Numerical simulation of temperature field of CRTS III ballastless track with Tarmac in Harbin area

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Abstract. The three-dimensional transient thermal analysis technology of ABAQUS is used to analyze the temperature field and temperature stress characteristics of CRTS Ⅲ ballastless track with thin layer of asphalt concrete under the typical climatic conditions of summer and winter in seasonal freezing area due to the influence of heat transfer such as solar radiation, wind speed and temperature amplitude. The results show that the temperature distribution of track structure is nonlinear along the vertical direction, and there is a lag phenomenon; After adding asphalt concrete layer, the temperature of Subgrade under the layer is reduced, which has a good heat insulation effect; Asphalt concrete layer is more prone to interlayer damage in winter than in summer.

Keywords: Ballastless track, Temperature field, Damage tendency.

1. Introduction

In recent years, CRTS III ballastless track developed independently has gradually replaced the structure of the first two generations and assumed the burden of China's high-speed railway construction. CRTS III ballastless track board generates a cyclic temperature field guided by time and external environment change during the service period with the seasonal change of ambient temperature and the rise and fall of day and night, and then produces the corresponding temperature stress. When the temperature stress reaches the structural design strength, the structure will warp or crack, which will weaken the mechanical properties of ballastless track and shorten its service life[1,2]. More than half of China's land is seasonally frozen, mainly in northern China. Its climate is characterized by hot and hot summer, cold and cold winter, and large temperature difference between morning and evening. Asphalt concrete is a poor conductor of heat, and its mechanical properties (viscoelasticity) are greatly affected by temperature. If the distribution characteristics and evolution law of temperature field of ballastless track in seasonal freezing region can be accurately analyzed, it can provide effective theoretical support for rational design and stable operation of CRTS III ballastless track structure with asphalt concrete sealing layer in seasonal freezing region.

The application of asphalt concrete in China's railway started slowly. At first, it was only applied to both sides and between the main lines of newly-built passenger dedicated lines, such as The Suiyu Line and the Beijing-Tianjin intercity line[3]. Based on foreign experience, the asphalt concrete test section of Xu-Zheng high-speed railway was laid. At present, Ou Zumin [4] used meteorological data to describe the thermal boundary conditions of the environment where the orbit is located, and analyzed the effects of solar radiation, wind speed and temperature amplitude on the temperature distribution inside the orbit structure. Liu Fushan[5] constructed a three-dimensional finite element analysis model based on the basic theory of meteorology, so as to analyze the temperature field of continuous ballastless track structure. Liu Weibin[6] obtained the temperature gradient characteristics of composite track plate through statistical analysis of measured data, and estimated the reasonable temperature gradient value of composite track structure in different areas. Yang Rongshan [7] conducted long-term temperature monitoring of double-block ballastless track bed plate and supporting layer in the test site, explored the vertical temperature evolution of double-block track structure, and laid a test foundation for the study of temperature stress and deformation. The above mentioned research results have significantly improved the cognition of temperature deformation mechanism of track structure, but the scientific research results of temperature field of CRTS III ballastless track with asphalt concrete layer in seasonal freezing region are still in the precipitation

stage. Based on heat transfer theory and ABAQUS three-dimensional transient thermal analysis technology, this paper studies the temperature field characteristics and damage occurrence trend of CRTS III ballastless track with asphalt concrete layer in seasonal freezing region.

2. Ballastless track interlayer temperature action basis

2.1. Basic equation of heat conduction of ballastless track

Ballastless track structure studied in this paper is a layered longitudinal continuous structure composed of track plate, self-compacting concrete, base plate and asphalt concrete layer from top to bottom. Since the longitudinal plane area of the rail structure is much larger than the area of air contact on the vertical sides of the structure, only the vertical influence on the thermal transfer of the structure is considered in the study. Therefore, the two-dimensional heat transfer in air and concrete is reduced to the one-dimensional heat transfer of the structure. According to the solid heat transfer mechanism, when analyzing the temperature field distribution of ballastless track plate, it is usually assumed that the temperature conductivity coefficient of the i layer is a_i, heat transfer coefficient is λ_i, Layer thickness is $h_i(h_n = \infty)$, The temperature function is $T_i(x,t)$, Then it should satisfy the one-dimensional heat conduction equation[8]:

$$\frac{\partial T_i}{\partial t} = a_i\left(\frac{\partial^2 T_i}{\partial x^2}\right) \quad (i = 1,2,\cdots,n) \tag{1}$$

Among them: t is the time variable; $\frac{\partial T(z,t)}{\partial t}$ is the temperature at depth Z of the orbital structure changes with time at time t;

The heat transfer problem of CRTS III ballastless track structure can be regarded as one-dimensional heat transfer in homogeneous semi-infinite space because the temperature conductivity coefficient of concrete materials in each layer is very close. The boundary condition of homogeneous semi-infinite space structure is the key to solve the equation. If the surface temperature of the structure is known, it is the first type of boundary condition. If the heat flow velocity is known, it is the boundary condition of the second kind. If only the surface temperature of the structure is known as a function of periodic change, it is the third boundary condition. The simulation in this paper applies to the first type of thermal boundary conditions.

2.2. Factors affecting heat conduction of ballastless track

According to the basic principle of heat transfer, the surface heat transfer of ballastless track structure exposed to natural environment is realized through thermal radiation, heat conduction and thermal convection, which is also related to the geometric characteristics and material characteristics of track structure [9]. Thermal radiation is the most heat source of the track structure. With the periodic change of solar radiation, the temperature distribution inside and outside the ballastless track structure also presents a trend of periodic evolution. The solar radiation received by the surface layer of ballastless track structure is affected by solar altitude Angle, day and night duration, weather conditions, solar radiation absorption rate of structural layer and other factors [10]. The variation of solar radiation intensity over time can approximately follow the sine or cosine distribution, and Fourier series expansion is adopted [4], which can be specified as follows:

$$I(t) = \begin{cases} \frac{I_0}{\pi} + \frac{I_0}{2}\sin\frac{\pi(t-6)}{12} + \frac{2I_0}{\pi}\sum_{k=1}^{\infty}\frac{1}{1-(2k)^2}\sin\left(\frac{k\pi(t-6)}{6} + \frac{\pi}{2}\right) & m = 1 \\ \frac{I_0}{m\pi} + \frac{2mI_0}{\pi}\sum_{k=1}^{\infty}\frac{\cos\frac{k\pi}{2m}}{m^2-k^2}\sin\left(\frac{k\pi(t-6)}{12} + \frac{\pi}{2} - \frac{k\pi}{2}\right) & m \neq 1 \end{cases} \tag{2}$$

Among them: $I_0 = 1.31mI_d$, I_d is the total daily solar radiation ,W/m^2; $m = 12/t_{\mathrm{d}}$, is the proportion coefficient of sunshine time. t_{d} is the sunshine duration in one day.

Two sine waves can be used to simulate the diurnal variation of air temperature, and the air temperature at a certain time on a certain day can be expressed as：

$$T_{\text{air}}(t) = \bar{T}_{\text{air}} + \tilde{T}_{\text{air}} \times [0.9\sin\ \omega(t - t_0 - 6) + 0.14\sin\ 2\omega(t - t_0 - 6)] \tag{3}$$

Among them: $T_{\text{air}}(t)$ is the daily temperature amplitude ,℃； t_0 is the difference between the maximum solar radiation (12:00 noon solar time) and the maximum temperature in a day plus one； t is the time； $\omega$is the angular frequency,ω=π/12 ,rad/s.

Part of the solar radiation on the surface of the orbital plate is reflected, and the other part is absorbed by the plate and enters the orbital structure. Effective radiation is the radiation difference between these two parts, and the heat flux acting on the surface of ballastless track plate [11] is

$$q_{\text{r}}(t) = h_{\text{r}}[T_{\text{air}}(t) - T(t,0)] \tag{4}$$

$$h_{\text{r}} = \varepsilon[4.8 + 0.75(\bar{T}_{\text{air}} - 5) \tag{5}$$

Among them: q_{r} is the heat flux produced by effective radiation ,W/m^2 ； h_{r} is Coefficient of long-wave thermal radiation ,W/(m^2·℃)； ε is blackness coefficient of concrete, 0.9； T_{air} is daily mean temperature,℃； $T(t,0)$is Surface temperature of track plate.

The convective heat exchange between track surface and air is affected by environmental temperature, structure surface temperature, wind speed V and other factors, and the heat exchange coefficient is:

$$a_{cv} = \begin{cases} 4v + 6 & v \leqslant 5\text{m/s} \\ 7.41v^{0.78} & v > 5\text{m/s} \end{cases} \tag{6}$$

2.3. Model establishment and calculation parameters

Based on the heat transfer principle of CRTS III track plate mentioned above, ABAQUS software is used to establish the three-dimensional transient heat transfer model of CRTS III ballast track with asphalt concrete sealing layer, as shown in Figure 1. Material parameters are shown in Table1:

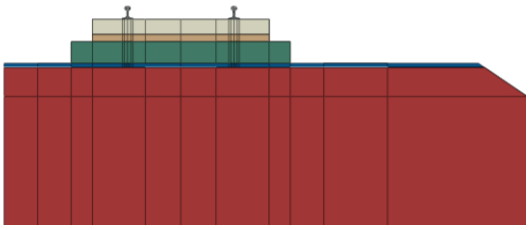


Figure 1. Structure of CRTS III Ballastless track.

Table 1. Structural material parameters of ballastless track.

Parts	Modulus of elasticity/MPa	Poisson's ratio	Specific heat capacity / [J/(kg·℃)]	Coefficient of thermal conductivity [J·/(m·k)]
Track plate	3.6×10^4	0.2	950	5616
Self compacting concrete	3.25×10^4	0.2	950	5616
The base plate	3.25×10^4	0.2	950	5616
Bituminous concrete	—	0.25	925	4680
The bed surface	150	0.3	900	5600

DC3D8 unit was used for temperature field analysis and C3D8 unit was used for temperature stress analysis, with a total of 71479 units. Each component is simulated by solid element, and binding constraint is used between track plate and self-compacting concrete layer. The Cohesive Zone Model (CZM) is used to simulate the complex interaction between asphalt concrete layer and supporting layer. The bottom surface of the base bed is fully constrained, while the two ends of the asphalt concrete layer and the base bed are longitudinally symmetric constrained.

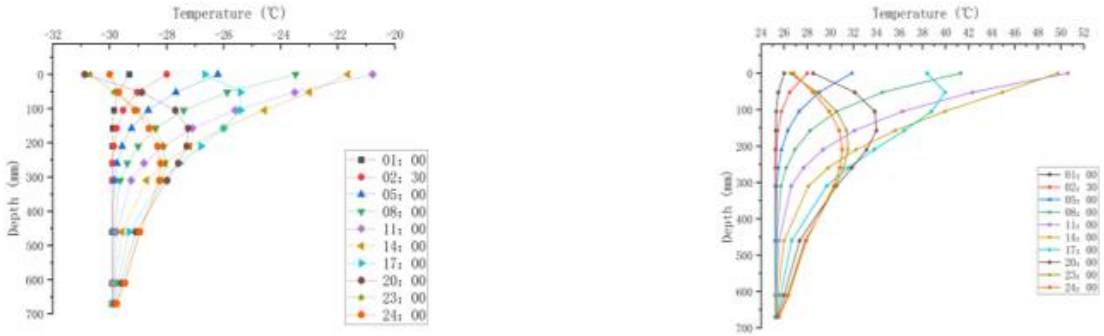
All manuscripts must be in English, also the table and figure texts, otherwise we cannot publish your paper. Please keep a second copy of your manuscript in your office. When receiving the paper, we assume that the corresponding authors grant us the copyright to use the paper for the book or journal in question. Should authors use tables or figures from other Publications, they must ask the corresponding publishers to grant them the right to publish this material in their paper.

3. Simulation results

In order to reduce the influence of the overall boundary effect of the structure, the length of four rail plates was selected longitudinally, and the data of the second and third plates were read in the temperature field. The temperature field and damage trend of the structure under the coupling effect of solar radiation, air temperature and air convection under extreme weather conditions in winter and summer are calculated. The selected meteorological conditions in this paper are Harbin's winter day on January 24, 2018, and summer day on June 2, 2018.

3.1. Vertical distribution of structure temperature

Read the temperature values at different depths below at the center of the track plate within 24 hours of the model, and draw the depth-temperature distribution curve, as shown in Figure 2:



1) January 24, 2018 2) June 2, 2018

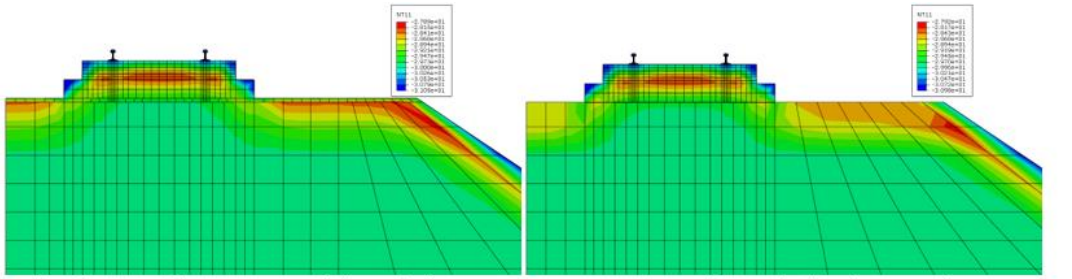
Figure 2. Temperature distribution of orbit structure with depth at different time.

It can be seen from Figure 2 that within 24 hours, the temperature of the track structure presents a nonlinear distribution along the depth direction. With the increase of depth, the slope of the curve increases, that is, the slope of temperature change decreases gradually. Temperature changes at different depths form an envelope, which presents an inverted cone and eventually tends to the same point. The temperature of the upper part of the orbit structure varies greatly, and the temperature difference at different time can even reach tens of degrees Celsius. With the increasing of the depth, the temperature variation range gradually decreases, and the temperature variation of the track plate and asphalt concrete layer at the bottom of the structure is very small, keeping within 5℃. The temperature gradient of the contact position of each structural layer has a sudden change, and the temperature gradient of the track structure can be considered linearly after approximately stratification. In the whole day, the temperature range is mainly concentrated in 0-0.3m depth, that is, the temperature gradient at the location of track plate and self-compacting concrete layer changes greatly. In both winter and summer conditions, the temperature of the track structure is negative after 17:00, and positive at the rest of the time. The maximum positive temperature gradient appeared from 11 to 14, and the maximum negative temperature gradient appeared at about 20, which was basically

consistent with the occurrence time of the highest and lowest temperature on the top surface of the track plate. However, the temperature gradient of the base plate is almost unchanged, and the whole day shows a positive temperature gradient, indicating that the temperature distribution of the base plate layer and below is less affected by the external environment.

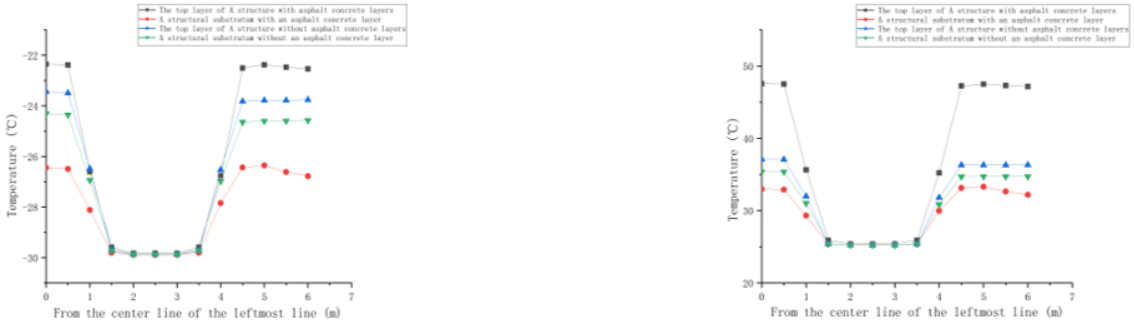
3.2. Comparison of temperature distribution between asphalt concrete layer and asphalt concrete layer

The overall temperature cloud diagram of ballastless track with or without asphalt concrete layer is shown in Figure 3. After the addition of asphalt concrete layer, the temperature on the upper and lower surfaces of asphalt concrete layer and the upper and lower surfaces of equal thickness embankment gravel layer without asphalt concrete layer is distributed along the transverse direction, as shown in Figure 4.



1)Ballastless track structure with asphalt concrete 2) Ordinary ballastless track structure

Figure 3. Temperature distribution of orbit structure with depth at different time.



1)Transverse temperature distribution on January 24 2) Transverse temperature distribution on June 2

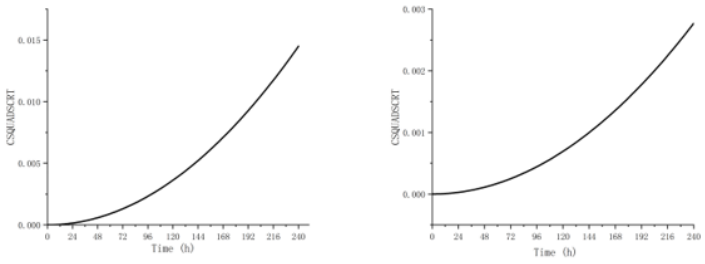
Figure 4. Transverse temperature distribution with and without asphalt concrete layer.

It can be seen from Figure 4 that the addition of asphalt concrete layer has no influence on the transverse distribution of structure temperature field, and the curve is still concave. However, the temperature difference between the exposed part under the line and the exposed part of the kerb line increases significantly, and the temperature at the bottom of the asphalt concrete layer decreases significantly due to its excellent heat insulation effect. Because the superstructure of the asphalt concrete layer at the lower edge of the rail has only the base plate, the temperature at the outer edge is higher than the temperature at the center of the unexposed rail, and the temperature response is intense within 45cm on both sides of the base plate. Because during the use period of more than 50℃, the commonly used asphalt concrete is easy to cause permanent irreversible deformation under a certain degree of load [12]. Therefore, in the design of ballastless track structural materials, it is advisable to set the high temperature design temperature as the median temperature in the area with strong response. In view of engineering practice, technical measures should be taken to reduce the temperature sensitivity of asphalt concrete, and then reduce the deformation damage.

3.3. Trend of interlayer damage

Because the asphalt concrete material itself has the viscoelastic characteristics, so in the simulation of the contact relationship between the asphalt concrete and the upper layer of the bond is chosen. In

this paper, CZM is used to simulate the complex interaction between asphalt concrete layer and supporting layer, and the initiation of cohesive unit damage is judged according to the quadratic nominal stress criterion. When the simulation results CSQUADSCRT value reaches 1, the interfacial stress reaches the ultimate strength and stiffness degradation begins to appear, which is considered as damage occurs. The damage degree is represented by the damage factor (CSDMG). The value 0 means that the interface has no damage. When the value reaches 0.8-1, it can be considered that the interface element has been completely damaged and the interlayer bonding contact is no longer. In order to better display the damage trend, the temperature was repeatedly added 10 times for two days, and the CSQUADSCRT value at the expansion joint between the two layers was read for 240 hours, as shown in Figure 5:



1)Time variation of injury factors on January 24 2) Time variation of injury factors on June 2

Figure 5. Time-varying curves of damage factors

After 240h temperature loading field, there was no stiffness degradation in the two working conditions, that is, the interlayer contact still maintained bond contact, and no damage occurred. However, the damage trend of the expansion joint between asphalt concrete layer and base plate layer increases gradually with the increase of the number of cycles, and the rising rate is increasing. It can be seen that with the increase of service time, asphalt concrete layer will be more prone to crack failure. In addition, the numerical comparison shows that the damage parameters in winter condition are larger than those in summer condition, that is, asphalt concrete layer is more prone to damage and cracking in winter service.

4. conclusion

In this paper, the vertical distribution characteristics of temperature field of CRTS III ballastless track structure with asphalt concrete layer are analyzed by using ABAQUS software based on the meteorological data in winter and summer in typical seasonal freezing area of Harbin. The influence of asphalt concrete on temperature field of ballastless track structure and the damage trend under temperature stress are evaluated. The conclusions are as follows:

(1) The temperature of the track structure presents nonlinear distribution along the vertical direction, and there is hysteresis phenomenon. The vertical temperature variation is mainly concentrated in the range of 0-0.3m, that is, the depth of track plate and self-compacting concrete. The diurnal variation of the vertical temperature of the other parts is generally maintained at about 5℃.

(2) After the addition of asphalt concrete layer, the temperature of subgrade below the layer is reduced by 3-5℃, which has a good heat insulation effect.

(3) The damage trend of asphalt concrete layer increases with the service time, and interlayer damage is more likely to occur in winter than in summer.

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