Research on Stresses of Narrow Joints Caused by Construction Process of CRTSII Slab Track

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Abstract. A separate finite element model of 1/4 unit track slab of CRTS II slab track was established for the analysis of the influence of construction process on stresses of narrow joints. When track slabs were connected by tension and when wide joints hardened, the impacts of the longitudinal connection of CRTS II slab on stresses of narrow joints were analysed. The results show that when track slabs are connected by tension, the bonding states between track slab and mortar layer have little effect on track slab expansion displacement and the re-compression of narrow joints caused by the tensioning force cannot be ensured. If track slabs are connected by tensioning force after the concrete hardening of narrow joints, compressive stresses of narrow joints can be increased by 3.03 MPa. Due to the influence of longitudinal connection of CRTS II slab, the respective track slab temperature for wide joints hardening T_k and narrow joints hardening T_z are difficult to keep consistent. When wide joints hardened, it potentially makes the compressive stresses of narrow joints zero or very large. In order to keep the narrow joints compressed when wide joints hardened, the measures to control T_z and T_k should be taken to make T_k slightly higher than T_z .

1 Instruction

CRTS II slab track mainly consists of track slab, cement emulsified asphalt mortar layer, base plate or support layer. In addition to that the mortar layer, base plate or support layer is the longitudinal continuous structure, track slabs are also connected through joints between slabs to become a longitudinal continuous reinforced concrete structure. Since this structure was used in Beijing-Tianjin inter-city railway in 2008, the overall quality is in good condition, which meets the requirements of high-speed railway for high smoothness and high stability. However, the high-speed railway has been widely constructed in a variety of districts, in which the climatic conditions vary greatly. As a longitudinal continuous structure, the temperature effect of CRTS II slab track caused by temperature load is very significant. Affected by the environment, temperature, temperature gradient and so on, the gap under slabs was generated, and joint-defects and arch between slab joints appeared. It brought not only maintenance and repair work, but also adverse effects to normal operation. The uneven stresses in joints are an important cause leading to track slab arch and joint-defects. Therefore, it is very necessary to study the mechanical characteristics of joints between slabs.

In addition to the influence of construction quality, joint-defects and joint-deformation between slabs were mainly influenced by temperature. At present, there have been many researches on behaviour of joint-defects, the stress and deformation and dynamic response of track

structure caused by joint-defects [1-3]. However, there were few studies on influences of construction process of II slab on joint stresses. Through the analysis of mechanical relationships between track slab and mortar layer, steel bars, joints, the finite element model was established. The influences of construction process of II slab under the action of temperature force on stresses of narrow joints were analysed.

2 Longitudinal connection of CRTS II slab

CRTS II track slabs are prefabricated structure in the factory. After the laying of track slabs, they are connected to become a longitudinal continuous structure through joints between slabs. Joints between slabs are shown in Figs. 1~2. Six steel bars with a diameter of 20 mm connect two adjacent track slabs together by the tensioning slack adjusters at the end of slabs. According to the construction process [4], joints between slabs are poured firstly after the strength of emulsified asphalt cement mortar (CA mortar) under slab reaches 7 MPa, which is known as narrow joints with a height of 0.1m; When the strength of CA mortar reaches 9MPa and the concrete strength of narrow joints reaches 20MPa, the six longitudinal steel bars will be connected by the tensioning slack adjusters, and each bar has a tensile load of 50kN. Then the rest of joints will be poured at last, which are known as wide joints. The narrow joints

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consist of three parts, whose lengths are about 0.2m, 0.4m, and 0.2m respectively [4].

Figure 1. Picture of joints between slabs.

Figure 2. Narrow joints which had been Finished.

Judging from the construction process, compared with the continuous pouring of reinforced concrete structure, the concrete of narrow joints of CRTS II slab are poured firstly, then the concrete of wide joints. Therefore, there is a difference in slab temperatures when the narrow joints and wide joints hardened, and there is also a pre-tension when the longitudinal steel bars are connected. So the longitudinal connection characteristic of CRTSIIslab track is very obvious. When wide joints hardened, this characteristic made the stresses of narrow joints very complicated, which could be zero or very large. Zhou Min et al.'s research [5] shows that there is indeed some phenomenon on site that when the crack between wide joints and slabs is inexistent, there are cracks between narrow joints and slabs at the same place. This is in conflict with the design concept of II slab, which is "the compressive stresses of narrow joints should be always existent when track slabs are connected completely or the wide joints harden". It shows that some improvements are needed for current construction process control measures, so it is of certain engineering significance to carry out the research.

3 Models and parameters

3.1 Model assumption

(1) The deformation and stress of track slab are of symmetric distribution under the loads of longitudinal tension, joints between slabs and temperature.

(2) The displacements of track slab cross-section are evenly distributed.

(3) The stresses and strains of steel bars cross-section are evenly distributed.

(4) The stresses of narrow joints cross-section are evenly distributed.

(5) Considering that the interfaces between the concrete of joints and the end face of track slab are new-old concrete joint surfaces, and the end face of track slab is vertical and its roughness is small, the interface bond stresses are small. Therefore the tensile restraints from the concrete of joints on track slab are neglected.

3.2 Finite element model

Track slab is simulated by solid element solid45. Its length, breadth, and height are 6.45m, 2.55m, and 0.2m respectively. Its elastic modulus is 3.60×10^4 MPa. Its Poisson's ratio is 0.2. Its thermal expansion coefficient is 1.0×10^{-5} . The top width, bottom width, and height of pre-splitting crack are 38mm, 4mm and 28mm respectively. The constraints of mortar layer and steel bars on track slab are simulated by ANSYS 3D nonlinear spring element COMBIN39, which parameters are shown in sections 2.3 and 2.4 respectively. The longitudinal and horizontal steel bars are simulated by LINK1 and LINK8 respectively. Its elastic modulus is 2.0×10^5 MPa. Its thermal expansion coefficient is 1.2×10^{-5} . The length of horizontal common steel bars is 2.45m, and that of horizontal pre-stressed steel bars is 2.55m. The lengths of longitudinal steel bars are 6.2m and 6.35m in the positions of wide and narrow joints respectively. The length of tensioned rebar is 6.45m. The number and locations of steel bars are seen in literature [7].

Narrow joint is simulated by the bar element LINK10 with only compression. The differences in the cross section of joints are neglected. According to the symmetry of the model, a finite element model of 1/4 track slab was established.

In order to consider the constraints of mortar on track slab at joints, the bottom thickness of track slab at wide joints is kept as 20mm. The final separate finite element model of 1/4 track slab is shown in Fig. 3.

Figure 3. Finite element model of 1/4 track slab.

3.3 Bond slip behavior between track slab and tensioned rebar

The steel bars, which are adopted by CRTSII track slab, all are hot rolled ribbed steel bars [7]. *Code for design of concrete structures* (GB50010-2010) provides the constitutive relation of the bond stress-slip between concrete and hot rolled ribbed steel bar. For CRTS II

track slab, whose axial tensile stress $f_{t,r}$ is 3.55MPa [8], the value is not quite different from the average value of tensile strength of C55 concrete, which is 3.60MPa [9]. Then, there are $\tau_{cr}=2.5f_{t,r}$, $\tau_u=3f_{t,r}$, $\tau_r=f_{t,r}$, $s_{cr}=0.025d$, $s_u=0.04d$, $s_r=0.55d$ [9], where d is the diameter of steel bar. Taking the tensioned rebar as an example, the relationship between bond stress τ_s and relative slip displacement s between track slab and tensioned rebar is shown in Fig. 4.

Figure 4. Bond slip curve between track slab and tensioned rebar.

For the rest of steel bars with a diameter of 8mm, 10mm and 16mm respectively, the corresponding slip curves can be obtained by calculating the corresponding s_{cr} , s_u , and s_r .

3.4 Friction characteristics between track slab and mortar layer

The constraint of mortar layer on track slab was influenced by ambient temperature, and gradually decreased with time. Through analysis of the indoor and field tests between track slab and mortar layer at home, the bonding states between track slab and mortar layer are divided into three stages, which are good bond, partial bond and poor bond respectively, and will be simulated by a piecewise linear model.

When mortar layer was stiffened, the bonding state between track slab and mortar layer was little influenced by the environment. At this time, the interlayer state was regarded as good bond, and the selection of parameters were based on the indoor tests. When the bonding state between track slab and mortar layer is in good bond condition, the relative displacement between track slab and mortar layer was very small before the micro cracks were generated. It is considered that the angle of shear is directly proportional to the shear stress. When the bonding state between track slab and mortar layer is good bond, the inter-laminar shear stiffness k_c is:

$$k_c = G_c/h_c \quad (1)$$

$$G_c = E_c/2/(1+\nu_c) \quad (2)$$

Where E_c - elastic modulus of mortar, 8000MPa;
 ν_c - Poisson's ratio of mortar material, 0.2;
 h_c - thickness of mortar layer, 0.03m.

It is known from the indoor shear tests between track slab and mortar layer [2,11] that, the inter-laminar shear strength of 28d age is about 0.44~0.78MPa. When the model simulation was analyzed, the parameter was taken

as 0.5 MPa in most of the model. When the bonding state between track slab and mortar layer is in good bond condition, the inter-laminar shear strength is 0.5 MPa.

In the plate pushing test in China, the temperature of mortar was controlled at $20 \pm 2^\circ\text{C}$ after mortar perfusion. The push plate force was about 120t, while the corresponding longitudinal shear stress was about 72KPa, and the corresponding inter-laminar displacement was about 0.02mm [10]. At this time, the bonding state between track slab and mortar layer was less affected by external environment, and the interlayer state was regarded as partial bond.

In the plate pushing test in German, the plate pushing force was about 41t, while the corresponding longitudinal shear stress was about 24KPa, and the corresponding inter-laminar displacement was about 0.5mm [12]. At this time, the bonding state between track slab and mortar layer was greatly influenced by external environment, and the interlayer state was regarded as poor bond.

In summary, the relationship between shear strength τ_c and relative displacement y_{bc} between track slab and mortar layer was obtained as shown in Fig. 5.

Figure 5. Relation ship of friction between track slab and mortar layer.

In Fig. 5, A, B and C points are the critical points of good bond, partial bond and poor bond respectively. The curve OABCD is a weakening curve of the bonding state between track slab and mortar layer when environmental factors are considered.

3.5 Boundary conditions

(1) Displacement constraints were adopted at the end of narrow joints, and the values of displacement constraints took the displacement values of common nodes between track slab and narrow joints when narrow joints hardened.

(2) The shear constraints of mortar layer on track slab were simulated by springs, and the bottom was fully constrained.

(3) Except degree of freedom along the length of steel bars, the remaining two degrees of freedom were restrained, only allowing the steel bars to expand freely along the length direction.

(4) Displacement constraints were adopted at the end of tensioned rebar after track slabs were connected by tension. The values of displacement constraints took the end displacements of tensioned rebar calculated by the corresponding working condition.

4 Result analysis

Narrow joints are mainly affected by temperature expansion of track slab. The overall temperature rise and fall of track slab were mainly considered. From the mortar layer hardening to the concrete hardening of wide joints, the variation of track slab temperature was mainly affected by monthly temperature difference. For calculation the variation of track slab temperature is 30°C, and the maximum of one-way temperature is 20°C.

4.1 Track slabs connected by tension

The main influence factors of stresses of narrow joints are: the maximum of track slab temperature rise or fall $\Delta T_{\max}$ before concrete hardening of narrow joints, the ascending range of track slab temperature ΔT_{sl} from concrete hardening of narrow joints to the connection between track slabs, and the tensioning force.

The initial interlayer states between track slab and mortar layer were divided into three working conditions: good bond, partial bond and poor bond. The corresponding interlayer weakening curves are OABCD, OBCD and OCD respectively in Fig 5.

When the stresses of narrow joints were analysed, the initial interlayer state between track slab and mortar layer was regarded as in good bond condition, and the corresponding interlayer weakening curve is OABCD in Fig 5. When calculating stresses of narrow joints, assuming that the narrow joints hardened after $\Delta T_{\max}$ was exerted on the model, and then ΔT_{sl} and the tensioning force were exerted on the model. When analysing the effect of tensioning force on narrow joints, the above results were applied to subtract results of the model which exerted $\Delta T_{\max}$ and ΔT_{sl} simultaneously. In the calculation, $\Delta T_{\max}$ are 0°C, 4°C, 5°C, 6°C, 7°C, 10°C, 20°C respectively, and ΔT_{sl} are 5°C, 10°C, 20°C respectively. Relationships between end displacements of track slab y_{bd} and $\Delta T_{\max}$ are shown in Fig. 6. The increments of end displacements of track slab caused by the tensioning force Δy_{bd} are shown in Fig. 7. Compressive stresses of narrow joints caused by tensioning force σ_{zl} are shown in Fig. 8. Relationships between compressive stresses of narrow joints σ_z caused by ΔT_{sl} and $\Delta T_{\max}$ are shown in Fig. 9.

Figure 6. Relationships between end displacements of track slab y_{bd} and $\Delta T_{\max}$.

Figure 7. The increments of end displacements of track slab Δy_{bd} caused by tensioning force.

Figure 8. Compressive stresses of narrow joints σ_{zl} caused by tensioning force.

Figure 9. Relationships between compressive stresses of narrow joints σ_z caused by ΔT_{sl} and $\Delta T_{\max}$.

Figure 6 shows that with the increase of $\Delta T_{\max}$, end displacements of track slab y_{bd} increase gradually. Combined with Fig. 5, it is not difficult to see that the bonding states between track slab and mortar layer are weakening gradually. As the initial interlayer states between track slab and mortar layer changing from good bond to partial bond or poor bond, y_{bd} increase slightly, and the increments of y_{bd} decrease gradually with the increase of $\Delta T_{\max}$. When $\Delta T_{\max}$ increases from 4°C to 20°C, the increment of y_{bd} decreases from 0.048mm or 0.088mm to 0.000088mm or 0.0086mm as the initial interlayer state between track slab and mortar layer changing from good bond to partial bond or poor bond. When $\Delta T_{\max} > 6^\circ\text{C}$, the maximum increment of y_{bd} is

about 0.0029mm or 0.038mm as the initial interlayer state between track slab and mortar layer changing from good bond to partial bond or poor bond. When considering tensioning force, the increments of y_{bd} decrease slightly. It is indicated that y_{bd} are mainly related to the temperature rise and fall of track slab, and the bonding states between track slab and mortar layer has little effect on track slab expansion displacement.

Figure 7 shows that under the action of tensioning force, the end displacements of track slab increase, and the increments Δy_{bd} are related to the interlayer bonding states. When the interlayer state is the best, namely $\Delta T_{max} = 0^\circ\text{C}$, Δy_{bd} increase gradually as the initial interlayer state between track slab and mortar layer changing from good bond to poor bond. When the interlayer state is weakened, namely $\Delta T_{max} = 4\sim 20^\circ\text{C}$, the tensioning force will accelerate interlayer weakening, which leads to the release of energy accumulated in track slab. And the better the interlayer bonding state, the more the release of energy. At the same time, Δy_{bd} decreases gradually as the initial interlayer state between track slab and mortar layer changing from good bond to poor bond, and then tend to be constant. When $\Delta T_{max} > 6^\circ\text{C}$, Δy_{bd} caused by the tensioning force is 0.047~0.051mm, 0.047~0.048mm and 0.045~0.046mm respectively as the initial interlayer state changing from good bond to poor bond.

Figure 8 shows that under the action of tensioning force, compressive stresses of narrow joints increase. When the interlayer state is the best, namely $\Delta T_{max} = 0^\circ\text{C}$ and $\Delta T_{sl} = 5^\circ\text{C}$, tensioning force has the constraint of mortar layer on track slab strengthened, which leads to the small increment of compressive stresses of narrow joints σ_{zl} . When the interlayer state is weakened, tensioning force will lead to the release of energy accumulated in track slab, which leads to σ_{zl} very large; When $\Delta T_{max} = 4\sim 5^\circ\text{C}$, the release of energy accumulated in track slab reaches the maximum, the maximal value of σ_{zl} is about 3.3 MPa. Then with the weakening of interlayer states, the release of energy accumulated in track slab decreases gradually, and then σ_{zl} tend to be constant. When $\Delta T_{max} > 6^\circ\text{C}$, σ_{zl} caused by tensioning force is about 3.01~3.05MPa, and the change rule of σ_{zl} is basically the same as the change rule of solid line in Fig. 7.

Figure 9 shows that with the increase of ΔT_{sl} , compressive stresses of narrow joints increase gradually. When the interlayer state is the best, namely $\Delta T_{max} = 0^\circ\text{C}$, the constraint of mortar layer on track slab is strengthened gradually with the increase of ΔT_{sl} , and σ_z gets to the minimum values. When the interlayer state is weakened, ΔT_{sl} leads to the release of energy accumulated in track slab. When $\Delta T_{max} = 4\sim 5^\circ\text{C}$, the release of energy accumulated in track slab reaches the maximum, and σ_z reaches the maximum. Then with the weakening of interlayer states, the release of energy accumulated in track slab decreases gradually, and σ_z decreases gradually and then tends to be constant. When $\Delta T_{max} > 6^\circ\text{C}$, σ_z is mainly related to ΔT_{sl} . When ΔT_{sl} are 5°C 、 10°C and 20°C respectively, σ_z are 13.65~13.73 MPa、24.28~24.41MPa and 45.55~45.77 MPa

respectively. The change rule of σ_z is basically the same as the change rule of solid line in Fig. 7.

ΔT_{max} is the maximum of track slab temperature rise or fall before the concrete hardening of narrow joints, which is mainly related to diurnal temperature difference and should be more than half the maximum of that. The diurnal temperature difference is usually $10\sim 20^\circ\text{C}$, so the possibility that ΔT_{max} is less than 6°C is very small. Therefore, the interlayer bonding state had been very weak when track slabs were connected by tensioning force. When $\Delta T_{max} > 6^\circ\text{C}$, is about 0.045~0.051mm, and σ_{zl} is about 3.01~3.05MPa. Also σ_z is mainly related to ΔT_{sl} . When ΔT_{sl} is $5^\circ\text{C}\sim 20^\circ\text{C}$, σ_z is about 13.65~45.77 MPa.

End displacements of track slab caused by the tensioning force are very small. If track slab is cooled down and contracted after the concrete hardening of narrow joints, the pre-compression of narrow joints caused by tensioning force cannot be ensured. Therefore, when track slabs are connected by tensioning force, narrow joints may not be stressed, or they may be subjected to large compressive stresses due to larger ΔT_{sl} .

4.2 Wide joints hardened

From the connection between track slabs to concrete hardening of wide joints, the temperature expansion of track slab is affected by mortar layer, narrow joints and tensioned rebar. The main influence factors of stresses of narrow joints are ΔT_{max} , track slab temperature T_l when track slabs are connected by tension, track slab temperature T_z when narrow joints hardened, track slab temperature T_k when wide joints harden.

For calculation simplification, it is assumed that the narrow joints harden when track slabs are connected by tension and $T_l = \Delta T_{max}$. ΔT_{max} are 0°C , -4°C , -5°C , -6°C , -7°C , -10°C respectively, the corresponding values of displacement constraints at the end of tensioned rebar are 0.250235mm, 0.377998mm, 0.416053mm, 0.451592mm, 0.486573mm, 0.590754mm respectively. T_k are 5°C , 10°C , 15°C , 20°C respectively. After ΔT_{max} and the tensioning force were exerted to the model, narrow joints began to bear force, and then T_k was exerted on the whole model. When wide joints harden, the end displacement of track slab y_{bc} is shown in Fig.10, and compressive stresses of narrow joints σ_z are shown as Fig. 11.

Figure 10. End displacements of track slab y_{bc} when wide joints harden.

Figure 11. Compressive stresses of narrow joints σ_z when wide joints harden.

Figure 10 shows that with the increase of T_k , end displacements of track slab y_{bc} increase gradually, but the increments are small. When $T_1 = \Delta T_{\max}$ is 0~10°C and T_k is 20°C, namely the temperature rise amplitude of track slab ΔT_z is 20~30°C after the concrete hardening of narrow joints, the increment of y_{bc} is about 0.02157~0.03851mm.

Figure 11 shows that with the increase of T_k , σ_z increase gradually. When $\Delta T_{\max} > 6^\circ\text{C}$, σ_z increase linearly. Because the possibility that $\Delta T_{\max}$ is less than 6°C is very small. When $\Delta T_{\max} > 6^\circ\text{C}$, the relationship between σ_z (MPa) and ΔT_z ($^\circ\text{C}$) is fitted to linear formula (3), and in this formula: $\Delta T_z = T_k - T_1$.

$$\sigma_z = -2.13\Delta T_z \quad (3)$$

When considering the tensioning force, -3.03 should be added to the formula (3). Therefore, ΔT_z in the formula (3) can be approximately $(T_k - T_z + 1.42)$.

Extension displacements at the end of track slab will become very small after the concrete hardening of narrow joints. The compressive stresses of narrow joints caused by tensioning force are only equivalent to the effect of temperature rise 1.42°C of track slab after the concrete hardening of narrow joints. If $(T_z - T_k)$ is more than 2°C , narrow joints may not be stressed when wide joints hardened, and the narrow joints may not be stressed during the operation forever. This analysis result is also supported by the survey of literature [5], and which is contrary to the design concept of CRTSII slab.

If the constraints of steel bars, pre-splitting cracks and mortar layer on track slab are ignored, the relationship between σ_z and temperature rise amplitude of track slab ΔT after the concrete hardening of narrow joints was deduced in formula (4).

$$\sigma_z = -2.20\Delta T \quad (4)$$

Compared with formula (3), σ_z increases by 3.2%. Therefore, σ_z is mainly related to ΔT .

If $T_k > T_z$, when $\Delta T \geq 12^\circ\text{C}$, σ_z will exceed the compressive strength design value 25.3MPa of concrete, and narrow joints have the possibility of crushing.

In construction of joints between track slabs, it is required that the environment temperature is not more than 25°C during the construction of narrow joints, and wide joints should be constructed at the lowest

temperature of the day and the environment temperature should be not more than 25°C [4]. In fact, σ_z is mainly determined by the difference of track slab temperatures when wide joints and narrow joints hardened (namely $T_k - T_z$) and the tensioning force. In order to keep compressive stresses of narrow joints existent when wide joints hardened, it is not enough to control the pouring temperatures of joints only, we should also take measures to control T_k and T_z . Furthermore, when track slab temperature is high, in order to keep σ_z not too large, we should also make T_k slightly higher than T_z .

5 Conclusions

(1) When track slabs are connected by tension, the interlayer bonding states between track slab and mortar layer have little effect on track slab expansion displacement. If the tensioning force is applied on model after the concrete hardening of narrow joints, the increments of end displacements of track slab is about 0.045~0.051mm. The increments of compressive stresses of narrow joints is about 3.01~3.05MPa.

(2) When wide joints hardened, if track slab temperature for wide joints hardening T_k is less than track slab temperature for narrow joints hardening T_z over 2°C , narrow joints may not be stressed and may not be stressed during the operation forever, which is contrary to the design concept of CRTSII slab. With the increase of T_k , compressive stresses of narrow joints σ_z increase gradually, and the relationship between σ_z and ΔT_z is $\sigma_z = -2.13\Delta T_z$ where $\Delta T_z = T_k - T_z + 1.42$.

(3) We should take measures to control T_k and T_z , and make T_k slightly higher than T_z .

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