

# Damage destruction evolution law of high-speed railway CRTS II slab ballastless track interface under train braking and temperature load

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**Abstract:** The train braking and temperature load are simplified as shear loads and based on the cohesive stress constitutive model and test parameters, an interfacial nonlinear finite element model for the cohesion-displacement relationship of high-speed railway CRTS II slab ballastless track interface was established and verified by theoretical analysis. Damage destruction evolution law of the interface under shear loads, and the influence of shear steels on the interfacial longitudinal maximum cohesion and ultimate yield displacement are studied. Results indicates that the error between axial force difference of track slab and the interfacial constraint reaction is no more than 2%, which verified the correctness of the interfacial nonlinear finite element model; the longitudinal displacement of track slab increases with the increase of shear loads, and it decreases as the distance from the loading end increases; the interfacial longitudinal cohesion can fluctuate up and down at a certain value with the increase of longitudinal displacement, and then the interface gradually loses cohesion until it is completely destroyed and enters the sliding state. The three shear steels layout forms are all made the interfacial longitudinal maximum cohesion and ultimate yield displacement increase, the contributions of interfacial longitudinal maximum cohesion are 21.46%, 23.54% and 53.03%, respectively, and the contributions of ultimate yield displacement are 9.72%, 15.61% and 44.92%, respectively. Shear steel plays an important role in satisfying deformation demand of track structure.

## 1. Introduction

High-speed railway CRTS II slab ballastless track structure is generally a composite material structure formed by laying and curing the bed plate, CA mortar layer and track slab<sup>[1, 2]</sup>, the stability of track slab is ensured by the cohesion between CA mortar material and track slab, and the cohesion between CA mortar material and bed plate interface transfers load to bridge or subgrade. CRTS II slab ballastless track structure has become the mainstream mode of modern high-speed railway track structure because of its better line static and dynamic smoothness, higher structural durability and stability<sup>[3]</sup>.

High-speed railway CRTS II slab ballastless track structure is easy to damage under external factors, current researches on track structural damage characteristics are mostly focusing on the crack and stiffness degeneration of track slab, bed plate and bearing layer structure etc.<sup>[4, 5]</sup>, and ignoring the destruction and failure problem of structural interlayer interface, however, the structural interlayer interface is vulnerable to damage in practical engineering. Under train braking and temperature load,



the shear force difference will occur between structural layers so that the structural interface is damaged, even leads to destruction. There are two main destruction forms, one is the crack both appeared on the interface between CA mortar layer and track slab and between CA mortar layer and bed plate, the other is the crack only appeared on the interface between CA mortar layer and track slab. Previous studies had shown that CA mortar layer and track slab interfacial crack width was generally less than 0.5mm, with the maximum length could reach 2-3mm, but the interfacial crack length was different, the maximum length was more than ten meters<sup>[6]</sup>. The interfacial crack will seriously affect the stability of track structure and the line smoothness, bringing safety hazards to the operation of high-speed train<sup>[7, 8]</sup>. Under three special circumstances, such as the gaps between the girder and girder, between the girder span and abutment, and between the abutment and friction plate; the first track slab on the transition plate at bridge and subgrade, and subgrade adjacent to the transition plate; when the longitudinal construction of track slab is interrupted for more than 12h and so on, the track structure interfacial damage is more obvious under the train braking and temperature load, track slab and bed plate are laid out with the shear steels to connect them into a whole to reduce such damage in practical engineering. However, the influence of shear steels on the interfacial longitudinal maximum cohesion and ultimate yield displacement are not clear, needing to study.

The train braking and temperature load are simplified as shear loads in this paper and based on the cohesive stress constitutive model and test parameters, an interfacial nonlinear finite element model for cohesion- displacement relationship of high speed railway CRTS II slab ballastless track interface was established and verified by theoretical analysis. The error between axial force difference of track slab and the interfacial constraint reaction is no more than 2%, which verified the correctness of the interfacial nonlinear finite element model; Damage destruction evolution law of interface under shear loads, and the influence of shear steels on the interfacial longitudinal maximum cohesion and ultimate yield displacement are studied.

## 2. Theoretical analysis

In practical engineering, the interfacial cohesion of CA mortar layer and bed plate is much larger than that of CA mortar layer and track slab with the influence of construction method, which makes the damage is mainly on the interface between CA mortar layer and track slab<sup>[9]</sup>. As shown in Fig. 1, taking a section of track structure with length  $L$ , and the shear load  $p_0$  is applied at one end of track slab to analyze its stress state. Due to the interfacial cohesion of CA mortar layer and bed plate is large enough, the interface has little relative displacement under shear load, it can be further simplified, CA mortar layer's subface was completely fixed as structure boundary condition.

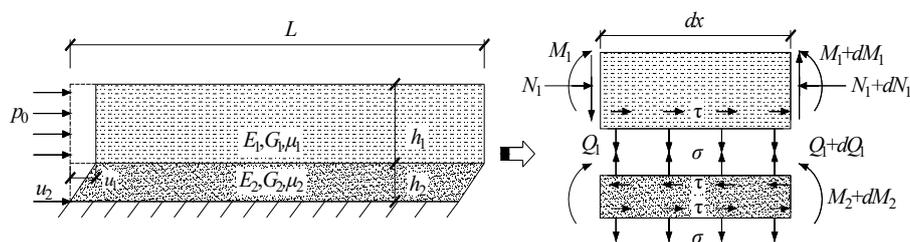


Figure 1. The interfacial damage mechanism of CRTS II slab ballastless track

In figure 1,  $G_1, G_2$  are the shear modulus of track slab and CA mortar layer, respectively;  $\mu_1, \mu_2$  are the longitudinal displacement of the bottom edge of track slab and the top edge of CA mortar layer, respectively;  $E_1, A_1$  is the elastic modulus and interfacial area of track slab, respectively;  $N_1, Q_1, M_1$  are the axial force, shear force and bending moment of track slab, respectively;  $M_2$  is the bending moment of CA mortar layer;  $\sigma, \tau$  are the interfacial normal stress and shear stress, respectively;  $h_1, h_2$  are the thickness of track slab and CA mortar layer, respectively;  $b$  is the width of track slab;  $L$  is the length of the track structure.

Force analysis of track slab was carried out [7]:

$$\sum N = 0; \frac{dN_1}{dx} = -b\tau(x) \quad (1)$$

$$\sum Q = 0; \frac{dQ_1}{dx} = -b\sigma(x) \quad (2)$$

$$\sum M = 0; \frac{dM_1}{dx} = Q_1 - \frac{h_1}{2} b\tau(x) \quad (3)$$

Force analysis of CA mortar layer was carried out:

$$\sum M = 0; \frac{dM_2}{dx} = h_2 b\tau(x) \quad (4)$$

It can be seen that there are certain shear stress and normal stress at interface between track slab and CA mortar layer under shear load, and shear stress is the main stress. If the interface is always in an elastic working state, according to literature[10], the shear stress is:

$$\tau(x) = -\frac{\lambda}{b}(c_1 e^{\lambda x} - c_2 e^{-\lambda x}) \quad (5)$$

Wherein,  $c_1$ 、 $c_2$  are the undetermined coefficients related to boundary condition,  $\lambda = \sqrt{bG / h_2 E_1 A_1}$ .

It can be seen that the shear stress is at its maximum at position of  $x=0$  and  $x=L$ , the maximum shear stress  $\tau_{\max} = -\lambda / b(c_1 - c_2)$ . Therefore, the structural damage, cracking and destruction are easy to occur at the end of track slab. However, considering the interfacial stress under the influence of internal bending moment and the mechanical behavior after the interface enters the elastic-plastic state, further analysis needs to be carried out through numerical simulation, as described below.

### 3. Interfacial nonlinear finite element model

#### 3.1. CA mortar constitutive model

CA mortar constitutive model that adopted in this paper was established by Fu et al.<sup>[11]</sup>, he conducted CA mortar compression stress-strain test by using microcomputer control electronic universal testing machine, through introducing a damage variable  $D$  into a flexible body in Kelvin model and modifying to a damage body, then a new strain rate CA mortar constitutive model was established. The stress-strain relationship curve of CA mortar is shown in figure 2, the constitutive relationship is as follows:

$$\sigma_{ca} = E \varepsilon_{ca} \exp\left[-\left(\frac{\varepsilon_{ca}}{m}\right)^n\right] + \eta \theta \quad (6)$$

Where,  $\sigma_{ca}$ ,  $\varepsilon_{ca}$  are the CA mortar normal stress and normal strain, respectively;  $E$  is the CA mortar elastic modulus;  $\eta$  is the CA mortar viscosity coefficient;  $m$ ,  $n$  are the distributed parameter of Weibull distribution;  $\theta$  is the strain rate.

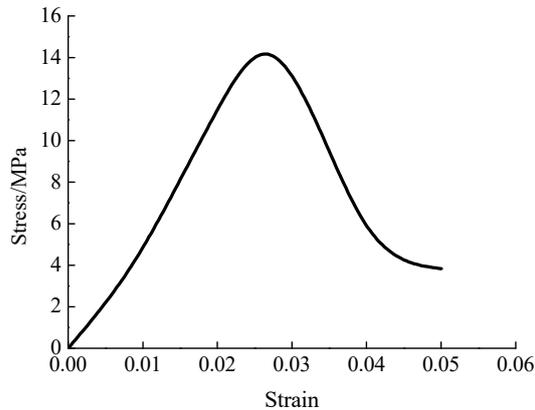


Figure 2. CA mortar stress-strain curve

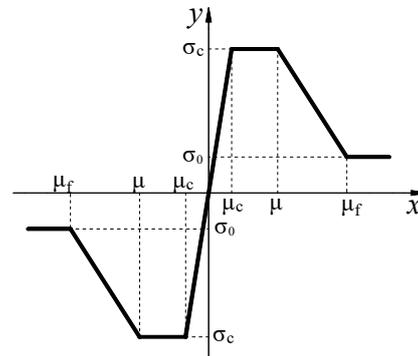


Figure 3. Interfacial cohesion stress-strain curve

### 3.2. CA mortar layer and track slab interfacial cohesion constitutive model

CA mortar layer and track slab interfacial cohesion and relative displacement is a kind of nonlinear relationship, when the interfacial stress reaches cohesion, the initiation and extension of crack, and delaminating crack failure will occur at the interface. Some studies had shown that the cohesive stress model can be much closer to describe the interfacial behavior<sup>[12]</sup>. Therefore, the interfacial properties of CA mortar layer and track slab in CRTS II slab ballastless track structure are described by section by section linear tension and displacement rule of the cohesive stress constitutive model<sup>[13, 14]</sup>, the interfacial cohesion stress-strain curve is shown in figure 3. The interfacial cohesion stress-displacement control equation is shown as follows:

$$\sigma = \begin{cases} \sigma_c \mu / \mu_c & (\mu < \mu_c) \\ \sigma_c & (\mu_c \leq \mu \leq \mu_0) \\ \sigma_c (\mu_f - \mu) / (\mu_f - \mu_0) & (\mu_0 < \mu < \mu_f) \\ \sigma_0 & (\mu \geq \mu_f) \end{cases} \quad (7)$$

Where,  $\sigma_c$ ,  $\mu_c$  are the interfacial longitudinal cohesion and its corresponding displacement, respectively;  $\mu_f$  is the critical displacement when the interfacial longitudinal cohesion decreases to zero.

According to the push test in the school of railways, Central South University<sup>[15]</sup>, the push test of the German Company Berg<sup>[7, 8]</sup> and test results of China Railway Science Research Institute<sup>[16]</sup>, it can be obtained that the interfacial longitudinal maximum cohesion between CA mortar layer and track slab is 0.0249MPa, ...,  $\mu$ ,  $\mu_f$  are 0.01mm, 0.015mm and 0.03mm, respectively.

### 3.3. Establishment of interfacial nonlinear finite element model

This article used the finite element software ANSYS to establish "CA mortar layer - track slab" interfacial nonlinear finite element model, CA mortar layer and track slab both adopted 8 node Solid65 solid elements to simulate, track slab constitutive model used multilinear isotropic reinforcement model MISO, CA mortar layer used multilinear kinematic hardening MKIN<sup>[17]</sup>; the interface between CA mortar layer and track slab is connected by nonlinear spring element combin39, which is used to simulate the interfacial nonlinear stress-strain relationship. Parameter's selection refers to the industry standards and experimental research<sup>[18]</sup>.

## 4. Verification and analysis

### 4.1. Model verification

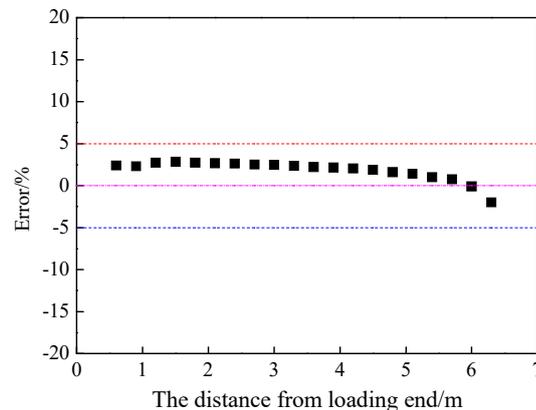


Figure 4. The error of the axial force difference and interfacial constraint reaction

For the interfacial nonlinear finite element model, a layer of nonlinear spring element is used to simulate the interfacial working state between CA mortar layer and track slab, the internal force of the nonlinear spring element is equal to the interfacial constraint reaction. The axial force difference of track slab can be obtained from Eq.(1), and  $\Delta N_1 = -\int_0^L \tau(x) \cdot b dx$ . The shear stress  $\tau$  on the contact surface of CA mortar layer and track slab was integrated, and the interfacial constraint reaction was obtained that is induced by CA mortar layer interfacial shear stress  $F = -\int_0^A \tau_x dA_b$ , so it should be  $\Delta N_1 = F$  [19]. To verify the correctness of the interfacial nonlinear finite element model, figure 4 shows the error of the axial force difference of track slab and interfacial constraint reaction at a certain distance in the interfacial nonlinear finite element model, it can be seen from figure 4 that the error of the axial force difference of track slab and interfacial constraint reaction is no more than 2% along track slab's length, which verifies the correctness of the model.

#### 4.2. Damage destruction evolution law of interface

Figure 5 shows that the interfacial longitudinal cohesion-displacement curve between CA mortar layer and track slab under shear loads. As can be seen from figure 5, the interfacial longitudinal maximum cohesion is 244.732kN, the ultimate yield displacement is 0.051mm. When the cohesion reaches its maximum, the displacement continues to increase, the interfacial longitudinal maximum cohesion maintains for a period of time and then begins to decline, at this point, the interface has started to damage, and the displacement continues to increase. After the interface completely invalidates, it enters the sliding state. When reaching the maximum longitudinal cohesion, the interfacial longitudinal displacement corresponding to the five position points selected (Loading end and the distance from loading end  $L/8, L/4, L/2, L$ ) in the track slab are 0.050mm, 0.042mm, 0.033mm, 0.017mm, 0.005mm, respectively. It can be found that the further away from loading end, the smaller the interfacial longitudinal displacement is. When the cohesion is less than 200.884kN, the longitudinal displacement and cohesion basically show a linear relationship, and then the increase rate of the longitudinal displacement is accelerated, indicating that the interface has entered the elastic-plastic state. Due to the long transmission length of interfacial shear stress during longitudinal loading, the interfacial longitudinal cohesion can fluctuate up and down at a certain value with the increase of relative displacement between CA mortar layer and track slab.

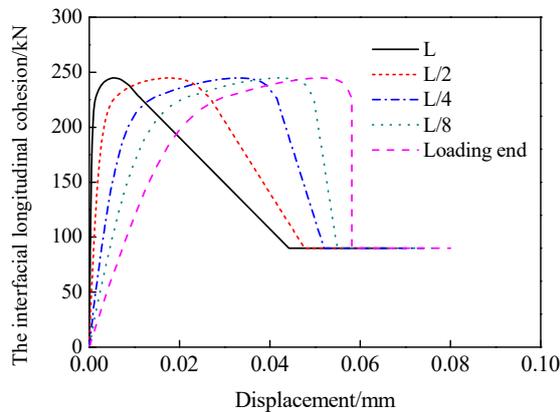


Figure 5. The interfacial longitudinal cohesion-displacement curve

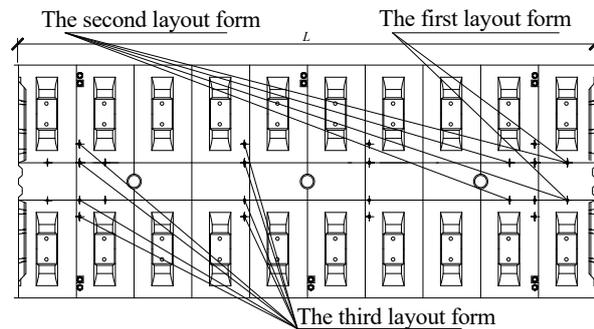


Figure 6. The arrangement of shear steels

### 4.3. Influence of shear steels on interfacial longitudinal cohesion and ultimate yield displacement

#### 4.3.1. Layout of shear steels in practical engineering

In order to satisfy the structural deformation demand, three special circumstances to lay out shear steels were usually used in the construction of track structure. The first layout form: on the bridge or subgrade, when the longitudinal construction of track slab is interrupted for more than 12h, shear steels should be laid out on three track slabs at the discontinuity immediately after interrupting the construction, and four shear steels are laid out on each track slab; the second layout form: the gaps between the girder and girder, between the girder span and abutment, and between the abutment and friction plate, track slab is variable in the longitudinal direction relative to girder gaps, and the distance between girder gaps and the location of drilling hole is also variable, eight shear steels must be laid out on both sides of girder gaps; the third layout form: the first track slab on the transition plate at bridge or subgrade and subgrade adjacent to the transition plate, sixteen shear steels are laid out on track slab. Due to the space limitation, the three shear steels layout forms above are all reflected in the same track slab as shown in figure 6.

#### 4.3.2. Calculation for shear strength of shear steels

The shear strength of shear steels of the three shear steels layout forms are calculated as follows <sup>[19]</sup>:

$$V = Vu(1 - e^{-\delta})^{0.558} / n_s \tag{8}$$

$$Vu = \min(0.43A_b\sqrt{E_c f_c}, 0.7A_b f_u) \tag{9}$$

Where,  $f_c$  is the axial compressive strength of CA mortar layer ;  $E_c$  is the CA mortar elastic modulus;  $A_b$  is the cross-section area of steel;  $f_u$  is the ultimate tensile strength of steel;  $n_s$  is the number of steel;  $\delta$  is the slip of steel.

Table1. The influence of shear steels on interfacial longitudinal maximum cohesion and ultimate yield displacement

Results analysis	No steel	The first layout form	The second layout form	The third layout form
Interfacial longitudinal maximum cohesion /kN	244.732	297.2414	302.3499	374.5074
Ultimate yield displacement /mm	0.0051	0.0559	0.0589	0.0738
$C_{cohe}$ /%	0.00	21.46	23.54	53.03
$C_{disp}$ /%	0.00	9.72	15.61	44.92

The influence of shear steels on interfacial longitudinal maximum cohesion and ultimate yield displacement between CA mortar layer and track slab as shown in table 1 and figure 7.  $C_{cohe}$  represents the contribution of shear steels to the interfacial ultimate yield displacement;  $C_{disp}$  represents the contribution of shear steels to the ultimate yield displacement.

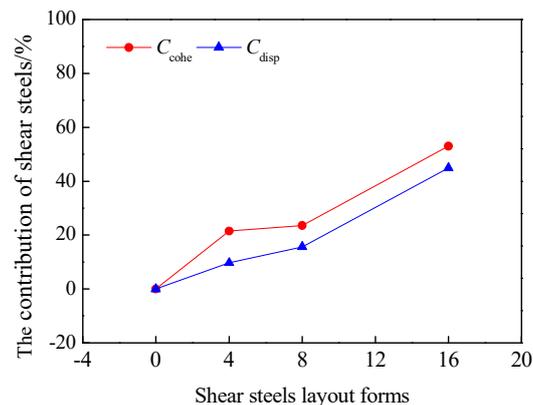


Figure 7. The contribution of shear steels to the interfacial longitudinal maximum cohesion and ultimate yield displacement

It can be seen from table 1 and figure 7, the interfacial maximum longitudinal cohesion and ultimate yield displacement of CA mortar layer and track slab increase after shear steels are taken into account. In the three shear steels layout forms, the contribution of shear steels to the interfacial longitudinal maximum cohesion  $C_{cohe}$  are 21.46%, 23.54% and 53.03%, respectively; the contribution of shear steels to the ultimate yield displacement  $C_{disp}$  are 9.72%, 15.61% and 44.92%, respectively. It can be seen that shear steel plays an important role in satisfying deformation demand of track structure.

## 5. Conclusion

The longitudinal displacement of track slab increases with the increase of shear loads, and it decreases as the distance from the loading end increases; with the increase of longitudinal displacement, the interfacial longitudinal cohesion can fluctuate up and down at a certain value, and then the interface gradually loses the cohesion until it is completely destroyed and enters the sliding state.

The three shear steels layout forms all made the interfacial longitudinal maximum cohesion and ultimate yield displacement increase, shear steel plays an important role in satisfying deformation demand of track structure.

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