Temperature Features of CRTSII Slab Ballastless Track in Severe Cold Region

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ABSTRACT: Damages, such as slab end warped, gaps of slab and bed, and cracks of track bed, of CRTSII Slab-Ballastless-Track (SBT) in high speed railway were studied for temperature changing significantly in severe cold regions. First, Contact-Thermal-Resistance (CTR) between Concrete-Asphalt (CA) mortars of the SBT and roadbed were defined. Then, the first, second and fourth types of heat transfer boundary conditions’ subprograms of SBT changing with environment were programmed, and temperature fields of SBT under extreme weathers conditions in severe cold regions were received. Then, on couple thermal mechanical analysis platform of ABAQUS, the temperature fields are imported into mechanical model of SBT to obtain temperature stresses, slab end warped, and displacements, so that provide a reference for the design and application of CRTSII SBT in severe cold region.

INTRODUCTION

CRTSII SBT including concrete track slab, CA mortar layer, and concrete track bed, as a longitudinal continuous structure as figure 1. It is affected greatly by environments changing. Damages, such as slab end warped, gaps, freeze-thaw, and bed cracks, are caused by temperature stresses in the severe cold region (WANG Jijun 2010, OU Zu-min 2014, 2015, LIU Yu 2013, 2014, ZHAO Lei 2014). Spatial and temporal distribution characters of CRTSII SBT temperature fields on theories of heat transfer, numerical simulation, indoor and field tests were studied by many experts (ZHAO Dongtian 2008, X. Chapeleau 2013, Lu Sun 2013, Ping Wang 2014, Jing Liu 2015). On coupled thermal mechanical analysis under extreme weather conditions in the severe cold region, the temperature fields and stresses end warped and gaps of CRTSII STB were received and that provided references for application of this SBT.
CRTSII SBT TEMPERATURE FEATURES

Equation Heat Transfer of CRTSII SBT Temperature Fields

As Figure 1, CRTSII SBT has three layers: the first is track slab with length of 6.45m, width of 2.55m, thickness of 0.2m; the second is CA mortar with thickness of 0.03m; the third is continuous concrete track bed with width of 3.0m, thickness of 0.3m. The temperature fields of the SBT are analyzed as figure 2:

A cross section is selected as figure 2, the $i$ layer’s conductive coefficient of temperature is $a_i$, conductive coefficient of thermal is $\lambda_i$, the thickness is $h_i$, the temperature function is $T_i(x,t)$, and it should meet the heat transfer equation:

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

Figure 1. Damages of CRTSII SBT.

Figure 2. Temperature features of CRTSII.
CTR of CA mortar between slab and bed meets the third type of heat transfer boundary condition before the gap appearing, and the fourth type as gaps appearing.

\[
\begin{align*}
\lambda_1 \frac{\partial T_1}{\partial x} &= \frac{1}{R_e} \left( T_{2b} - T_{2A} \right) \\
\lambda_1 \frac{\partial T_1}{\partial x} &= \lambda_2 \frac{\partial T_2}{\partial x}
\end{align*}
\]

(2)

\(T_{2A}\) = temperature at the bottom of slab; \\
\(T_{2B}\) = temperature at the top of bed.

\[
\frac{\partial T_1}{\partial x} = \frac{T_{2A} - T_{2B}}{L_\varphi / 2\lambda_1 A_e + L_\varphi / 2\lambda_2 A_c} + \lambda_f A_c \frac{T_{2A} - T_{2B}}{L_\varphi / R_e} 
\]

(3)

\[
h_e = \frac{1}{L_\varphi} \left( \frac{A_e}{A_e + \lambda_f A_c} + \frac{A_e}{\lambda_1 + \lambda_2} \right) 
\]

(4)

\[
R_e = \frac{1}{h_c A}
\]

(5)

\(L_\varphi\) = thickness of CA mortar layer; \\
\(A_e\) = contact area of CA mortar with track slab; \\
\(A_c\) = gap area of CA mortar with track slab; \\
\(A\) = bottom area of track slab; \\
\(\lambda_f\) = air thermal conductive coefficient; \\
h_c = contact coefficient of track slab with CA mortar; \\
The solution must meet the boundary conditions, as following:

\[
|T_1(x, t)| \leq M \quad (x \to \infty)
\]

(6)

M is a finite constant value.

**Boundary Conditions of Temperature Field**

**Solar Radiation**

Solar radiation can be approximately described as periodical change in function:

\[
q(t) = \begin{cases} 
0 & \text{if } 0 \leq t < 12 - \frac{C}{2} \\
q_0 \cos \omega(t - 12) & \text{if } 12 - \frac{C}{2} \leq t \leq 12 + \frac{C}{2} \\
0 & \text{if } 12 + \frac{C}{2} < t \leq 24
\end{cases}
\]

(7)

\(q_0\) = maximum radiation in a day;
q_0 = 0.131 \, \text{mQ}; \\
m = 12/c; \\
Q = \text{total solar radiation in a day (J/m}^2); \\
c = \text{effective time of sunshine (h)}; \\
\omega = \text{the earth's rotation frequency, } \omega = 2\pi/24, \text{ rad.}

**Air Temperature**

A linear combined method of double sine functions is used to simulate air temperature variation:

\[ T_a = \overline{T}_a + T_m \left[ 0.96 \sin(\omega(t - t_0)) + 0.14 \sin(2\omega(t - t_0)) \right] \]  \hspace{1cm} (8)

\( \overline{T}_a \) = average temperature, \\
\( T_m \) = temperature amplitude, \\
\( t_0 \) = initial time, usually, taking \( t_0 = 9h \).

**Air Convection**

The heat exchange coefficient of atmosphere to slab surface is influenced by speed of wind, and there is a linear relationship between them:

\[ h_c = 3.7 + 9.4c \]  \hspace{1cm} (9)

\( h_c \) = heat exchange coefficient, W/(m^2°C); \\
\( c \) = the speed of wind, m/s.

**Effective Radiation of the STB**

The effective radiation of slab is calculated by Stefan-Boltzmann's law:

\[ q_e = \varepsilon \sigma \left( T_1 \right]_{z=0} - T_z \right)^4 - (T_a - T_z)^4 \]  \hspace{1cm} (10)

\( q_e \) = effective radiation of the slab surface, W/(m^2°C); \\
\( \varepsilon \) = track slab surface emissivity (blackness), \( \varepsilon = 0.7 \); \\
\( \sigma \) = black body radiation coefficient; \( \sigma = 5.6697 \times 10^{-8} \text{W/(m}^2\text{K}^4) \); \\
\( T_1 \) = slab surface temperature; \\
\( T_a \) = atmospheric temperature; \\
\( T_z \) = absolute zero degree value, \( T_z = -273°C \).

Subprogram of CTR of CA mortar with SBT and track bed, solar radiation, air convection, and radiation are input ABAQUS heat transfer platform. Temperature fields, stress and deflection of CRTSII STB in winter or summer extreme weathers in severe cold region are calculated. The thermodynamic parameters and the geometrical dimension are in table 1. As analyzing temperature fields, 8-node first-order thermal conduction hexahedral elements (DC3D8) are used, as analyzing stresses, 8-node first-order stress hexahedral elements (C3D8) are used, the total number is 1378.
Numerical Analysis of the CRTSII Slab Ballastless Track Temperature Field

Temperature field of half cross section of the track slab is taken to analysis, and the highest temperature appearing at 14:00/PM in summer, and the minimum appearing at 6:00AM in winter. The analysis results are shown in figure3-4. The temperature field appears step at the interfaces of CA mortar with slab and roadbed along the depth, for the CTR. Comparing with continuous temperature fields, the SBT is more easily affected by the environmental temperature changing in severe cold region.

Table1. Thermal Physical Parameters and Size of CRTSII.

<table>
<thead>
<tr>
<th>Mat</th>
<th>Heat $J\cdot(\text{kg} \cdot \text{°C})^{-1}$</th>
<th>$\rho$ kg·m$^{-3}$</th>
<th>$\lambda$ $J\cdot(\text{m} \cdot \text{h} \cdot \text{°C})^{-1}$</th>
<th>Diam (m)</th>
<th>$E$ (MPa)</th>
<th>$\eta$</th>
<th>Exp (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>slab</td>
<td>973</td>
<td>2500</td>
<td>9450</td>
<td>0.2</td>
<td>$3.25 \times 10^{4}$</td>
<td>0.15</td>
<td>$1\times 10^{-5}$</td>
</tr>
<tr>
<td>CA</td>
<td>925</td>
<td>1800</td>
<td>4680</td>
<td>0.03</td>
<td>$5\times 10^{2}$</td>
<td>0.3</td>
<td>-</td>
</tr>
<tr>
<td>bed</td>
<td>973</td>
<td>2500</td>
<td>9450</td>
<td>0.3</td>
<td>$3.25 \times 10^{4}$</td>
<td>0.15</td>
<td>-</td>
</tr>
</tbody>
</table>

The temporal and spatial of the temperature field in extreme summer or winter weather in 24 hours in the severe cold region is shown in Figure 5-6: The maximum of the track slab temperature gradient is 65°C/m that appears at 14:00 PM. So large temperature gradient will cause large temperature stresses, and lead to the track slab end warped.

In summer, the maximum of the track slab temperature gradient is 65°C/m that appears at 14:00 PM. So large temperature gradient will cause large temperature stresses, and lead to the track slab end warped.

In winter, the temperature changing amplitude of the track slab surface is the same with the air temperature. Although the phase is lightly deviate, all of them appear at the 14:00PM. The maximum of the track slab temperature gradient is 40°C/m appearing at 12:00AM. Although the temperature gradient in winter is smaller than the summer, it is opposite to the temperature gradient in summer. Therefore, the track end warped was superposed by temperature gradient vector sum of winter and summer.

Figure 5. Temperature with time.  Figure 6. Temperature-depth of center.

Note: W-Winter, T-Temperature, S-Summer, h-depth
CRITSII TEMPERATURE STRESSES

The temperature field is imported into the mechanical model of the track slab to calculate temperature stresses, by coupled thermal mechanical analysis.

The temperature stresses of STB with time, at 14:00 PM and 6:00 AM, as the highest and lowest temperature of one day in summer or winter are shown in figure 7-10: The tensile stresses in winter is larger than that of compressive stresses in summer in all directions. The temperature tensile stresses reach to 1MPa in depth direction at the edge of slab. It is larger than the bond strength of the CA mortar with the track slab. This leads to the gaps of the CA mortar with the slab and the track bed. The lengths of the gaps will change with time, as water invasion damage as figure 1-b.

The longitudinal temperature stresses at different points are analyzed in extreme winter or summer weathers. The temperature stresses present alternative characteristics between winter and summer, and the amplitude reaches 10MPa, it will lead to the track slab appears gaps even fracture.

FIG.7. T-stress at 6:00 AM/winter FIG.8. T-stress at 14:00 PM/summer

Figure 9. Displacement of slab. Figure 10. Displacement of slab U3/U2.

Note: U2- longitudinal displacement; U3-transverse displacement

Vertical (U3) and longitudinal (U2) warped deformations appear along the track slab, as figure 9-10: the slab presents a four angular up warped concave in winter. The slab presents a four angular down warped convex at 14:00PM in summer. The deflection of slab is symmetrical basically with the deflection at 6:00AM in winter.

The maximum of the track slab temperature stresses reach 10MPa, the maximum of temperature gradient stress reaches 35MPa/m, and the displacement of slab end reaches 0.5mm. The direction of above temperature stress will be reversed with the temperature change of winter and summer, it will makes temperature stress difference range of the track slab reaches more than 20MPa and the displacement of slab end reaches 1mm. So
large temperature stress and displacement will cause gap between each structure layers, reduce the track regularity and increase the impact load of the train on the track. The freeze-thaw damage of track structure will be caused further when the surface water invading, so the application of the CRTSII STB in severe cold region need further study.

CONCLUSIONS
Coupled thermal-mechanical analysis was used to research the temperature stresses and deformation of the CRTSII STB in winter or summer extreme weather within 24 hours on ABAQUS heat transfer analysis platform.

The temperature field of STB is strongly affected by air temperature and solar radiation, and presents a nonlinear periodical change with time and depth. CTR of CA mortar make the temperature field appears a step in the contact surface. In summer, the highest temperature of STB appears at 14:00PM, at the same time, the temperature gradient is $65^\circ$C/m. In winter, the surface temperature of STB is synchronous with ambient temperature, and the lowest temperature appears at 6:00AM, at the same time, the temperature gradient is $40^\circ$C/m and its direction is opposite with that in summer.

In summer or winter, the temperature stresses of the track slab are periodically vibrational with the temperature field. In winter, the temperature stresses of the track slab are tensile stresses, the maximum reaches 10MPa at 6:00AM, at the same time, and the maximum gradient stresses reach 35MPa/m. In summer, the temperature stresses of the track slab are compressive stress, the maximum reach 10MPa at 14:00PM, at the same time, the maximum reach 35MPa/m.

The slab end warped and the displacement present periodical change, as winter or summer alternate. In winter, the STB present temperature shrinkage, longitudinal shrinkage reaches 0.5 mm at 6:00AM, the up deflection of STB corner reaches the maximum of 0.2 mm at the same time. In summer, the STB presents thermal expansion, longitudinal expansion reaches 0.5 mm at 14:00PM, the down deflection of corner reaches the maximum of 0.2 mm at the same time.

On the temperature field, stresses, and heat warped deformation in summer and winter extreme weathers, the illustrates of the damage formation mechanism of CRTSII STB, which includes slab end warped, gaps of structure layers, and even cracks, are researched. It provides theoretical basis for the design and application of this STB in severe cold region.

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