Crack Resistance Reliability Study of CRTS III Rail Slab on Bridge

Bingliang Jia
Graduate Student, Civil and Transportation Engineering, Beijing University of Technology, Beijing, China

Yangang Zhao
Professor, Civil and Transportation Engineering, Beijing University of Technology, Beijing, China

Xuanyi Zhang
Professor, Civil and Transportation Engineering, Beijing University of Technology, Beijing, China

Zhaohui Lu
Professor, Civil and Transportation Engineering, Beijing University of Technology, Beijing, China

ABSTRACT: Reliability of CRTS III track slab on bridge corresponding to cracking failure mode is analyzed, under multiple loads. A finite element model of CRTS III slab-type ballastless track on bridge is established; considering the uncertainties of train load, temperature gradient, fastener resistance, bridge deflection and the most unfavorable location, the reliability index of CRTS III track slab on bridge corresponding to cracking failure mode is analyzed with the aid of the method of moments, considering both horizontal and vertical directions; and the sensitivity analysis of important random parameters is carried out. It is found that: the cracking reliability indices of the track slab in both horizontal and vertical directions satisfy the specification requirements; the track slab is more likely to crack longitudinally than transversely; the change of load will lead to the change of the most unfavorable position, which makes the changing tendency of reliability index with load show strong nonlinearity.

1. INTRODUCTION

CRTS III ballastless track structure system on bridge is widely used in many high-speed railroads at home and abroad, and will be widely used in subsequent high-speed railroad construction as the main type (Jiang 2020). As an important structural layer of CRTS III ballastless track structure on bridge, the track slab has been cracked in different degrees of transverse and longitudinal directions under the joint action of train load, temperature action and foundation deformation (Zhou 2017), as shown in Figure 1. The generation and development of cracks will lead to accelerated corrosion of the internal reinforcement of the track slab and decrease of the concrete bearing capacity; reduce the safety, applicability and durability of the track slab, and affect the safety of high-speed train traffic (Liu 2017). In actual engineering, the load effects such as train load, temperature action and foundation deformation and the location of crack occurrence have obvious randomness, so it is very important to carry out the evaluation of the reliability of CRTS III rail slabs on bridges in cross and longitudinal directions considering the above randomness.

Many scholars have conducted deterministic studies on the cracking mechanism of CRTS III rail slabs through theoretical analysis, test comparison and simulation verification (Wang 2010, Liu 2017), but there is no research on the reliability of CRTS III rail slab cracking considering the load uncertainty. In recent years, scholars have introduced the reliability theory into the ballastless track service condition assessment and systematically studied the cracking reliability of CRTS type II track slabs (Tong 2020, Zhang 2020). Unfortunately, the uncertainty of the most unfavorable location of cracking under random loading has not been considered in the above studies, and the developed method cannot be directly applied to the analysis of the cracking reliability of CRTS III track slabs.

In view of this, this paper carries out the cracking reliability analysis of CRTS III rail slabs on bridges considering the randomness of the most unfavorable location. Specifically, the finite element model of CRTS III ballastless track on bridge is established; the calculation methods of train load, temperature, concrete shrinkage and creep, pre-stress and foundation deformation on track slab transverse and longitudinal effects are compared and determined; the transverse and longitudinal cracking limit state functions are established considering the randomness of the most unfavorable location of track slab cracking; the typical ambient temperature conditions and static wheel weight of train are selected. The high order moment method (Zhao 2001, Lu2016), which is easy to combine with finite element, is used to carry out the analysis of the reliability of the crack resistance of the track plate.

Figure 1: Cracking of CRTS type III track plate on the bridge

2. ANALYSIS OF THE EFFECT OF THE LOAD

The CRTS III slab ballastless track structure on the bridge is subjected to the following loads during its service life: train load, temperature load, foundation deformation, concrete shrinkage creep and prestressing. According to the different degrees of influence on the response of the track slab structure, this paper adopts the finite element method to analyze the effects of train load, temperature gradient and pre-stress, which have a greater influence on the response of the track slab structure; the analytical method is used to calculate the effects of overall temperature difference, foundation deformation and concrete shrinkage creep, which have a smaller influence on the response of the track slab structure.

2.1. Finite element model

Because the ballastless track foundation of passenger dedicated line is not allowed to have plastic deformation under the train load (Liu 2010), it can be simulated by elastic foundation model approximately. In this study, to balance the calculation efficiency and accuracy, the elastic foundation beam-body theory (Liu 2010) is used to establish the finite element model of CRTS III type slab ballastless track on bridge by ANSYS APDL parametric modeling language. The structural components mainly include rails, fasteners, bearing platform, track slab, self-compacting concrete, base plate, lower foundation, geotextile isolation layer, elastic bedding layer and prestressing reinforcement.

The steel rail is standard CHN60 rail. The fasteners are WJ-8 type system with a spacing of 0.630 m. To avoid stress concentration, this paper uses multiple spring simulated fastener system to make the force transmitted down from the rail evenly distributed in the area of 0.28 m × 0.4 m. The fasteners are made of a spring type system with a spacing of 0.630 m. The fastener stiffness and resistance are distributed according to the ratio shown in Figure 2, where the circle represents 1/64, the triangle represents 1/32, and the square represents 1/16. the track slab adopts P5600 type two-way post-tensioned prestressed concrete structure with concrete strength grade C60. 12 transverse single-layer and 4 longitudinal double-layer prestressing bars of 13mm diameter are arranged in the slab, and each transverse prestressing bar has a tensile strength of 127kN. The strength grade of self-compacting concrete is C40, and it forms a "composite slab" structure with the upper rail slab, and the longitudinal slab joints between adjacent slabs are 70mm. 1m long, 1m wide, 0.1m high grooves are arranged symmetrically in the slab, and the same size tabs of self-compacting concrete are fitted together to play the role of restriction.

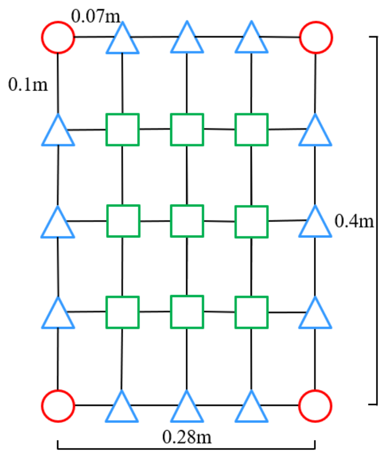


Figure 2: Fastener stiffness, resistance distribution diagram.

The overall finite element model is shown in Figure 3. The macro file function in ANSYS APDL and the *do loop command are used to realize the linkage between the higher order method of moments and the finite element model, i.e., to set multiple random variables in the finite element in any order and number of times for automatic loop calculation.

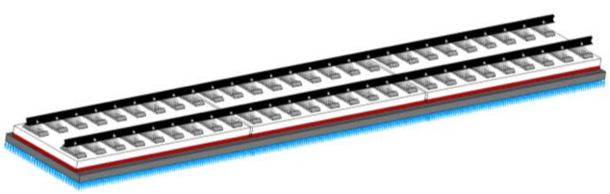


Figure 3: Finite element model of CRTS III plate ballastless track structure on the bridge.

2.2. Multi-load effect analysis

When designing the main structure of ballastless track, in order to ensure the stability of the main structure in longitudinal, transverse and vertical directions, the train load is mainly considered as vertical load, transverse load and braking force. The vertical train load P_d and the transverse train load Q is one of the most basic live loads of ballastless track in service and is the main force, which is calculated according to the "Design Code for High-Speed Railway" (TB 10621-2014) using the following formula.

$$P_d = \alpha \cdot P_j \tag{1}$$

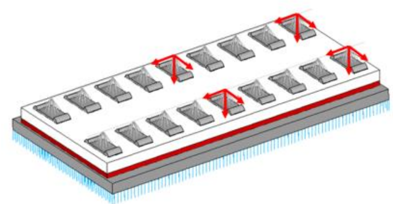
$$Q = 0.8 \cdot P_j \tag{2}$$

Where: α *is the* dynamic load amplification factor, taken as 3.0; P_j is the static wheel load.

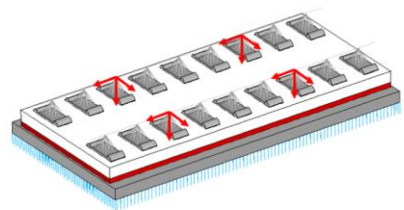
Although the braking force or traction force of the train has a smaller probability of occurrence than the vertical load of the train, it is still calculated and analyzed as the main force together with the above two loads in this paper based on safety considerations.

$$P_z = \mu_z \cdot \alpha \cdot P_j \tag{3}$$

Where: P_z is the braking force or traction force; μ_z is the wheel-rail adhesion coefficient, taken as 0.164.



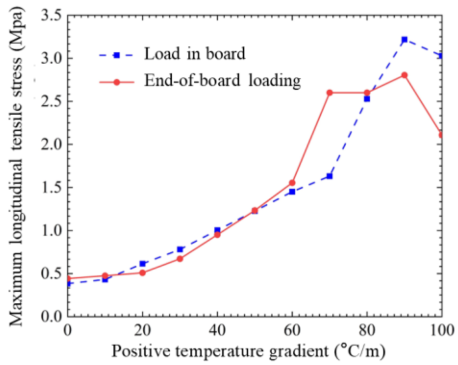
(a) End-of-board loading



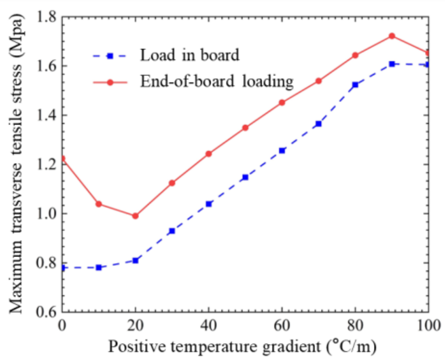
(b) Loading in the board

Figure 4: Train load plate end, plate in the loading schematic

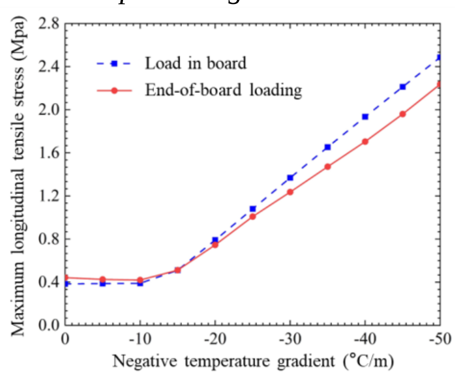
A bogie of a high-speed train was simulated with four concentrated forces (Liu 2019), and the static wheel weight of the train was taken to be 85 kN, and the maximum tensile stresses in the track plate were calculated under positive and negative temperature gradients using plate end loading and plate in loading (Sun 2013) (as shown in Figure 4), respectively, and the results are shown in Figure 5. From the figure, it can be seen that the transverse tensile stress of the track plate loaded at the end of the plate is much larger than that of the loading in the plate, and the longitudinal tensile stress of the track plate loaded in the plate is basically the same as or slightly larger than that of the loading at the end of the plate. Comprehensive view, the plate end loading is the most unfavorable position. In this paper, the subsequent analysis and calculation all adopt the way of plate end loading.



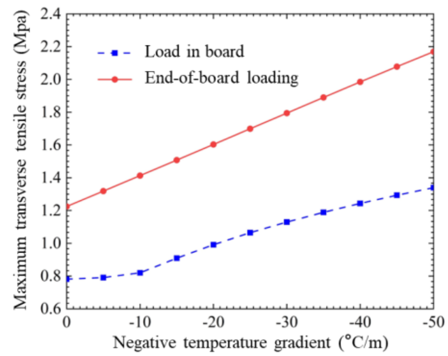
(a) Variation of longitudinal maximum tensile stress with positive temperature gradient



(b) Variation of transverse maximum tensile stress with positive temperature gradient



(c) Variation of longitudinal maximum tensile stress with negative temperature gradient



(d) Variation of maximum tensile stress in the transverse direction with negative temperature gradient

Figure 5: Maximum tensile stress in the track plate under loading in the train load plate and the end of the plate

This paper uses the analytical formula to calculate the overall temperature effect and the tensile stress s in the track slab caused by the shrinkage creep of concrete $\sigma_{\triangle T}$ (Liu 2010, Q/CR 9130-2015):

$$\sigma_{\Delta T} = \frac{F_k N_k}{2A_s} + \frac{W_g L}{2A_s} f_w \tag{4}$$

Where: F_k is the fastener resistance of each group of fasteners; N_k is the number of fastener groups; W_g is the weight of the unit length rail slab; L is the length of the rail slab; f_w is the friction coefficient between the rail slab and the self-compacting concrete, taken as 0.3; A_s is corresponding cross-sectional area of track plate.

The effect of temperature gradient on the track slab is calculated using the established finite element model. Since the geotextile isolation layer between the self-compacting concrete and the base plate has good thermal insulation (Jin 2020), the temperature gradient is loaded on the track slab and the self-compacting concrete in the calculation.

The bridge deflects under the train load, resulting in additional load effects on the upper track structure. Considering that the probability of bridge deflection and train load are basically the same, it is calculated as the main force. The tensile stress σ_q in the track slab caused by the bridge deflection is (Liu 2010).

$$\sigma_q = \frac{Eh\delta\pi^2}{2L_1^2} \tag{5}$$

Where, *E is the* modulus of elasticity of the track plate; *h is the* thickness of the track plate; δ is the bridge deflection; L_1 is the bridge span.

The prestressing force is simulated by the cooling method in the finite element, and the cooling value is calculated using the following equation.

$$T_1 = \frac{F_{pre}}{E_1 \times \alpha_1 \times A} \tag{6}$$

Where: T_1 is the cooling magnitude; F_{pre} is the tension force applied to a single prestressing bar; E_1 is the modulus of elasticity of the prestressing bar; α_1 is the coefficient of thermal expansion of the prestressing bar; A is the cross-sectional area of a single prestressing bar.

3. ESTABLISHMENT OF THE LIMIT STATE FUNCTION OF THE CRACK RESISTANCE OF THE TRACK PLATE

The CRTS III track slab on the bridge is a two-way prestressed concrete structure, and the Code for Design of Prestressed Concrete Structures (JGJ369-2016) stipulates that cracking is not allowed when the environmental category of the structure belongs to IIb. The Code for Thermal Design of Civil Buildings (GB 50176-2016) stipulates that Beijing and Henan are cold regions; Heilongjiang, Liaoning and other places are severe cold regions. According to the classification of environmental category of concrete structures in the Code for Design of Concrete Structures (GB 50010-2010) , the environmental category of open-air environment in severe cold and cold regions is IIb. In summary, CRTS III track slabs on bridges in severe cold and cold regions are not allowed to crack in both transverse and longitudinal directions.

In this paper, considering the maximum tensile stress of concrete at any position of the track slab in the transverse and longitudinal directions under the joint action of train load, temperature load and foundation deformation, the limit state of cracking occurs when the maximum tensile strength of concrete exceeds its tensile strength, and the limit state function of cracking resistance of track slab in the transverse and longitudinal directions is established as follows.

$$G_1(\mathbf{X}) = f_{tk} - \sigma_{z1}(N_{p1}, P_j, T_g, F_k, f_{tk}, f_{ck}, \Omega_s) - \frac{W_g L_2}{2A_s} f_w \tag{7}$$

$$G_2(\mathbf{X}) = f_{tk} - \sigma_{z2}(N_{p2}, P_j, T_g, F_k, f_{tk}, f_{ck}, \Omega_s) - \frac{F_k N_k}{2A_s} - \frac{W_g L_3}{2A_s} f_w - \frac{Eh\delta\pi^2}{2L_1^2} \tag{8}$$

Where: G_1 **(X)** and G_2 **(X)** are the limit state functions of the transverse and longitudinal crack resistance of the track slab, respectively; f_{tk} is the standard value of the tensile strength of the concrete of the track slab, which is taken as 2.85 MPa; L_2 and L_3 are the width and length of the track slab, respectively; σ_{z1} and σ_{z2} are the maximum values of the transverse and longitudinal tensile stresses at all positions in the spatial domain of the track slab, respectively; Ω_s is the parameter of the spatial domain of the track slab. σ_{z1} and σ_{z2} are the implicit functions of N_p, column P_j, T_g, F_k, f_{tk}, f_{ck} *and* Ω_s of the implicit functions, which are calculated using finite element analysis. Observing Eq. (7) Eq. (8), it can be found that, unlike the existing method in which stress analysis is carried out for fixed most unfavorable locations, this paper calculates and compares the stresses at all locations in the spatial domain to determine the stress maximum, which can eliminate the influence of the randomness of the most unfavorable locations on the analysis results and improve the accuracy of the analysis.

4. CRACKING RELIABILITY OF TRACK PLATE UNDER TYPICAL LOAD

4.1. Identification of random variables

From Eq. (7) and Eq. (8), it can be seen that G_1 **(X)** and G_2 **(X)** contain many parameters. Since the CRTS III track plate is prefabricated, its factory quality has a strict inspection process, and the load parameters have stronger randomness compared with the structural parameters (Zhang 2021), so the structural parameters of the track plate itself are taken as constants in this paper, and the specific values are shown in Table 1; the load parameters, i.e., static wheel weight of the train, temperature gradient, bridge deflection and longitudinal resistance of the fasteners are calculated as random variables, and the statistical information is shown in Table 2.

The current commonly used passenger train design speed is 350km/h, its axle weight is 170kN and static wheel weight is 85kN. The static wheel weight is taken as the mean value of P_j, and the coefficient of variation is selected as the larger value in the existing research for the calculation (Zhang 2021). In recent years, China has developed high-speed trains with speeds of 400km/h and above, and for safety reasons, the average static wheel weight of 100kN is selected as the second typical case for calculation in this paper. In this paper, two typical temperature gradient probability models, monthly average value and daily maximum value, are selected for analysis and calculation.

Table 1: Constant values

Constants	Value
Standard value of tensile strength of C60 concrete for track slabs f_{tk} (Mpa)	2.85
Number of fastener groups on a single track plate N_k	9
Unit length track plate weight W_g (kN/m)^3	25
Friction coefficient between track slab and self-compacting concrete f_w[8]	0.3
Modulus of elasticity of track plate E (Gpa)	36
Track plate thickness h (m)	0.2
Track plate width L_2 (m)	2.5
Track plate length L_3 (m)	5.6
Bridge span L_1 (m)	32

Table 2: Statistical information on random variables

Random Variables	Load conditions	Distribution	Average value	Coefficient of variation
P_j (kN)	350km/h	Normal	85	0.22
P_j (kN)	≧400km/h	Normal	100	0.22
T_g (°C/m)	Monthly average of low temperature	Weibull	33.96	0.14
T_g (°C/m)			-18.40	0.23
T_g (°C/m)	Monthly average of high temperature		40.68	0.16
T_g (°C/m)			-19.43	0.31
T_g (°C/m)	Day Best Value	Extreme value type I	79.24	0.19
T_g (°C/m)			-41.20	0.23
F_k (kN)	-	Lognormal	10	0.3
δ (mm)	32m simply supported box girder	Normal	28.38	0.09

4.2. Reliability comparison analysis under typical loading parameters

Based on the information of constant and random variables described in 3.1, the higher-order moment method is used to calculate the reliability of the track slab in transverse and longitudinal crack resistance. The reliability indices under the action of different train static wheel weights and temperature gradients are listed in Table 3.

Table 3: Reliability indicators under the combined effect of train load and temperature gradient

μ_{Pj} (kN)	μ_{Tg} (°C/m)	Cross-sectional reliability index	Longitudinal reliability index
	33.96	9.55	5.04
85	40.68	17.45	3.92
	79.24	5.16	0.62
	33.96	6.08	10.93
100	40.68	7.88	3.34
	79.24	5.71	0.98
	-18.46	5.69	2.93
85	-19.43	5.29	4.84
	-41.20	2.70	2.02
	-18.46	4.19	2.93
100	-19.43	3.93	4.40
	-41.20	2.11	1.95

5. CONCLUSIONS

In this paper, a finite element model of CRTS III slab ballastless track structure on bridge, which can be linked with the higher order moment method, is established to carry out the analysis of the reliability of CRTS III track slab on bridge under the joint action of train load, temperature action and foundation deformation in cross and longitudinal crack resistance. It was found that:

1. The longitudinal crack resistance reliability index of track plate is smaller than the transverse crack resistance reliability index of track plate, which means that the long side direction of track plate is more likely to produce cracks. The actual project should pay more attention to the cracks in the long side direction during the track inspection and maintenance and repair.
2. Under typical load combinations, the cracking reliability index of track slabs in both transverse and longitudinal directions meet

the requirements of the code. It should be noted that under the extreme positive temperature gradient (79.24°C/m), the longitudinal reliability index of the track slab is less than 1, and there is a higher possibility of cracking.

3. In some cases, the reliability index does not decrease monotonically with the increase in temperature gradient or static wheel weight of the train, but shows a trend of increasing and then decreasing. The reason for this is that the position of the maximum tensile stresses in the transverse and longitudinal directions of the track slab changes as the loading parameters change. For different locations, the direction of stress generated by temperature gradient or train load will be different, and the rate of change will also be different. Therefore, when analyzing the cracking of the track plate, the change of the most unfavorable position and the specific effect of the complex load on it should be considered comprehensively.

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