of tube section prefabrication quality remain unknown.

The concrete filled steel tube composite structure has avoided the shortcomings of steel structure and concrete structure and given full play to their advantages, thus reaching a “win-win” effect. The constraint formed by steel plates to concrete can prevent the concrete tensile cracking, and the favorable compressive performance of concrete is capable of preventing the instability of steel plates in the compression zone [7-8]. In the steel shell-concrete composite structure, the bond quality problem [9] between steel shell and concrete directly affects the mechanical properties and failure modes of this steel shell-concrete composite structure. During the practical construction process, the poor bond quality between steel shell and concrete will result in the disengagement of steel shell-concrete contact surface, thus affecting the construction quality and structural bearing capacity. The mechanical properties of steel shell-concrete interface during the prefabrication process of steel shell concrete immersed tube have been less probed, and the local stress conditions of immersed tube are also unknown.

Under the engineering background of Shenzhen-Zhongshan Bridge immersed tube tunnel, the influence laws of temperature field generated by the concrete hydration heat on the deformation and local stress conditions of steel shell concrete immersed tube were analyzed in consideration of influences of time-varying characteristic of concrete strength, concrete self-constriction and tube section pouring process. Based on the control requirements for the deformation and local stress condition of immersed tubes, the concrete molding temperature control index was proposed to support the high-precision and high-quality prefabrication of immersed tubes in Shenzhen-Zhongshan Bridge.

2. Project Profile

Shenzhen-Zhongshan Bridge is of two-way eight-lane design with the speed per hour of 100 km and full length of 6,845 m, where the length of immersed tube section, which is composed of 32 tube sections and one final joint, is 5,035 m. The steel shell concrete composite structure is adopted in the immersed tube tunnel, and the steel shell structure mainly consists of inner and outer panels, transverse and longitudinal diaphragms, transverse and longitudinal stiffening ribs and welding studs. The inner and outer panels in the main structure are made of Q420C and Q390C, transverse diaphragm is made of Q390C, and others are made of Q345B or Q390C. The E1 tube section of steel shell concrete composite immersed tube is 123.5 m in length, 46 m in width and 10.6 m in height, and the thickness of both roof and floor is 1.5 m.
A single standard tube section of steel shell concrete immersed tube in Shenzhen-Zhongshan Bridge is composed of 2,257 sealed chambers as shown in Figure 2. The self-compacting concrete filling is adopted to form an overall structure. Following the pouring principles of “symmetry and balance”, a blanking pipe is used for the concrete blanking, the blanking hole is placed at middle of chamber with an outer diameter of 273 mm, and PVC tube with the inner diameter of 275 mm is used to case the blanking hole. Vent holes are arranged at the edge of chamber, with outer diameters of 48 mm and 89 mm, organic glass tubes are used as the vent pipes with inner diameters of 50 mm and 90 mm, and the gas is vented via the vent pipes. Studies have shown that the vent holes arranged can improve the self-compacting concrete pouring quality. During the pouring process, the height from the blanking port to the liquid level is not greater than 500 mm, the pouring speed is not higher than 30 m³/h in the earlier phase, and then not greater than 15 m³/h after the concrete liquid level is 20 cm away from the roof, and after the height of concrete liquid level in all vent pipes in the chamber reaches 30 cm, the concrete pouring in the chamber is thus finished.

The concrete pouring of steel shell concrete immersed tube in Shenzhen-Zhongshan Bridge is implemented using intelligent pouring machine as seen in Figure 3. The intelligent pouring machine integrates the functions of automatic/manual walking, self-localization and automatic hole seeking, and a liquid level detection unit is equipped to conduct the real-time monitoring of concrete liquid level. During the pouring process, the pouring speed and flow quantity are automatically regulated according to the concrete liquid level fed back, the terminal tube is elevated timely to ensure that the falling height of concrete does not exceed 500 mm, and the concrete pouring is automatically stopped when the concrete liquid level reaches the elevation, thus realizing the automation of chamber concrete pouring in the intermediate corridor.
3. Influence Analysis of Temperature Field on Overall Immersed Tube Deformation

The hydration heat-induced deformation is nonnegligible in the large-volume concrete pouring in this project. If the final residual deformation is too large, it will be difficult to realize the splicing of tube sections or satisfy the normal operating requirements. The roof deformation of immersed tube is relatively difficult to control, so the roof deformation will be mainly analyzed in this study.

The influence laws of concrete hydration heat-induced temperature field on the deformation of immersed tube are explored through the simulation calculation. In the simulation calculation model, the solid elements are used for the concrete and plate elements for steel shell, and the structural parameters of concrete are as follows: Elasticity modulus is 35 GPa and volume weight is 2,500 kg/m³; temperature characteristics of rolled steel and concrete: The specific heat capacity and heat conductivity coefficient of concrete are taken as 0.973 kJ/(kg·°C), respectively, and those of rolled steel are 0.46 kJ/(kg·°C) and 180 kJ/(m·h·°C), respectively. The model loads are mainly self-weight and concrete hydration heat, and the boundary condition is to constrain the vertical displacement at the floor support position.

The acquisition of reasonable temperature field is a key to the concrete hydration heat analysis. Two chambers were selected on the field, their concrete core temperatures were tested, and the test results showed that the calculated temperature field accorded with the measured temperature field as seen in Figure 4.

![Figure 4 Comparison Chart of Calculated Temperature Field and Measured Temperature Field](image)

The deformation difference of immersed tubes under the independent action of self-weight and joint action of self-weight and concrete hydration heat was analyzed. Figure 5a) is the immersed tube deformation diagram under the action of self-weight, and the maximum roof deformation was 4.5 mm. The immersed tube deformation diagram under the joint action of self-weight and hydration heat is presented in Figure 5b), the maximum roof deformation was 4.2 mm, meaning that the concrete hydration heat mitigated the roof deformation of immersed tubes to some extent, because when the temperature rose, the concrete experienced volume expansion and extrusion, which, to a certain extent, applied precompression to the roof, but the temperature had a minor influence on the final deformation of immersed tubes.
In order to acquire the temperature control indexes during the immersed tube prefabrication process, the influence of concrete molding temperature on the tube section deformation will be hereby analyzed. Four molding temperatures—20°C, 22°C, 24°C and 26°C—were chosen, and the corresponding temperature change curves of chambers are shown in Figure 6.

Figure 7 shows the deformation diagram of the top plate under the action of the temperature field alone after the concrete hydration heat temperature is completely cooled. The temperature field reduces the final state deformation of the immersed pipe roof, but increases the deformation non-uniformity correspondingly. The influence of four molding temperatures on the final deformation of the pipe joint is very small, and the order of magnitude is about 0.1 mm.

To sum up, the temperature field formed by concrete hydration heat reduced the overall deformation in the immersed tube prefabrication process, and contributed to the deformation control of tube section to a certain degree, but the influence degree was low, and the tube section deformation bore little influence from the molding temperature. Therefore, the concrete temperature field generated a minor influence on the overall deformation of tube section.

4. Influence Analysis of Temperature Field on Local Stress Conditions of Immersed Tube

4.1. The chamber poured and chambers around not poured
When the chamber was poured while the chambers around were not (Figure 8), after the complete cooling of concrete hydration heat-induced temperature field, the concrete force of the chamber is displayed in Figure 9.

It could be known from Figure 9 that due to the constraint action of steel shell, the secondary temperature stress existed at the junction between steel shell and concrete. The bond quality between steel shell and concrete directly influenced the mechanical characteristics of steel shell concrete composite structure, and the secondary temperature stress gave rise to the cracking risk of steel shell and concrete.

Hereby the influence laws of concrete molding temperature on local stress conditions of the chamber will be analyzed. The variation diagram of secondary concrete temperature stress with the concrete molding temperature at ambient temperature of 25°C is shown in Figure 10.

As shown in Figure 10, the secondary concrete temperature stress at the steel shell-concrete contact part presented a linear growth trend with the molding temperature, and it was controlled according to the tensile stress of 2.64 MPa permitted by C50 concrete specification. At the ambient temperature of 25°C and molding temperature of <24°C, no cracking phenomenon would take place at the steel shell-concrete contact part, and about 25 MPa of secondary temperature stress was generated to the steel shell.

The variation diagrams of secondary concrete temperature stress with the concrete molding temperature at ambient temperature of 28°C and 30°C are shown in Figure 11, respectively. From Figure 10, at ambient temperature of 28°C and molding temperature of <27°C, no cracking would take place at the steel shell-concrete contact part. It could be observed from Figure 11 that the cracking would not happen, either, at ambient temperature of 30°C and molding temperature of <29°C.
To sum up, when the chamber was poured while the chambers around were not, due to the constraint action of steel shell, the temperature field led to the secondary temperature stress at the junction between steel shell and concrete. Under the condition of concrete molding temperature ≤ ambient temperature-1 °C, cracking would not occur at the steel shell-concrete contact part. Under the condition of concrete molding temperature > ambient temperature-1 °C, the cracking risk existed at the steel shell-concrete contact part, which was not good for the overall mechanical characteristics of steel shell concrete composite structure.

4.2. The chamber poured and chambers at two sides poured
When the chamber was poured and those at two sides were also poured (Figure 12), after the complete cooling of concrete hydration heat-induced temperature field, the concrete force of the chamber is displayed in Figure 13.

Figure 12 Model of the Chamber Poured with Chambers at Both Sides Poured

Figure 13 Principal Tensile Stress Diagram of Concrete in the Chamber

As shown in Figure 13, due to the constraint action of steel shell and already poured chambers, the secondary temperature stress existed at the junction between steel shell and concrete, especially, the stress on the junction surface between steel shell and concrete at the side of already poured chambers was relatively large, which was ascribed to the already poured chambers.

Figure 14 Variation Diagram of Secondary Concrete Temperature Stress with Molding Temperature (Ambient Temperature: 25 °C)

Figure 14 is the variation diagram of secondary concrete temperature stress with concrete molding temperature at ambient temperature of 25 °C. It could be seen that the secondary concrete temperature stress at the steel shell-concrete contact part showed a linear growth trend with the molding temperature. No cracking would occur at the steel shell-concrete contact part at ambient temperature of 25 °C and molding temperature of <22 °C (ambient temperature-3 °C).
4.3. The chamber poured and chambers around poured
When the chamber was poured and those around were also poured (Figure 15), after the temperature field induced by the concrete hydration heat was completely cooled, the local stress conditions of concrete in the chamber are presented in Figure 16.

![Figure 15 Model Graph of the Chamber Poured and Chambers Around Poured](image1)

![Figure 16 Principal Tensile Stress Diagram of Concrete in the Chamber](image2)

As shown in Figure 16, because of the constraint action of steel shell and already poured chambers, the secondary temperature stress existed at the junction between steel shell and concrete, and the stress on the junction surface between steel shell around the chamber and concrete was relatively large, which might be attributed to the already poured chambers. The tensile stress of concrete on the contact surface between steel shell and concrete was 2.64 MPa, and at the time, the ambient temperature and concrete molding temperature were 25℃ and 22℃, respectively.

In conclusion, after the concrete hydration heat-induced temperature field was completely cooled during the concrete pouring of the chamber, the temperature field generated the secondary temperature stress at the junction between steel shell and concrete due to the constraint action of steel shell. Under the condition of concrete molding temperature ≤ ambient temperature-3℃, the cracking would not occur at the steel shell-concrete contact part. But when concrete molding temperature > ambient temperature-3℃, the cracking risk appeared at the steel shell-concrete contact part, which would go against the overall mechanical characteristics of steel shell concrete composite structure. Therefore, when the cracking risk at the steel shell-concrete contact part was taken as the control objective, the concrete molding temperature should be controlled at over 3℃ lower than the ambient temperature.

5. Conclusions and Suggestions
in consideration of influences of time-varying characteristic of concrete strength, concrete self-constriction, creep deformation and tube section pouring process, the influence laws of concrete hydration heat-generated temperature field on the deformation and local stress conditions of steel shell concrete immersed tube were analyzed. Based on the control requirements for the deformation and local stress conditions of immersed tube, the concrete molding temperature control index was put forward.

1) The concrete hydration heat-induced temperature field reduces the overall vertical deformation of roof in the immersed tube construction process and final state, and it contributes to the deformation control of tube section to some extent, but the influence is minor. Moreover, the tube section deformation is influenced by the molding temperature to the minimum extent, and the concrete temperature field has a minor influence on the overall deformation of tube section.

2) Due to the constraint action of steel shell, the secondary temperature stress is generated at the junction between steel shell and concrete. When the cracking risk at the steel shell-concrete contact part is taken as the control objective, the concrete molding temperature should be controlled at over 3℃ below the ambient temperature.

3) The influence laws of concrete hydration heat-generated temperature field on the deformation and local stress conditions of steel shell concrete immersed tube are analyzed to support the selection
of concrete molding temperature for the steel shell concrete immersed tube in Shenzhen-Zhongshan Bridge and realize the high-precision and high-quality immersed tube prefabrication.

Acknowledgment
All the authors gratefully acknowledge the support of Guangzhou Pearl River science and Technology Star special fund (No. 201806010162) and Special funding for national key R & D programs (No. 2017YFC0805303) of China.

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