Effect of gap on vertical deformation and deterioration stress of CRTS-I ballastless track

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Effects of gap on vertical deformation and deterioration stress

Abstract: To explore the influence of gap on deformation and deterioration stress of track structure, a finite element model of CRTS-I slab ballastless track with gap is established by ABAQUS on the basis of plastic damage constitutive relation of concrete. The effects of different sizes and different positions of gap on displacement and stress of the track structure are calculated and analysed. The influence law of gap on deformation and deterioration stress is drawn by comparison with the calculation of normal track structure. The results show that increasing gap size sharply increases vertical displacement of both rails and slab and also seriously deteriorates transversal and longitudinal stress on the track slab to a great extent. Moreover, the effect of gap at slab centre on deteriorated stress and deformation is less than that of gap at slab end. The study can obviously provide theoretical reference for the maintenance standard.

Keywords: railway engineering; ballastless track; gap; deformation; deterioration stress.


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1 Introduction

Since 1960s, many countries in the world have carried out ballastless track research with unique features successively, which lay foundation for the subsequent research (Zhao, 2006; Esveld, 2001; Nakagawa and Hatoko, 2007). Mortar, as the filling layer of ballastless track structure, plays a vital role in maintaining structural smoothness and stability. CRTS-I slab ballastless track is mainly used in Harbin-Dalian passenger line, Shanghai-Nanjing intercity railway, Harbin-Qiqihar high speed railway line, etc., in China. According to field investigation, the uneven quality of materials, unreasonable operation in the construction process and impact of temperature and train load in the service process may result in mortar delamination, block falling at the edge, gap in the contact surface and so on. When the mortar deterioration becomes rather serious, it even affects the stability of the ballastless track structure and its service period. Obviously, this brings new challenges to the maintenance and the safe operation of high-speed railway. It has become a new topic to be solved urgently to reveal the laws of influence of mortar gap on the static performance of CRTS-I slab track and ensure the safety use of CRTS-I slab ballastless track structure during the operation.

As the ballastless track with the longest laying miles in China’s High-Speed Rail, the use safety of slab ballastless track structure has been widely noticed. There are many explorations at home and abroad that study early causes and mechanisms of the gap of the ballastless track structure (Jeong, 2003; Gao et al., 2014). Zhou et al. (2016), Zhu and Cai (2014) and Lin et al. (2010) studied the expansion process of the track structure crack by considering the temperature load and train load. The analysis result is of valuable reference in the study of track structural gap. Xu et al. (2013a, 2013b), Liu et al. (2014), Liu and Zhao (2013) and Han and Sun (2011) further study CRTS-II track slab warpage caused by the temperature gradient and gap even disengaging occurring at the local area of the contact surface between the track slab and the mortar layer under the combined action of train dynamic load. Yang et al. (2013, 2014) analysed the effect of gap with different height and length on the vertical deformation and stress of CRTS-I ballastless track structures in small range (0.6 m) considering the action of dynamic train load only. Moreover, Zhao et al. (2017) analysed the effect evaluation of different gap quantity and gap ranges on the dynamic characteristics and the vehicle operation safety of the CRTS-II slab ballastless track in a rather large range. Xiang et al. (2009) and Li et al. (2014) stimulate the gap by adopting stiffness coefficient degradation of the supporting layer, analyses the influence of the mortar gap (including void) on the high-speed train-ballastless track system and summarises that the range of gap (including disengaging) has great impact on the smooth operation of the vehicle.

The above results show that current research is mainly focused on the influence of small-scale mortar gap under different temperature loads and train loads on the structural performance or dynamic response of CRTS-I slab ballastless track. There is little research on the influence of large-scale mortar layer gap on the deformation and deterioration of CRTS-I slab. Especially, there are few suggestions on the limiting values of length and depth of gap on account of the plastic damage constitutive relation of concrete.

Therefore, in face of defects of existing research, based on the plastic damage constitutive relation of concrete and the finite element method, this paper proposes the nonlinear finite element calculation model of CRTS-I slab track with gap and the model is applied to the ABAQUS numerical analysis. Meanwhile, the influence of temperature gradient and axle load is considered in the ABAQUS. The influence of mortar gap and
The paper discusses the effect of different size (mainly in terms of length and depth) and different position of gap on the maximum deterioration stress and deformation of damage track structure, through comparison with the performance of normal track structure. Then, the influence rule of gap on the CRTS-I slab track structure is drawn. It is further clarified to provide a theoretical basis for the maintenance, optimisation, construction of CRTS-I slab ballastless track structure.

The structure and layout of the paper is as follows. In Section 2, the nonlinear finite-element calculation models of CRTS-I slab track and gap are established to verify the correctness and feasibility of model. In Section 3, the result of gap on deformation and deterioration stress of CRTS-I slab simulations will be presented. The change law of system parameters with different loads, different position of gap, different length and depth of gap and their effects on the comprehensive performance of track structure are obtained. In Section 4, the relevant conclusions are drawn.

2 Analysis method

The remainder of this analysis method is organised as follows. Firstly, the nonlinear finite-element calculation model of CRTS-I slab track with gap is established by ABAQUS and the plastic damage constitutive relation is proposed in Section 2.2; and they are verified the correctness in Section 2.5. While in Section 2.3 and Section 2.4, the calculation parameter and condition of the simulation model are selected and explained.

Figure 1 The implementation process of the effect analysis of gap on CRTS-I slab track

The implementation process of the effect analysis of gap is shown in Figure 1. Firstly, the basic model database of CRTS-I slab track such as geometry, material and load, etc., are added to the ABAQUS; and the position and size of gap are determined and input. Then,
the damage model database with gap is generated. Furthermore, the nonlinear finite element model of CRTS-I slab track with gap is established to simulate calculation. Secondly, python post-treatment is started from the storage of simulation result and reprocess the data. In both of these processes, you can loop over the storage or reprocess. Lastly, the results and coloured stress is output.

2.1 Model establishment

Based on plastic damage constitutive relation of concrete and finite element method, the paper establishes the calculation model of CRTS-I slab ballastless track by using ABAQUS.

2.1.1 Track model

The finite element model is simulated for the static effect of CRTS-I slab track. There are three factors mainly in constraint condition, grid partition and constitutive relation, which influence the calculation precision of the simulation. First, three pieces of slab are selected to perform numerical simulation in order to eliminate the boundary effect. Based on the symmetry of the CRTS-I slab track structure and the reasonable constraint on the section of the structure, only 1/2 model of one unit slab track structure is selected without taking the influence of the partial load on the track structure into account as shown in Figure 2. The model shows that the degree of freedom (DOF) of the boundary of the slab in the longitudinal direction of the line is constrained. At the same time the foundation is treated as rigid material and the degrees of freedom of three directions at bottom of the base are completely fixed; and the normal DOF simulation boundary conditions of two axisymmetric surfaces are constrained. Through above method, it is obvious that the cross section of the structure is reasonably constrained, so that the static effect of the structure is closer to the simulation result of that of the complete structure. Second, the precision of grid partition is determined as follow. Based on the experience of Zhou et al. (2016), the grid density of the track slab and the track structure is 50 mm and the base slab is 100 mm respectively. In addition, the second precision of the isoparametric element is only used at the middle track slab and the roadbed slab, to ensure the reliability of the results on the premise of preserving resources as much as possible. Last, the constitutive relation of CRTS-I slab track is modified in Section 2.2.

Figure 2 1/2 model of CRTS-I slab ballastless track
2.1.2 Gap model

It can be seen from Figure 3(b) that the shaded area represents the size and location of gap distribution of the calculation model: Gap can be categorised into ‘C-gap’ and ‘E-gap’ (including of ‘B-gap’ and ‘F-gap’); C means the damage at the centre of track slab, C-gap (gap at slab centre); E means the damage at the end of slab; B means the damage in the backward direction of the train, B-gap (gap at the back end of slab); F means the damage in the forward direction of train, F-gap (gap beneath the front end of slab). Each gap area contains both length (L) and depth (D), two size parameters. The X axis is the track transverse direction, the Y coordinate axis is the longitudinal direction of the track and the Z axis is the orbit vertical direction.

Considering the influence of friction between track slab and mortar layer, the mortar gap can be simulated by the way of the nonlinear spring element for considering the local stiffness degradation, $k_1$ in the position of gap was seen as equation (1) and equation (2). The relation between force and displacement of nonlinear spring of the mortar layer with gap is shown in Figure 4 to Figure 5.

**Figure 3** The location of mortar gap, (a) the scene (b) the overhead view of model (see online version for colours)
Figure 4  Sketch of mortar gap beneath the end of slab, (a) front view (b) side view (see online version for colours)

\[ F = \begin{cases} 0 & u \leq u_0 \\ k_1 (u - u_0) & u > u_0 \end{cases} \] (1)

In which

\[ k_1 = \frac{E l_0 (b_0 - b)}{h} \] (2)

\( k_1 \) the elastic coefficient of the mortar layer
\( F \) the force acting on the mortar layer
\( E \) elastic modulus of mortar
\( u_0 \) initial gap value of the mortar layer
\( u \) the relative displacement between the bottom of track slab and the top surface of mortar layer
\( l_0 \) the length of track slab
\( b_0 \) the width of track slab
The gap length of track slab

the gap width of track slab.

Figure 5  The relationship between force and vertical displacement for mortar gap

2.2 The plastic damage constitutive relation of concrete

The concrete grade of slab track in high speed railway is C60, which belongs to high strength concrete. An elastic segment should be modified in the stress-strain constitutive relationship by using the CDP module in the ABAQUS. Firstly, the constitutive relation of high strength concrete is modified on the basis of relevant literature (Yu and Ding, 2003; Ding and Yu, 2004; Ding et al., 2008); and then the damage factor of model is calculated; lastly, the unified plastic damage constitutive model of concrete is established.

2.2.1 Modified constitutive relation of concrete

The unified constitutive model is shown as equation (3).

\[
\begin{align*}
y &= \frac{Ax - x^2}{1 + (A - 2)x} & 0 \leq x \leq 1 \\
y &= \frac{x}{a(x-1)^\eta + x} & x > 1
\end{align*}
\]

Then, the tension constitutive relation is shown as equation (4) and equation (5).

\[
\begin{align*}
y_t &= \frac{Ax - x^2}{1 + (A_t - 2)x} & 0 \leq x \leq 1 \\
y_t &= \frac{x}{a_t(x-1)^\eta + x} & x > 1
\end{align*}
\]
in which, \( \sigma \) – stress, \( \varepsilon \) – strain, \( E \) – modulus of elasticity, \( f_{\text{cu}} \) – concrete strength grade.

When \( f_{\text{cu}} \) is taken into the equation (6), the relevant parameters in equation (5) can be calculated. The compression constitutive relation is shown as equation (6). Similarly, when \( f_{\text{cu}} \) is replaced into equation (7), the parameters of equation (5) can be obtained.

\[
\begin{align*}
y_c &= \frac{A_c x - x^2}{1 + (A_c - 2)x} \quad 0 \leq x \leq 1 \\
y_c &= \frac{x}{\alpha_c (x - 1)^2 + x} \quad x > 1
\end{align*}
\]  

(6)

\[
\begin{align*}
y_c &= \sigma / f_c \\
x &= \varepsilon / \varepsilon_c \\
f_c &= E_c \varepsilon_c / A_c \\
\varepsilon_c &= 383 f_{\text{cu}}^{3/18} \times 10^{-6} \\
\alpha_c &= 2.5 f_{\text{cu}}^{1/3} \times 10^{-5} \\
A_c &= 9.1 f_{\text{cu}}^{-4/9} \\
E_c &= 9500 f_{\text{cu}}^{1/3}
\end{align*}
\]  

(7)

**Figure 6** Comparison of secant and tangent elastic modulus method (see online version for colours)
An elastic segment should be provided in the stress-strain constitutive relation by using the ABAQUS’s CDP module; otherwise, the constitutive relationship cannot be inputted. But the constitutive equation (1) does not give this elastic segment rising in a straight line. Therefore, this constitutive model needs to be modified in a reasonable range. There are two main correction methods of secant and tangent elastic modulus as shown in Figure 6.

The temperature load and the concrete self shrinkage will eventually react to the tensile cracking of concrete, so the constitutive relation is likely to be adopted by secant
correction method in Zhang et al. (2008). And the final modification results of constitutive relation are as follows.

\[
\begin{align*}
    y_i &= x & 0 \leq x \leq 1 \\
    y_i &= \frac{x}{\alpha_i (x-1)^{1/2} + x} & x > 1
\end{align*}
\]  

(8)

\[
\begin{align*}
    y_c &= \min \left( \frac{A_a x - x^2}{1 + (A_a - 2)x}, \frac{A_a x}{A_a} \right) & 0 \leq x \leq 1 \\
    y_c &= \frac{x}{\alpha_c (x-1)^{1/2} + x} & x > 1
\end{align*}
\]  

(9)

2.2.2 Damage factor

Based on the energy equivalence theory (Krajcinovic and Fonseka, 1981) and other literature (Qin and Zhao, 2013; Lubliner et al., 1989), equation (10) is used as the theoretical value of damage factor \(d\). It \(W_e\) can be calculated by subsection integral or Gauss integral. Moreover, the calculation method of damage factor is shown in Figure 8.

\[
d = \frac{W_0 - W_e}{W_0}
\]  

(10)

In which \(W_0 = \frac{E_0 \varepsilon^2}{2}\), \(W_e = \int_0^\varepsilon \sigma(\varepsilon) d\varepsilon\).

**Figure 8** The calculation method of damage factor

These scattered points must be inputted and interpolated in the CDP module of ABAQUS. Therefore, they need to be sampled in the revised constitutive curve. Then, the concrete constitutive relation of plastic damage can be obtained. Table 1 and Table 2 are given of the discrete values of C60’s tensile constitutive and compressive constitutive values, respectively, in which the meaning of \(\varepsilon^{in}_c\) and \(\varepsilon^{in}_t\) are the interpolated compressive and tensile respectively and the meaning \(d_c\) of \(d_t\) and are the compressive and tensile damage factor, respectively.
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<table>
<thead>
<tr>
<th>Table 1</th>
<th>Compressive constitutive discrete values and damage factors (C60)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_c$/MPa</td>
<td>$\varepsilon_c$</td>
</tr>
<tr>
<td>45.027604</td>
<td>0.001581180</td>
</tr>
<tr>
<td>47.466890</td>
<td>0.00182357</td>
</tr>
<tr>
<td>45.245736</td>
<td>0.002070593</td>
</tr>
<tr>
<td>30.329439</td>
<td>0.002597653</td>
</tr>
<tr>
<td>19.921243</td>
<td>0.003105889</td>
</tr>
<tr>
<td>15.082137</td>
<td>0.003501184</td>
</tr>
<tr>
<td>10.084931</td>
<td>0.004216480</td>
</tr>
<tr>
<td>4.0090786</td>
<td>0.007040016</td>
</tr>
<tr>
<td>2.4052468</td>
<td>0.009938846</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 2</th>
<th>Tensile constitutive discrete values and damage factors</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_t$/MPa</td>
<td>$\varepsilon_t$</td>
</tr>
<tr>
<td>3.6789894</td>
<td>0.000129191</td>
</tr>
<tr>
<td>3.0132142</td>
<td>0.000167948</td>
</tr>
<tr>
<td>2.4013942</td>
<td>0.000201537</td>
</tr>
<tr>
<td>2.0079206</td>
<td>0.000232543</td>
</tr>
<tr>
<td>1.5050443</td>
<td>0.000291971</td>
</tr>
<tr>
<td>1.2511740</td>
<td>0.000339771</td>
</tr>
<tr>
<td>1.0031459</td>
<td>0.000414702</td>
</tr>
<tr>
<td>0.8019437</td>
<td>0.000515471</td>
</tr>
<tr>
<td>0.6008953</td>
<td>0.000697629</td>
</tr>
</tbody>
</table>

2.3 Selection of track structure parameters

When the static property of track system is analysed by using ABAQUS, the structural parameters for the finite model of CRTS-I slab ballastless track are shown in Table 3. $\rho$ is the density of the material; $E$ represents the elastic modulus of the material; $\alpha$ represents the linear expansion coefficient of the material; $k$ represents the stiffness of the fastener, $k_y$ is transverse stiffness of the fastener.

<table>
<thead>
<tr>
<th>Table 3</th>
<th>Calculation parameters of CRTS-I slab track structure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameters</td>
<td>Value</td>
</tr>
<tr>
<td>Fastening system</td>
<td>Space distance (m)</td>
</tr>
<tr>
<td></td>
<td>$k/(kN/mm^2)$</td>
</tr>
<tr>
<td></td>
<td>$k_y/(kN/mm^2)$</td>
</tr>
<tr>
<td>Slab (C60 concrete)</td>
<td>Length (mm)</td>
</tr>
<tr>
<td></td>
<td>Breadth (mm)</td>
</tr>
<tr>
<td></td>
<td>Height (mm)</td>
</tr>
<tr>
<td></td>
<td>Density $\rho$ (kg/m$^3$)</td>
</tr>
<tr>
<td></td>
<td>Elastic modulus $E$ (MPa)</td>
</tr>
</tbody>
</table>
Table 3  Calculation parameters of CRTS-I slab track structure (continued)

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mortar layer</td>
<td></td>
</tr>
<tr>
<td>E/MPa</td>
<td>200</td>
</tr>
<tr>
<td>α/(1°C⁻¹)</td>
<td>0.2</td>
</tr>
<tr>
<td>length (mm)</td>
<td>4,962</td>
</tr>
<tr>
<td>breadth (mm)</td>
<td>2,400</td>
</tr>
<tr>
<td>height (mm)</td>
<td>50</td>
</tr>
<tr>
<td>Bed (C40 concrete)</td>
<td></td>
</tr>
<tr>
<td>length (mm)</td>
<td>15,076</td>
</tr>
<tr>
<td>breadth (mm)</td>
<td>2,800</td>
</tr>
<tr>
<td>height (mm)</td>
<td>300</td>
</tr>
<tr>
<td>density ρ (kg/m³)</td>
<td>2,400</td>
</tr>
<tr>
<td>E (MPa)</td>
<td>32,500</td>
</tr>
</tbody>
</table>

2.4 Conditions description

2.4.1 Gap condition description

Condition type is shown in Table 4. The method of solid element friction contact is adopted in this study. It studies difference of mortar under abnormal situation, having gap or even completely disengaging from that under normal working conditions. Each location area contains only length and depth, two size parameters. Gap can be categorised into ‘gap beneath the centre of slab’ and ‘gap beneath the end of slab’ and the size of gap considers depth D × length L as shown in equation (11). The length of the gap ranges from 200 mm to 1,400 mm, classified into four kinds in total and the depth ranges from 100 mm to 800 mm, classified into eight kinds in total, for a complete permutation and combination (see Table 1). For example, CL1400D800 is on behalf of the gap with length of 1,400 mm and depth of 800 mm beneath the centre of slab in forward direction.

\[
\text{area}_{\text{gap}} = \{D\} \times \{L\} \tag{11}
\]

In which

\[
\{D\} = [100, 200, 300, 400, 500, 600, 700, 800]^T
\]

\[
\{L\} = [200, 600, 1000, 1400]
\]

Table 4  Condition type

<table>
<thead>
<tr>
<th>Type</th>
<th>Load condition</th>
<th>Gap length/mm</th>
<th>Gap depth/mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>C-gap (gap at slab centre)</td>
<td>'F_T+' Axle load + positive temperature gradient</td>
<td>200, 600, 1,000, 1,400</td>
<td>100, 200, 300, 400, 500, 600, 700, 800</td>
</tr>
<tr>
<td></td>
<td>'F_T-' Axle load + negative temperature gradient</td>
<td>200, 600, 1,000, 1,400</td>
<td>100, 200, 300, 400, 500, 600, 700, 800</td>
</tr>
<tr>
<td>E-gap (gap at slab end)</td>
<td>'F_T+' Axle load + positive temperature gradient</td>
<td>200, 600, 1,000, 1,400</td>
<td>100, 200, 300, 400, 500, 600, 700, 800</td>
</tr>
<tr>
<td></td>
<td>'F_T-' Axle load + negative temperature gradient</td>
<td>200, 600, 1,000, 1,400</td>
<td>100, 200, 300, 400, 500, 600, 700, 800</td>
</tr>
</tbody>
</table>
2.4.2 Load condition description

Load working conditions have ‘axle load + positive temperature gradient’ and ‘axle load + negative temperature gradient’ two load modes. Load diagram with gap is shown in Figure 9. The statistical results of the temperature difference between the upper and lower surface of the track are obtained on the basis of Yan et al. (2016) in Figure 10. The vertical axis in the figure represents the temperature difference between the upper and lower surfaces of the track slab and the horizontal axis represents 24 hours a day. The specific temperature load is applied to the track slab in a way of temperature gradient. It should be noted that the temperature change belongs to a kind of sustained and slow loading and this kind of continuous loading will make the structural damage fully extended (Kumar Mehta and Monteiro, 2008). One calculation of a load cannot be equivalent to the load in an actual day and the loading times in this paper is the repeated number of temperature difference polylines in the figure. The load application method is described as follows:

1. applying prestressed steel load, track slab load and rail load
2. initialising the temperature load; provide a 0°C to 8°C application process once according to Figure 10.

Note that you cannot load directly from 0°C; otherwise it will result in that the calculations do not converge.

**Figure 9** Sketch overview of load condition with gap

![Figure 9](image1)

**Figure 10** Time history curve of temperature difference of track slab

![Figure 10](image2)
2.5 Model verification

2.5.1 Validation of plastic damage constitutive relation of concrete

2.5.1.1 Model description

In order to verify the reliability of the constitutive damage of concrete, a numerical simulation of the uniaxial compression of cubic concrete is carried out and the model of cube concrete is shown as Figure 11. The calculation parameter for the model is selected from Table 6.

Table 5  Calculation parameter explanation for cube concrete

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cube concrete (C60)</td>
<td></td>
</tr>
<tr>
<td>Size of pressure plate and cap/mm$^3$</td>
<td>$170 \times 170 \times 10$</td>
</tr>
<tr>
<td>Size of concrete block/mm$^3$</td>
<td>$150 \times 150 \times 150$</td>
</tr>
<tr>
<td>Dilation angle</td>
<td>$30^\circ$</td>
</tr>
<tr>
<td>Eccentricity</td>
<td>0.1</td>
</tr>
<tr>
<td>Biaxial compression and uniaxial compression</td>
<td>1.16</td>
</tr>
<tr>
<td>ultimate strength ratio ($fb0 / fc0$)</td>
<td></td>
</tr>
<tr>
<td>Invariant stress ratio $k$</td>
<td>1.16</td>
</tr>
<tr>
<td>Viscosity parameter</td>
<td>0.0005</td>
</tr>
</tbody>
</table>

Figure 11  The axial compression test of cubic concrete (see online version for colours)

2.5.1.2 Verification result

It can be seen from Figure 12 that the simulation results are extracted as plastic strain cloud images. The blue area represents the lower plastic strain area, which is unlikely to be damaged; both green and red area have a maximum magnitude ($1 \times 10^{-2}$) of plastic damage, which are tend to be a larger area of damage; the yellow green narrow band extends from the corner to the centre, which is marked with red arrows. The simulation results show that the uniaxial compression of concrete without lubricating oil is almost consistent with the actual conditions. Therefore, the plastic damage constitutive model of concrete is reasonable and feasible.
2.5.2 Verification of track model

2.5.2.1 Model description

Firstly, the model must be established in the first place for the purpose of proving the reasonableness and correctness. Then, it is proved that structural modelling is feasible by comparing with other models in the same or close working conditions. The validation model is described as follows.

The structure has been fully settled under the condition of self weight, so the self weight of the structure is ignored in the model. Based on the symmetry of the CRTS-I slab track structure and the reasonable constraint on the section of the structure, 1/4 graphic model of one unit slab track structure without taking the influence of gap into account, which can be conveniently understand the division of finite element meshes, is just adopted and analysed to further save the computation cost in this section as shown in Figure 13.
2.5.2.2 Verification result

To verify the correctness of the model, the model of CRTS-I slab track without gap proposed in Xiang et al. (2007) is adopted to perform the calculation. Positive temperature gradient should be 0.090°C/mm; the axle load including vertical load 100 kN, the lateral load 9 kN and the breaking force 10 MPa is added to rail on the middle of second track slab. The calculation without gap is compared with Xiang et al. (2007) which is shown in Table 6. When the width of gap is 0.5 mm and its length and depth is 1,000 mm and 1,200 mm respectively. The calculation with gap is compared with Yang et al. (2014). It can be seen from Table 6 that the maximum vertical displacement of rail and track slab due to temperature load are slightly larger than those of literature. Because the overall magnitude of calculations is the same as the value of literatures, it is indicated that the analysis model of CRTS-I slab track is reasonable and feasible. So, the model can be adopted to further analyse the effect of CA mortar gap.

<table>
<thead>
<tr>
<th>Type</th>
<th>Calculation Without gap</th>
<th>Xiang et al. (2007) Without gap</th>
<th>Calculation With gap</th>
<th>Yang et al. (2014) With gap</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical displacement of rail</td>
<td>1.388</td>
<td>1.137</td>
<td>1.523</td>
<td>1.34</td>
</tr>
<tr>
<td>Vertical displacement of slab</td>
<td>0.699</td>
<td>0.461</td>
<td>1.072</td>
<td>1.04</td>
</tr>
</tbody>
</table>
3 Results and discussion

3.1 Effect analysis of gap position

The vertical displacement and deterioration stress of CRTS-I slab track are worked out. When the load condition is ‘F_T+’ and the width of gap is 3 mm and its length is 1,400 mm. It should be noted that on the premise that structural stress tends to be worse, the value of deterioration stress is the maximum stress difference between damage track structure and normal track structure in the paper.

Figure 14  Comparison the effect of gap position on the maximum vertical displacement between the C-gap and E-gap under the gap length 1,400 mm and ‘F.T+’, (a) rail (b) slab
From Figure 14(a), under the same length 1,400 mm and ‘F_T+’, when the depth of gap is 800 mm, the maximum vertical displacements of rail with E-gap are 1.6176 mm, which is up 14.09% by comparison with that of rail with C-gap; from Figure 14(b), the maximum vertical displacements of slab with E-gap are 1.6176 mm, which is up 27.70% by comparison with that of slab with C-gap. It can be obtained that C-gap has quite small influence on the maximum displacement of rail and slab than E-gap has and the maximum vertical displacement is mainly determined by E-gap. In terms of the same length and width of gap, the vertical displacement with E-gap increases gradually with the increase depth of gap.

**Figure 15**  Comparison the effect of gap position on the maximum vertical displacement between the C-gap and E-gap under the gap depth 800 mm and ‘F_T+’, (a) rail (b) slab
From Figure 15(a), under the same depth 800 mm and ‘F_T+’, as the length of gap increases, the maximum vertical displacements of rail with E-gap are gradually enhanced, while those of rail with C-gap are barely changed. From Figure 15(b), under the same condition, as the length of gap increases, the maximum vertical displacements of slab with C-gap are little changed, while that of slab with E-gap are almost the same enhanced by comparison with that of slab without gap. Obviously, E-gap has more influence on the vertical displacement of both rail and slab than C-gap has. Thus, the effect of gap at slab end on the track deformation is more than that of gap at slab centre.

**Figure 16** Comparison the effect of gap position on the maximum deterioration stress of slab between the C-gap and E-gap under ‘F_T+’, (a) transversal stress (b) longitudinal stress
It can be drawn from Figure 16 that under the gap length 1,400 mm and ‘F_T+’, C-gap has quite small influence on the maximum deterioration transversal stress of slab than that of E-gap has. When the depth of gap is 800 mm, the vertical transversal stress of slab with E-gap is 4.8989 MPa, while that of C-gap is only 0.5224 MPa. The effect of E-gap on the transversal stress of slab rises 8.3 times by comparison with that of C-gap. Otherwise, when the depth of gap is less than 400 mm, the effect of E-gap on the deterioration longitudinal stress of slab is more than that of C-gap; when the depth of gap is more than 400 mm, the effect of E-gap on the deterioration longitudinal stress of slab is less than that of C-gap.

**Figure 17** Comparison the effect of gap position on the maximum deterioration stress of bed between the C-gap and E-gap under ‘F_T+’, (a) transversal stress (b) longitudinal stress
It can be seen from Figure 17(a), when the depth of gap increases from 100 mm to 800 mm, the deterioration transversal stress of bed with E-gap rises from 3.9069 MPa to 3.9386 MPa and that of C-gap also reaches to the same value 3.8733 MPa. Obviously, E-gap has significantly influence on transversal deterioration stress of bed as well as C-gap; but transversal deterioration stress of bed has hardly increases with the increasing gap area.

It can be drawn from Figure 17(b) that C-gap has quite small influence on the maximum deterioration longitudinal stress of slab than that of E-gap has. When the depth of gap is 800 mm, the vertical longitudinal stress of slab with C-gap is only 0.4340 MPa, while that of C-gap is 1.0889 MPa. Moreover, with the length of gap increases, longitudinal deterioration stress of bed increases and the growth rate of longitudinal deterioration stress of bed with E-gap is faster than that of bed with C-gap.

3.2 Effect analysis of gap size
3.2.1 Gap size on the vertical displacement of track structure

It can be obviously drawn from Section 3.1 that with same gap area (area = D × L), the influences of C-gap on maximum vertical displacement of track system are obviously weaker than that of E-gap. When determining damage level, the relevant size parameters of E-gap can be mainly studied in the section. When the load condition is ‘F₆T₊’ and the width of gap is 3 mm, the depth of gap is 100 mm, 200 mm, 300 mm, 400 mm, 500 mm, 600 mm, 700 mm, 800 mm and the length of gap is 200 mm, 600 mm, 1,000 mm and 1,400 mm. The vertical displacements of CRTS-I slab track structure are worked out.

It can be seen from Figure 18(a) that E-gap has influence on vertical displacement of the track. Vertical displacement increases with the increase of the depth and length of gap; the effect of transverse extension of gap length and longitudinal extension of gap length on the maximum vertical displacement of the track are different. For example, if the gap size is 600 mm × 100 mm, the vertical displacement of the track is 1.398 mm but the vertical displacement is 1.413 mm when the gap size is 100 mm × 600 mm. Moreover, in terms of the same width and length of gap, the influence of gap at slab end (E-gap) on the maximum vertical displacement of rail increase significantly with the increase depth of gap; in terms of the same width and depth of gap, the influence on the maximum vertical displacement of rail also increase significantly with the increase length of gap. When the gap area is 1,400 mm × 800 mm, the maximum vertical displacement of rail compared with normal slab track is up to 16.4%.

It can be known from Figure 18(b) that when the depth and width of gap is the same, the increase length of E-gap has little effect on the vertical displacement of slab; while when the length and width of gap is the same, the increase depth of E-gap has great effect on the vertical displacement of the track slab. For example, if the gap area is 1,400 mm × 800 mm, the maximum vertical displacement of slab compared with normal slab track is up to 17.9%.
Figure 18 The maximum vertical displacement with different size of E-gap under ‘F_T+’, (a) rail (b) slab (see online version for colours)

3.2.2 Gap size on deterioration stress of track structure

3.2.2.1 Effect of E-gap

In Figure 19(a), under ‘F_T+’ working condition, the longitudinal degradation of track slab does not certain increase with the increase of the gap; when the length of E-gap is 600 mm, 1,000 mm and 1,400 mm, the longitudinal degradation stress tends to grow with the increase of gap depth from 100 mm to 600 mm; and Once the depth of gap is more than 600 mm, it can be increased very slow (or negative). The change law of stress due to other gap length is not quite the same as that of stress due to the length 200 mm.
In Figure 19(b), under $F_{T+}$ working condition, if gap depth is the same, the transverse deterioration stress of slab increases gradually with the increase of the length of the E-gap; when gap length is the same and the maximum transverse deterioration stress of slab with E-gap increases with the increase of gap depth. The larger the gap area is, the faster the deterioration stress increases and the maximum of deterioration stress finally reaches 4.90 MPa when gap area is $1,400 \text{ mm} \times 800 \text{ mm}$.

Figure 19 Maximum deterioration stress of slab with E-gap ($F_{T+}$), (a) longitudinal deterioration stress (b) transversal deterioration stress (see online version for colours)

In Figure 20(a), under ‘$F_{T-}$’ working condition, the trend is stable when the depth of the E-gap is less than 400 mm and then rises rapidly later. For example, when the gap area is $200 \text{ mm} \times 100 \text{ mm}$, the maximum longitudinal deterioration stress of slab is only 0.06 MPa; when the gap area is $1,400 \text{ mm} \times 800 \text{ mm}$, it is up to 0.44 MPa. In
Figure 20(b), under ‘F_T-‘ working condition, the effect of gap size is great. With other calculation parameters unchanged, if gap depth is the same, the transverse deterioration stress of slab with E-gap increases gradually with the increasing length of gap; if gap length is 1,000 mm or 1,400 mm, the transversal degradation stress of slab with E-gap tends to grow with the increase of gap depth; and once the depth of gap is more than 600 mm, it can be increased very quickly. While the change law of deterioration stress due to other gap length is not quite the same as that of stress due to the gap length 200 mm and when the depth of gap is more than 400 mm, the transverse deterioration stress of slab is dropped to 0.12 Mpa.

Figure 20  Maximum deterioration stress of slab with E-gap (F_T-), (a) longitudinal stress (b) transversal stress (see online version for colours)
From Figure 20 and Figure 21, the load of ‘F_T+’ has significant influence on the transversal deterioration stress of slab, while the load of ‘F_T-’ has great effect on longitudinal deterioration stress of slab; moreover, the influence of ‘F_T+’ on the deterioration stress of slab is more than that of ‘F_T-’. For example, the maximum of transverse transversal deterioration stress of slab is 4.90 MPa under the working condition ‘F_T+’, while it is only 1.40 MPa under the working condition ‘F_T-’.

**Figure 21** Maximum deterioration stress of bed with E-gap (F_T+), (a) longitudinal stress (b) transversal stress (see online version for colours)
In Figure 21(a), under F_T+ working condition, gap at the slab end has a great influence on the longitudinal deterioration of the base slab, but the size effect is very small. For example, when the size of gap is 200 mm × 100 mm, the maximum longitudinal deterioration stress is 3.90 MPa; and when the size of gap is 1,400 mm × 800 mm, the maximum longitudinal deterioration value is 3.94 MPa, which rises only 0.04 MPa. In Figure 21(b), under F_T + working condition, the gap size effect is obvious. The maximum transverse deterioration stress of bed increases from 0.09 MPa to 1.09 MPa, increased by ten times.

Figure 22  Maximum deterioration stress of slab with C-gap (F_T+), (a) longitudinal stress (b) transversal stress (see online version for colours)
3.2.2.2 Effect of C-gap

In Figure 22(a), under $F_{T+}$ working condition, the maximum longitudinal deterioration stress of slab with C-gap increases with the increase of the gap depth. The larger the gap length is, the faster the stress rises. For example, if the gap size is 1,400 mm × 100 mm, the transverse deterioration stress reaches 0.426 MPa; if the gap size is 1,400 mm × 800 mm, the transverse deterioration stress reaches 1.732 MPa. In Figure 22(b), under $F_{T+}$ working condition, the maximum longitudinal stress of the track slab fluctuates with the increase of gap depth. If the gap length is 1,400 mm and the gap depth is 200 mm, the transverse deterioration stress of slab reaches 0.716 MPa; with the gap depth increasing to 400 mm, the stress gradually decreases to 0.492 MPa, then rise to 0.522 MPa. It is shown from Figure 22(b) that the change law for the transverse deterioration stresses of slab is fluctuating from rise to drop; and the greater the length of gap, the more obvious the fluctuation is.

**Figure 23** Maximum deterioration stress of bed with C-gap ($F_{T-}$), (a) longitudinal stress (b) transversal stress (see online version for colours)
Figure 24  Maximum deterioration stress of bed with C-gap (F_{T+}), (a) longitudinal stress
(b) transversal stress

In Figure 23(a), under working condition F_{T-}, when the length of C-gap is 200 mm, the maximum longitudinal deterioration stress to track slab increases with the increase of the depth of the gap on the whole and when the length of the gap is 600 mm, 1,000 mm and 1,400 mm, the maximum longitudinal deterioration stress fluctuates with the increase of the gap depth. The stress rises before the gap depth is 300 mm. As the depth of gap increases to a certain value and gradually decreases, there is an increasing trend later. In Figure 23(b), under working condition F_{T-}, when the gap length is 200 mm, the maximum longitudinal deterioration stress to the track slab decreases slowly with the increase of the gap depth on the whole and when the length of the gap is 600 mm, 1,000 mm and 1,400 mm and with depth of 200 mm, the maximum transverse deterioration stress of the track slab is in the trough and then it increases with the increase
of the gap depth and the longer the gap length is, the faster the transversal stress increases.

From Figure 24(a), it can be seen that under the positive temperature gradient load, the maximum longitudinal deterioration stress of bed increases with the increase of length and depth of C-gap and the value increased from 0.135 MPa (L200D100) to 0.442 MPa (L1400D800). So, the effect of gap size is great. From Figure 24(b), it can be found that as long as there is a gap, the bed has a large transverse deterioration stress value (3.8733 MPa). However, the maximum transverse deterioration stress of bed tends to be 3.8732 MPa with the increase of the length and depth. So, it can hardly be affected by the changes in the size of the gaps.

**Figure 25** Transverse deterioration stress of slab due to the depth 100 mm and different length of gap, (a) FL200D100 (b) FL600D100 (c) FL1000D100 (d) FL1400D100 (see online version for colours)
3.3 Distribution law analysis of gap

In order to better understand the distribution law of gap at slab end on the maximum deterioration stress of slab, we need more coloured stress in the post-processing of finite element to further explain. With other calculation parameters unchanged, the width of E-gap is 50 mm; gap depth is 100 mm; gap length is 200 mm, 600 mm, 1,000 mm and 1,400 mm, respectively; and the influence on the deterioration stress of track slab is analysed. The FEM coloured stress patterns are shown as follow.

Figure 26 Longitudinal deterioration stress of slab due to the depth 100 mm and different length of gap, (a) FL200D100 (b) FL600D100 (c) FL1000D100 (d) FL1400D100 (see online version for colours)

From Figure 25, there is small deterioration at the deposition of gap and most of transverse deterioration stresses of slab are too small to be overlooked. However, there is a stress concentration at the bolt hole of the fastener, which cannot be ignored. The
maximum of transverse deterioration stress in Figures 24(a) to 24(c) and Figure 25(d) is 0.10 MPa, 0.52 MPa, 0.57 MPa and 0.59 MPa, respectively. It indicates that under other conditions unchanged, with the length of gap increases, the maximum of transverse deterioration stress gradually increases. As to the gap that extends longitudinally, once the size of gap exceeds the range of 600 mm × 100 mm, the stress difference at the position of fastener bolt will occur. The stress state will be converted into tension state and stress difference will be concentrated. When the length of the gap is 1,400 mm, the stress difference is gradually stabilised at 0.60 MPa.

In Figure 26, the location of longitudinal stress difference varies with location of longitudinal gap. In the follow four cloud images, the maximum longitudinal stress difference of integration point is 0.79 MPa, 0.68 MPa, 0.65 MPa and 0.59 MPa, respectively. It can be found that the degradation of longitudinal stress is slowly decreased with the increasing of gap length. As to the gap that extends longitudinally, once the size of gap exceeds the range of 600 mm × 100 mm, the stress difference at the position of fastener bolt will occur. The stress state will be converted into tension state and stress difference will be concentrated. When the length of the gap is 1,400 mm, the stress difference is gradually stabilised at 0.80 MPa.

4 Conclusions

To explore the effect law of mortar gap on the static performance of different parts of CRTS-I slab ballastless track structure, the plastic damage constitutive relation and damage factor of CRTS-I slab track was considered. The nonlinear finite element model of CRTS-I slab track with gap was established under the temperature load and the static load of train and then the effect of gaps of different sizes, at different locations on the part of CRTS-I slab track was calculated and analysed under different load combinations by ABAQUS. The following conclusions could be drawn:

1 In terms of the same size of gap, the influence of gap at slab centre (C-gap) on deterioration stress and vertical deformation of track system are obviously less than that of gap at slab end (E-gap). And the influence of the load 'F_T+' on deterioration stress of track structure is more than that of the load 'F_T'. When determining damage level of track structure, the relevant size parameters of E-gap can be adopted under the load 'F_T+'.

2 In terms of the same width and length of gap, the influence of gap at slab end (E-gap) on the maximum vertical displacement of the track system increase significantly with the increase depth of gap. When the gap area is 1,400 mm × 800 mm, the maximum vertical displacement of rail and slab compared with normal slab track are up to 16.4% and 17.9%, respectively.

3 In terms of the same depth and width of gap, the influence of gap at slab end (E-gap) on the vertical displacement of rail increases gradually with the increase length of gap and while that of slab slightly increases as the length of gap increases.

4 In terms of the same width of gap, gap area has great effect on the deterioration stress of track structure. As to the gap that extends longitudinally, once the size of gap exceeds the range of 600 mm × 100 mm, the concentration of deterioration stress
also occurs at the bolt hole of the fastener; they are close to or even more than 0.60 MPa. It will threaten the durability of track structure when the gap area is too large.

5 The study can obviously provide theoretical reference for the formulation of maintenance and repair standard of CRTS-I slab track and the analysis method proposed may be further used to study critical size and damage rating of gap for CRTS-I slab track.

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