

Article

Influences of Under-Track Foundation Diseases on Track System

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Abstract

In order to study the influence of the under-track foundation disease on the track system, based on the CRTS II slab ballastless track in ABAQUS, this paper analyzes the influence of the overall temperature, temperature gradient, CA mortar layer stiffness and voiding, and fastener system stiffness changes on the track system. The results show that the tensile stress of the track slab, the vertical displacement of the rail and the track slab and the vertical compressive stress of the mortar layer are all linearly related to the change of the temperature field, and increase with the increase of the temperature load. The stiffness of the fastener mainly affects the deformation of the rail. The damage of the CA mortar layer deteriorates the service performance of the track structure. The stiffness of the CA mortar layer has a great influence on the transverse tensile stress of the track slab. Both the length and width of the void have adverse effects on the rail, track slab and mortar layer. And when the void width reaches 1.5 m, the transverse tensile stress of the track slab reaches the maximum value, while the impact of the void height on the track system is relatively small. The outcomes provide a quantitative basis for establishing scientific maintenance thresholds and optimizing repair strategies, essential for ensuring the long-term serviceability of high-speed railway infrastructure.

Keywords: ballastless track; CRTS II slab; temperature change; fastener rigidity; stiffness of mortar layer; void of mortar la; track maintenance

1. Introduction

The global expansion of high-speed railway networks has underscored the critical importance of track system durability and maintenance, particularly in ballastless track designs which are widely adopted for their high stability, minimal maintenance, and long service life. However, the structural integrity of ballastless tracks is increasingly challenged by the synergistic effects of environmental and operational factors, including temperature fluctuations, dynamic loads, and material degradation. Among these, subgrade-related defects—such as temperature-induced stresses, fastener stiffness variations, and mortar layer voids—have emerged as key contributors to track performance deterioration, affecting both safety and lifecycle costs. International research has advanced to sophisticated levels, employing novel methods to assess long-term performance under complex scenarios, such as simulating concrete deterioration and soil settlement under varying train speeds and extreme weather [1], and evaluating compression fatigue damage in concrete slabs using new fatigue criteria [2].



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In China, the world's most extensive high-speed rail network traverses diverse and often extreme climatic regions, imposing severe demands on its predominant CRTS II slab track system. The vast territory experiences significant annual temperature differentials, making temperature load a primary concern. Concurrently, long-term operational wear leads to fastener aging and CA mortar layer degradation, including the formation of voids. The late start of ballastless track application in China, compared to pioneers like Japan and Germany, has resulted in a relative scarcity of long-term performance data and maintenance guidelines tailored to these interacting degradation modes. This gap necessitates a comprehensive investigation that moves beyond isolated factor analysis to capture the system's response to combined pathologies.

A critical analysis of existing knowledge reveals a fragmented landscape. Studies on temperature effects, both internationally and within China, have established its profound influence [3–8]. For instance, Zhu [9] studied the deformation and stress changes of the track system under different temperature gradients based on the bonding model and the contact model. Walubita et al. [10] have demonstrated that increased temperature gradients can lead to significant slab uplift and dominate interface shear stresses that initiate damage. The thermal impact extends to special environments, with studies in tunnels revealing how high floor temperatures affect track distribution and warp deformation, thereby exciting vehicle–track dynamic responses [11].

In the realm of fastener stiffness, its critical role in dynamic response and safety has been highlighted [12,13]. Regarding the CA mortar layer, research has progressed from studying detachment limits [14] and stiffness reduction effects [15] to more nuanced investigations. Recent work has delved into the hydrodynamic pressure characteristics within voids under train loads and the influence of initial crack conditions on damage propagation [16]. Experimental efforts have advanced to full-scale bending tests to study stiffness degradation and crack propagation under fatigue [17], and to fracture tests on the slab–mortar interface to analyze damage mechanisms [18]. Notably, under combined train load and temperature gradient, the void length has been identified as highly sensitive, greatly affecting the longitudinal tensile stress of the track slab [19].

Despite these advancements, significant research gaps persist, which this study aims to address. First, while individual factors are studied, a comprehensive coupled analysis integrating temperature fields, variable fastener stiffness, and parametrically defined mortar voids into a single simulation of concurrent operation is lacking. Second, there is a simplification in defect modeling. Mortar voids are often modeled with reduced stiffness rather than as explicit geometric discontinuities, failing to capture 3D stress concentrations. Third, and critically, many models rely on simplified boundary conditions that may not accurately capture stress redistribution and load sharing in a continuous track system, potentially yielding non-conservative conclusions.

To bridge these gaps, this study is designed with the following primary objective: to quantitatively evaluate the individual and combined influences of temperature fields, fastener stiffness variation, CA mortar layer stiffness degradation, and geometrically defined mortar voids on the mechanical behavior of CRTS II slab ballastless track, and to establish critical thresholds for maintenance intervention. Based on the identified gaps, we posit three core research hypotheses: Firstly, the coupled effect of temperature decrease, and mortar layer voiding will induce tensile stresses in the track slab that significantly exceed those predicted by considering either factor alone, breaching concrete strength limits at specific void dimensions. Secondly, the width of a mortar void is a critical parameter influencing transverse tensile stress in the track slab, with a distinct optimum width causing peak stress, a phenomenon not revealed by models treating voids simply as areas of complete debonding. Thirdly, a three-panel finite element model, by minimizing boundary

constraints on the central panel of interest, yields fundamentally different and more realistic qualitative conclusions regarding stress redistribution and deformation patterns under localized defects compared to conventional single-panel models.

The novelty of this work is threefold. First, it provides a comprehensive coupled analysis of multiple key degradation factors, moving beyond the prevalent single-factor paradigm. Second, it introduces a high-resolution geometric parameterization of mortar voids, systematically evaluating the distinct influences of length, width, and height—a significant advancement over simplified material property reduction methods. Third, and most critically, it justifies and utilizes a three-panel track model. This modeling strategy is central to the study’s qualitative advancement, as it minimizes spurious boundary effects and allows for realistic longitudinal bending and load transfer, enabling the simulation of how a local defect affects not only the immediate slab but also how stresses are shed to neighboring units—a key mechanical behavior that single-panel models inherently suppress.

By integrating this advanced modeling framework with a multi-parameter analysis, this study aims to deliver a more realistic and comprehensive assessment of track system vulnerabilities. The findings are intended to provide robust, threshold-based guidance for inspection schedules and repair priorities, directly contributing to the lifecycle management and operational safety of China’s high-speed railway infrastructure.

2. Materials and Methods

In this paper, the CRTS II unit slab ballastless track model is established based on ABAQUS 2022. The unit size of the track slab is $6.45\text{ m} \times 2.55\text{ m} \times 0.2\text{ m}$. The cross-section sizes of the mortar layer and the bearing layer are $2.55\text{ m} \times 0.03\text{ m}$ and $(2.95\text{ m}/3.25\text{ m}) \times 0.33\text{ m}$, respectively. According to the Chinese railway material standards, the steel rails are made of grade 60 steel. The track plates are made of C60 concrete. The elastic modulus of the CA mortar layer is the nominal design value for the CA mortar used in CRTS II slab track, which is specified in technical specifications and widely cited in related studies [7,20]. The bearing plate was designed to simulate the combined behavior of the hydraulic bonding layer (HBL) and the underlying concrete support layer. An equivalent homogeneous material was used, equivalent C51 concrete. The material properties are shown in Table 1.

Table 1. Track system parameters [7].

Structure	Material	Modulus of Elasticity/MPa	Poisson’s Ratio	Density/kg·m ^{−3}	Coefficient of Thermal Expansion /m [°] C
Rail	60 steel	2.1×10^5	0.3	7850	1.18×10^{-5}
Track slab	C60 concrete	3.6×10^4	0.2	2500	1.0×10^{-5}
CA mortar layer	CA mortar	7×10^3	0.2	1900	1.5×10^{-5}
Bearing slab	Equivalent C51 Concrete	2.55×10^4	0.2	2500	1.5×10^{-5}

In ABAQUS, the rail is modeled with an eight-node linear hexahedral unit C3D8R to simulate the actual rail, as shown in Figure 1. As an important connecting element between rail and track slab, the fasteners can isolate and dampen vibrations. For example, the wheel rail force is weakened and transmitted to the track slab. In order to model the fastener system, the Catresian connectors and the standard length of ballastless track slab with 10 fasteners are utilized. For the details of the model parameters, see Table 2.

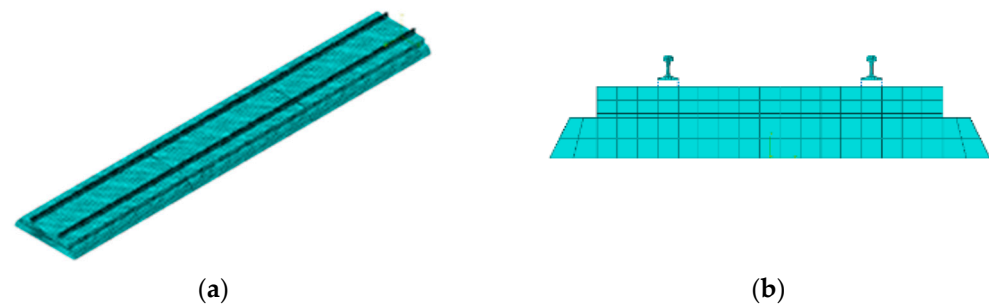


Figure 1. The finite element model of CRTS II ballastless track slab. (a) Finite element model; (b) Side views.

Table 2. The fastener parameters.

Parameters	Values
Distance between fasteners (m)	0.65
Vertical stiffness ($\text{MN}\cdot\text{m}^{-1}$)	23
Transverse stiffness ($\text{MN}\cdot\text{m}^{-1}$)	90
Vertical damping ($\text{kN}\cdot\text{s}\cdot\text{m}^{-1}$)	75
Transverse damping ($\text{kN}\cdot\text{s}\cdot\text{m}^{-1}$)	60

The longitudinal end of the track slab is assumed to be free in the vertical direction, while it is constrained in the horizontal direction to reflect the typical on-site support conditions. The foundation is simulated using uniformly distributed spring elements, namely foundation springs, with a stiffness coefficient of 76 megapascals per meter, which is applied to 2706 nodes on the bottom surface of the foundation slab. Through a nuanced calculation of spring stiffness at every individual node, an accurate emulation of the subgrade's mechanical behavior is achieved. Referencing Figure 1, which illustrates the sophisticated finite element model of a CRTS II slab track meticulously crafted within the ABAQUS software suite, one can appreciate the model's intricacy and adherence to engineering precision.

3. Results and Analysis

3.1. Influence of Temperature Field Change on Track System

China has a large temperature difference within a year. The highest temperature in summer is generally between $35\sim 45\text{ }^{\circ}\text{C}$, while the highest temperature in winter is generally between 0 and $-50\text{ }^{\circ}\text{C}$ [21]. Therefore, in ABAQUS, for the uniform temperature variation, an overall temperature increase of $5\text{ }^{\circ}\text{C}$ to $45\text{ }^{\circ}\text{C}$ and a decrease of $5\text{ }^{\circ}\text{C}$ to $-50\text{ }^{\circ}\text{C}$ was applied to the entire orbital system. For temperature gradient loading, it is assumed that there is a linear temperature distribution along the thickness direction of the plate. Table 3 presents the maximum temperature gradient threshold stipulated for China's ballastless track system [22]. In ABAQUS, the temperature difference is directly applied to the nodes of the track plate through the predefined temperature field option.

Table 3. Recommended value of maximum temperature gradient for ballastless track.

Regions	Warm Regions	Cold Regions	Severe Cold Regions
Maximum positive temperature gradient ($^{\circ}\text{C}/\text{m}$)	80~85	85~90	90~95
Maximum negative temperature gradient ($^{\circ}\text{C}/\text{m}$)	40~43	44~50	50~53

To systematically address temperature gradient variations, a simplified linear thermal loading profile is adopted through the slab's thickness. By considering the upper and lower

bounds of these gradients alongside the slab thickness, a temperature differential of $+20\text{ }^{\circ}\text{C}$ at the slab's surface relative to its base and $-10\text{ }^{\circ}\text{C}$ in reverse is utilized, encapsulating a broad spectrum of extreme climatic scenarios prevalent in regions where ballastless tracks are predominantly situated in China [9]. Within the ABAQUS simulation environment, this study examines five distinct thermal scenarios, with the slab surface temperature ranging from $4\text{ }^{\circ}\text{C}$ to $20\text{ }^{\circ}\text{C}$ above the base, and conversely, from $2\text{ }^{\circ}\text{C}$ to $10\text{ }^{\circ}\text{C}$ below, acknowledging the typical thermal influence depth of approximately 25 cm. Consequently, the analysis confines itself to the temperature gradient's effects on the track slab alone.

C60 concrete, with a tensile strength of 2.85 MPa and compressive strength of 38.5 MPa [23], ensures that the slab's compressive stress remains well within safe limits. Thus, the primary focus shifts to assessing whether the track slab's peak tensile stress adheres to acceptable criteria.

Temperature field dynamics induce warping deformations in the track slab. Under positive gradients, the slab's center convexes upwards while its corners depress, whereas negative gradients yield the opposite effect, with the center concaving and corners lifting. These deformations bear implications on the interface between the track slab and mortar layer, potentially compromising their bond integrity.

3.1.1. Influence of Overall Temperature Field Change on Track System

Illustrated in Figure 2 is an amplified depiction, by a factor of 500, of the track slab's warping deformation in response to thermal field variations. This magnified analysis reveals that sustained warping can induce misalignment between the track slab and mortar layer, potentially culminating in the mortar layer's total detachment. Such detachment exacerbates the degradation of the track structure's operational performance, highlighting the paramount importance of assessing thermal field impacts on the track system for the purposes of effective maintenance and rehabilitation strategies in ballastless track infrastructure.

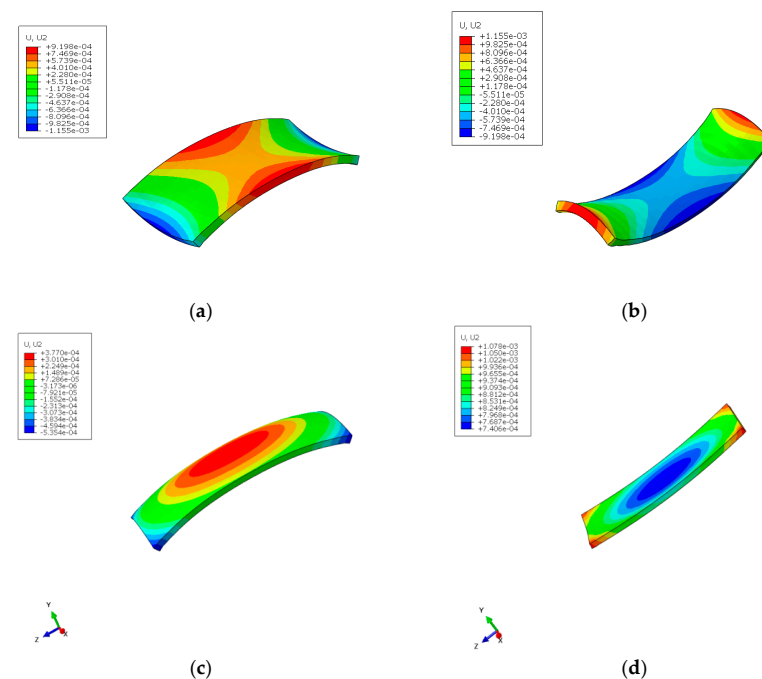


Figure 2. Effect of temperature field changes on vertical displacement of track slab. (a) The vertical displacement of the track slab under an overall warming of $30\text{ }^{\circ}\text{C}$; (b) The vertical displacement of the track slab under an overall cooling of $30\text{ }^{\circ}\text{C}$; (c) The vertical displacement of the track slab under an overall warming of $30\text{ }^{\circ}\text{C}$; (d) The vertical displacement of the track slab under an overall cooling of $30\text{ }^{\circ}\text{C}$.

Figure 3 elucidates the influence of uniform temperature variation on the tensile stress within the track slab. It is strikingly evident that an overall temperature increase exerts a profound effect on the slab's lateral tensile stress. Upon a 40 °C temperature escalation, this stress surges to 3.115 MPa, surpassing the slab's tensile strength threshold, thereby indicating a propensity for longitudinal cracking. Notably, a temperature decrease imparts a more significant influence on the longitudinal tensile stress compared to an increase. Specifically, with a 20 °C cooling, the transverse tensile stress spikes to 3.645 MPa, breaching concrete's tensile strength, instigating transverse cracking. This underscores the potential for crack propagation, exacerbating track system performance degradation. Consequently, strategic timing for track slab crack maintenance is imperative to mitigate these effects and prolong the infrastructure's operational lifespan.

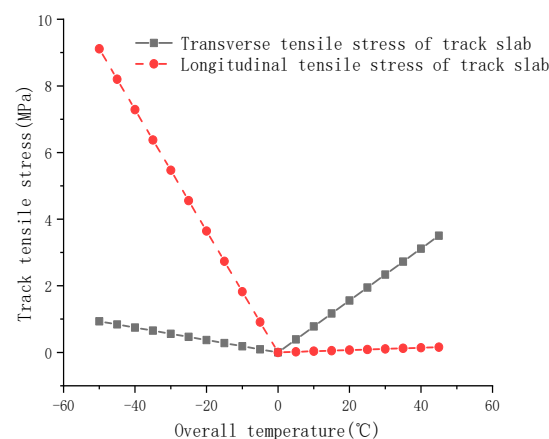


Figure 3. Maximum tensile stress of track slab.

Illustrated in Figure 4 is the vertical displacement of the rail and track slab under diverse thermal regimes, revealing thermal-induced geometric distortions. Notably, the track slab exhibits a more substantial vertical deformation compared to the rail's warping, with this deformation escalating in response to varying thermal loads. This could potentially result in detachment between the rail and mortar layer, alongside rail surface irregularities, subsequently impacting the dynamic response of the wheel–rail interaction.

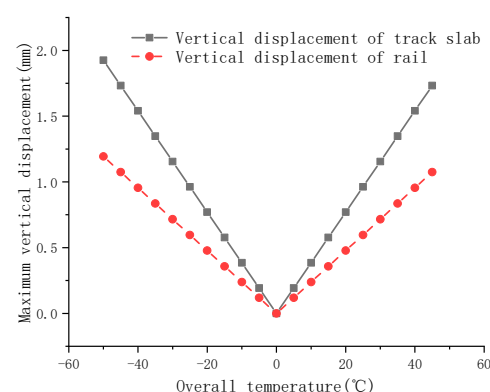


Figure 4. Maximum vertical displacement of rail and track slab.

Figure 5 depicts the thermal field's influence on the vertical stress profile of the CA mortar layer. It discloses that overall temperature decreases impose a more significant strain on the mortar layer in terms of tensile stress, whereas warming tends to increase compressive stress. The repetitive thermal cycling induces variations in mortar layer stiffness, compromising its bond with both the track slab and the underlying support,

thereby disrupting the integral cohesion necessary for the mortar layer's stable adhesion to the track structure.

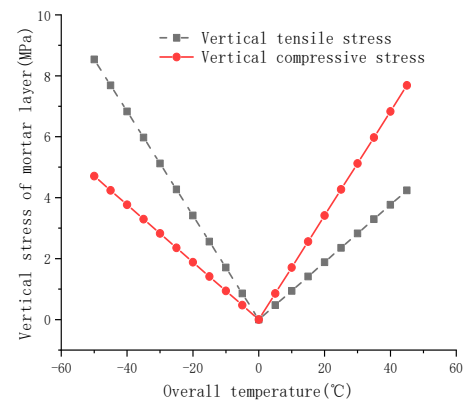


Figure 5. Vertical stress of mortar layer.

3.1.2. Influence of Temperature Gradient Change on Track System

Figure 6 elucidates the dynamics of tensile stress within the track slab subjected to temperature gradient loading. As depicted in Figure 6a, negative gradients notably influence tensile stress, with a particular emphasis on the longitudinal component. Under conditions where the slab base is 10 °C colder than the surface, the rail plate experiences a longitudinal tensile stress of 2.73 MPa, nearing concrete's tensile strength threshold, signaling potential for long-term transverse cracking. Conversely, under positive gradients, while transverse tensile stress is significantly impacted, it remains within concrete's tolerance, mitigating immediate crack risk. Figure 6b confirms that increasing positive temperature gradients exert a profound effect on rail and track slab vertical displacement, triggering substantial track slab warping. Figure 6c further reveals that these gradients significantly modulate mortar layer's vertical stress, with compressive stress variations exceeding those in tension. However, it is noteworthy that, relative to uniform temperature shifts, gradient-induced stress changes in the mortar layer are less pronounced, albeit still influential in the track system's stress distribution.

3.2. Influence of Stiffness Change of Fastener and Mortar Layer on Track System

For railway loading conditions, this study employs a simplified single-axle loading scheme, distinguishing between design and quasi-static reduced loads. The design wheel load is set at thrice the static wheel weight, equating to 300 kN, while the quasi-static reduced load, commonly used for analyses, is taken as 1.5 times the static weight, or 150 kN, as per industry standards [24]. Focusing on the track's response under deteriorated conditions, this work selects the reduced wheel load, imposing a vertical force of 150 kN. Recognizing that the slab's end is a critical loading point due to its vulnerability [25], the simulation positions the load application at the initial fastener location, with a double-wheel configuration pressing directly above, thereby capturing the most adverse loading scenario for the track slab.

3.2.1. Stiffness Change of Fasteners

In the realm of high-speed rail ballastless track systems, fasteners are designed with the key attributes of low stiffness and substantial adjustability [26]. Adhering to the interim technical specifications for passenger-dedicated line fastener systems in China, which specify a fastener stiffness range of 20 kN/mm to 50 kN/mm [27], and complemented by the design guideline setting the static stiffness of rail elastic pads at (25 ± 5) kN/mm [28], this study extends the analysis to consider the impact of fastener vertical stiffness from

20 kN/mm to 70 kN/mm on track performance, acknowledging the stiffness increase due to cushion aging.

Table 4 illustrates that as fastener vertical stiffness rises, track slab stress escalates. Specifically, the transverse tensile stress escalates from 0.165 MPa to 0.197 MPa, marking a 19.39% increase, while the longitudinal tensile stress experiences a 4.02% increase from 0.274 MPa to 0.285 MPa, highlighting a more pronounced effect on transverse stress. The track slab's vertical compressive stress experiences a notable amplification to 1.17 times its original value.

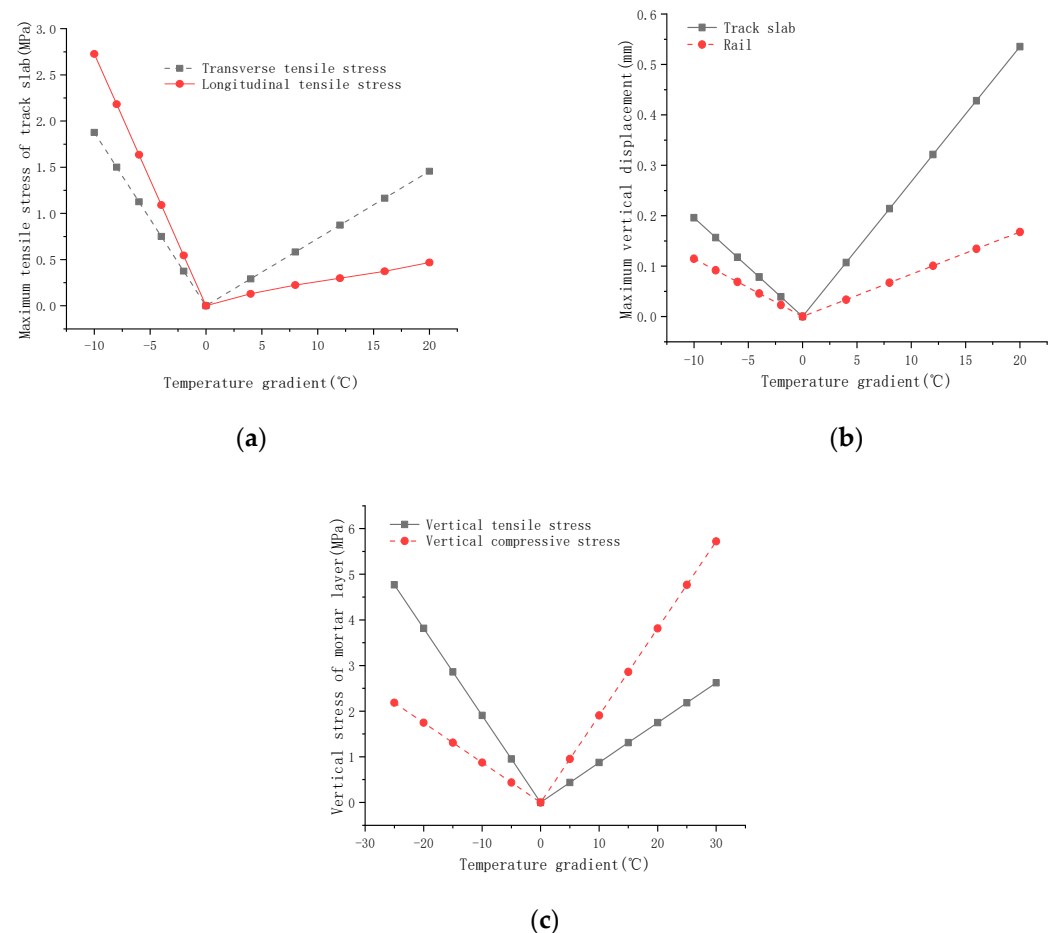


Figure 6. Stress displacement of track slab and mortar layer. (a) Maximum tensile stress of track slab; (b) Maximum vertical displacement of rail and track slab; (c) Vertical stress of mortar layer.

Table 4. The influence of fastener rigidity on rail and track slab.

Fastener Stiffness (kN/mm)	Track Slab Transverse Tensile Stress (MPa)	Longitudinal Tensile Stress of Track Slab (MPa)	Track Slab Vertical Compressive Stress (MPa)	Vertical Displacement of Track Slab (mm)	Vertical Displacement of Rail (mm)
20	0.165	0.274	2.098	0.379	2.087
30	0.176	0.278	2.227	0.384	1.853
40	0.184	0.280	2.311	0.388	1.729
50	0.190	0.282	2.370	0.390	1.653
60	0.194	0.283	2.415	0.392	1.600
70	0.197	0.285	2.451	0.393	1.562

Functioning as a vital elastic interface between the slab and rail, an increase in fastener stiffness prompts counteractive deformations, with track slab vertical displacement rising by 3.69% and rail displacement decreasing by 25.16%. This suggests that enhanced

fastener stiffness reduces rail flexibility, exacerbating vertical wheel–rail vibrations, thereby compromising train stability.

Figure 7 shows the influence of the stiffness of the reaction fasteners on the vertical compressive stress of the mortar layer.

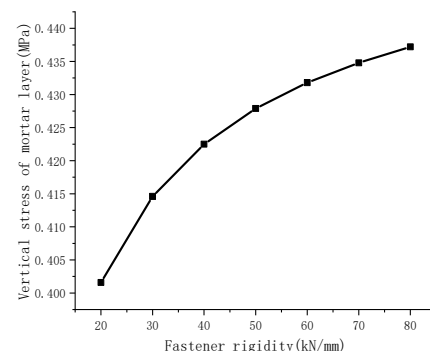


Figure 7. Variation of vertical stress of mortar layer with fastener stiffness.

Figure 7 underscores the moderate impact of fastener stiffness on mortar layer vertical compressive stress, which increments from 0.402 MPa to 0.437 MPa, a rise of 8.71%. This indicates that while the effect on the mortar layer is less significant, it still contributes to a measurable stress increase. Overall, the study underscores the critical role of fastener stiffness in balancing track stability and stress distribution, particularly emphasizing its influence on transverse slab stress and rail dynamics.

3.2.2. Stiffness Change of Mortar Layer

During the prolonged operational lifecycle of railway systems, track slabs and mortar layers can develop separations, facilitating the infiltration of rainwater that may erode and mobilize particles and calcium carbonate, forming slurry. This progressive process alters the mortar layer's properties, notably reducing its elastic modulus over time [29]. Notably, the CA mortar's elastic modulus can diminish up to 50% [15]. Typically, the CRTS II ballastless track's mortar layer possesses an elastic modulus of 7 GPa. This study investigates the implications for the track system as the elastic modulus is incrementally lowered to 90%, 80%, 70%, 60%, and 50% of its original value.

Table 5 reveals that as the mortar layer's elastic modulus declines, its stiffness diminishes, leading to heightened deformations under train loading. Specifically, the track slab and rail experience vertical displacements 1.84% and 0.78% greater than in the initial condition, respectively. It is pertinent to note that despite the mortar's degradation and modulus reduction, the impact on the track's overall structural deformation remains limited, indicating a degree of resilience. Furthermore, the internal stresses within the track slab escalate due to increased slab deformation. Notably, when the elastic modulus is halved, transverse and longitudinal tensile stresses in the track slab escalate by 33.73% and 0.73%, respectively. This is attributed to heightened vertical displacements at the slab ends under load, which exacerbates lateral tensile stress. Conversely, the increase in vertical compressive stress is relatively muted, rising by only 2.1%, highlighting the differential sensitivity of the track slab to various stress types under varying mortar layer conditions.

Furthermore, the mortar layer's elastic modulus significantly influences the magnitude of its internal compressive stress, as shown in Figure 8.

As Figure 8 illustrates, a reduction in the mortar layer's stiffness leads to a discernible decrease in its self-imparted vertical compressive stress, from 0.406 MPa to 0.341 MPa, representing a reduction of 16.01%. This insight suggests that optimizing the mortar layer's design to achieve a lower stiffness, without compromising its functional integrity, could

be beneficial. Such an approach potentially enhances the overall performance of the track system by mitigating compressive stress levels within the mortar layer, thereby contributing to a more resilient and efficient railway infrastructure.

Table 5. The effects of mortar layer stiffness on rails and track slab.

Modulus of Elasticity of Mortar Layer (GPa)	Track Slab Transverse Tensile Stress (MPa)	Longitudinal Tensile Stress of Track Slab (MPa)	Track Slab Vertical Compressive Stress (MPa)	Vertical Displacement of Track Slab (mm)	Vertical Displacement of Rail (mm)
7	0.169	0.275	2.144	0.381	1.792
6.3	0.175	0.275	2.150	0.382	1.795
5.6	0.182	0.276	2.158	0.383	1.799
4.9	0.190	0.276	2.167	0.384	1.800
4.2	0.206	0.277	2.177	0.386	1.803
3.5	0.226	0.277	2.189	0.388	1.806

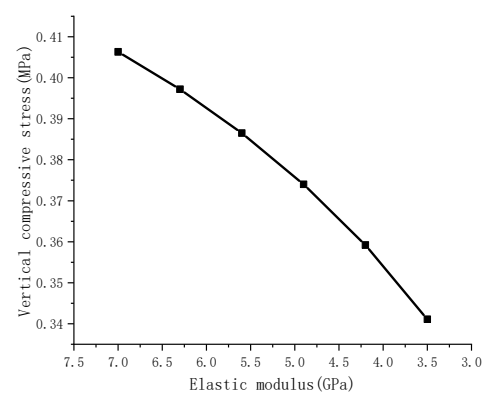


Figure 8. Vertical compressive stress.

3.3. Influence of Mortar Layer Void on Track System

When the railway track system encounters train loads in conjunction with prolonged exposure to temperature fluctuations, the predominant stressor is the temperature gradient load. Consequently, in assessing the mortar layer voids' influence on the track system, this study exclusively examines the effects of temperature gradient loads.

To accurately represent the mortar layer's void conditions, this research adopts a novel approach, simulating void dimensions of length, width, height, and location. Departing from conventional methods that utilize simplified spring-damping models, which may not accurately portray real-world conditions, this study employs solid elements to directly model the damaged state, enhancing the simulation's fidelity to actual scenarios. Given that the maximum length of voids in CA mortar layers typically does not exceed one-third of the slab length [30], four void lengths are studied: 0.5 m, 1.0 m, 1.5 m, and 2.0 m. Widths are varied across 0.5 m, 1.0 m, 1.5 m, 2.0 m, and 2.55 m, while heights are set at 5 mm, 10 mm, 15 mm, 20 mm, 25 mm, and 30 mm, to comprehensively capture the range of potential void dimensions. The detailed configuration of these voids within the mortar layer is visually depicted in Figure 9, providing a vivid illustration of the simulated damage scenarios.

In the context of analyzing a track in a deteriorated state, the study employs typical rather than extreme temperature gradients. Specifically, a standard positive temperature gradient of 45 °C/m and a negative gradient of −22.5 °C/m are applied to the CRTS II track slab [31]. Given the slab's thickness at 200 mm and incorporating a track slab correction factor of 1.05 to account for thermal behavior, this leads to calculated surface-to-bottom temperature differences of 9.45 °C for the positive gradient scenario and −4.725 °C for the negative, thereby establishing the thermal conditions for the simulation.

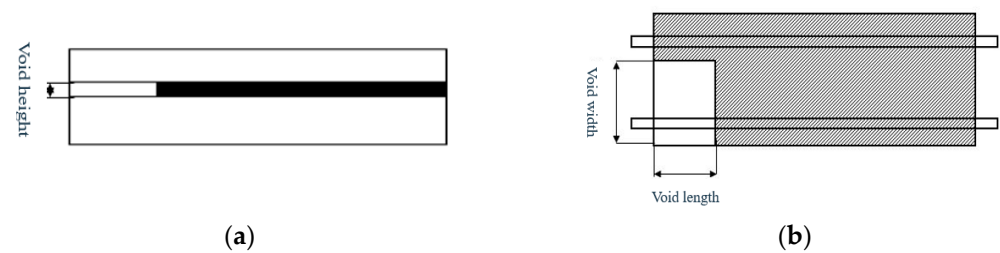


Figure 9. The void state of CA mortar layer. (a) Main view; (b) Top view.

3.3.1. Influence of Void Length on Track System

Figure 10 illustrates the modulation of fundamental parameters beneath the rail as influenced by void length under combined temperature gradient and train loading conditions. Under concurrent exposure to these loads, an intriguing dichotomy emerges: while the transverse tensile stress in the track slab increments at a moderate pace with void expansion, the longitudinal tensile stress experiences a sharp escalation. This phenomenon stems from the transverse void's complete traversal, contrasted with the longitudinal plane, where growing void lengths progressively diminish the slab–mortar layer contact, exacerbating longitudinal stress. Notably, negative temperature gradients induce higher longitudinal tensile stresses compared to positive gradients. Beyond a void length of 1.5 m, under both temperature gradient scenarios, the track slab's longitudinal tensile stress breaches concrete's tensile strength threshold.

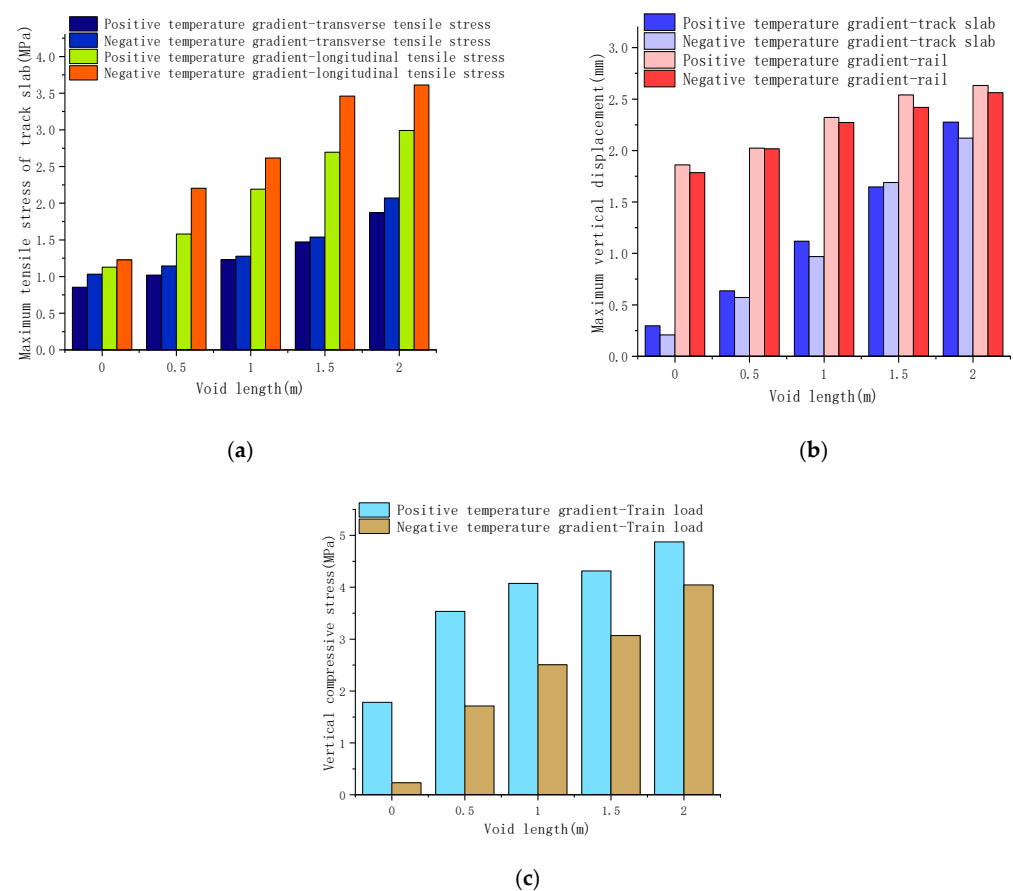


Figure 10. The parameters of the foundation under the rail vary with the length of the void. (a) Stress of track slab; (b) Maximum vertical displacement of rail and track slab; (c) Vertical stress of mortar layer.

As the void extends to 2 m, the longitudinal tensile stress escalates by factors of 1.65 and 1.94 under positive and negative gradients, respectively, while transverse stresses

increase by 1.19 and 1.01 times, highlighting a disproportionate impact on longitudinal stress. Accompanying this, rail and track slab vertical displacements escalate, with the track slab's vertical deformation accelerating dramatically. Reaching 2.27 mm and 2.12 mm under positive and negative gradients, these values are, respectively 6.71 and 9.17 times the baseline, indicating a profound impact. Consequently, the CA mortar layer's vertical compressive stress is shown to escalate with void length, with greater stress under positive gradients. Both temperature gradient orientations, however, negatively impact mortar layer stress under train loading, underscoring the criticality of void management in track maintenance.

3.3.2. Influence of Void Width on Track System

This study proceeds to examine the influence of varying void widths on the track system under both positive and negative temperature gradients, as depicted in Figure 11. The analysis reveals a pattern where the transverse tensile stress in the track slab initially rises and subsequently declines with changes in void width. Notably, the maximum transverse tensile stress emerges at a void width of 1.5 m. This phenomenon results from the partial bonding of the CA mortar layer, which, when not fully severed transversely, incrementally boosts lateral tensile forces. Once the mortar layer's discontinuity spans the entire width, the lack of bonding leads to a reduction in transverse stress.

In the longitudinal dimension, the track slab's longitudinal tensile stress escalates with void width expansion, across different temperature gradients. Notably, voids exceeding 1.5 m square induce longitudinal tensile stresses surpassing the slab's tensile strength, predisposing it to cracking and compromising performance. Under positive gradients, vehicle loading significantly impacts the mortar layer's vertical compressive stress, peaking at 4.955 MPa for a 2.0 m × 2.0 m void, highlighting the stress concentration as voids widen.

Regarding rail and track slab vertical displacement, both exhibit an upward trend with void width growth, under varied temperature gradients. Under positive gradients, with a 2.0 m × 2.55 m void, the track slab's load-induced vertical displacement balloons to 2.37 mm, an 8.03-fold increase from the baseline, while the rail's displacement reaches 2.75 mm, 1.47 times the normal state. This underscores the disproportionate impact of void width on the track slab's vertical displacement relative to the rail, underscoring the critical need for controlling void defects in the CA mortar layer to mitigate detrimental effects on the track system's integrity.

3.3.3. Influence of Void Height on Track System

This paper also analyzes the effect of the void height on the rail and track slab when the void is completely penetrated along the transverse direction, as shown in Tables 6 and 7.

Table 6. The influence of void height on tensile stress of track slab.

Void Height (mm)		Transverse Tensile Stress				Longitudinal Tensile Stress			
		Void Length 0.5 m	Void Length 1.0 m	Void Length 1.5 m	Void Length 2.0 m	Void Length 0.5 m	Void Length 1.0 m	Void Length 1.5 m	Void Length 2.0 m
positive temperature gradient	5	1.010	1.093	1.217	1.436	0.608	2.015	2.838	3.280
	10	1.008	1.094	1.215	1.436	0.606	2.019	2.844	3.273
	15	1.008	1.094	1.214	1.430	0.606	2.021	2.847	3.267
	20	1.008	1.095	1.214	1.416	0.606	2.022	2.849	3.262
	25	1.008	1.095	1.212	1.394	0.605	2.024	2.851	3.257
	30	1.007	1.096	1.213	1.392	0.594	2.033	2.888	3.276
negative temperature gradient	5	1.110	1.210	1.534	2.009	1.423	2.352	3.445	3.693
	10	1.111	1.211	1.534	2.017	1.423	2.359	3.456	3.693
	15	1.111	1.211	1.533	2.019	1.423	2.362	3.461	3.693
	20	1.110	1.211	1.532	2.015	1.422	2.364	3.464	3.695
	25	1.111	1.211	1.530	1.973	1.422	2.366	3.466	3.697
	30	1.111	1.212	1.530	1.987	1.421	2.367	3.467	3.696

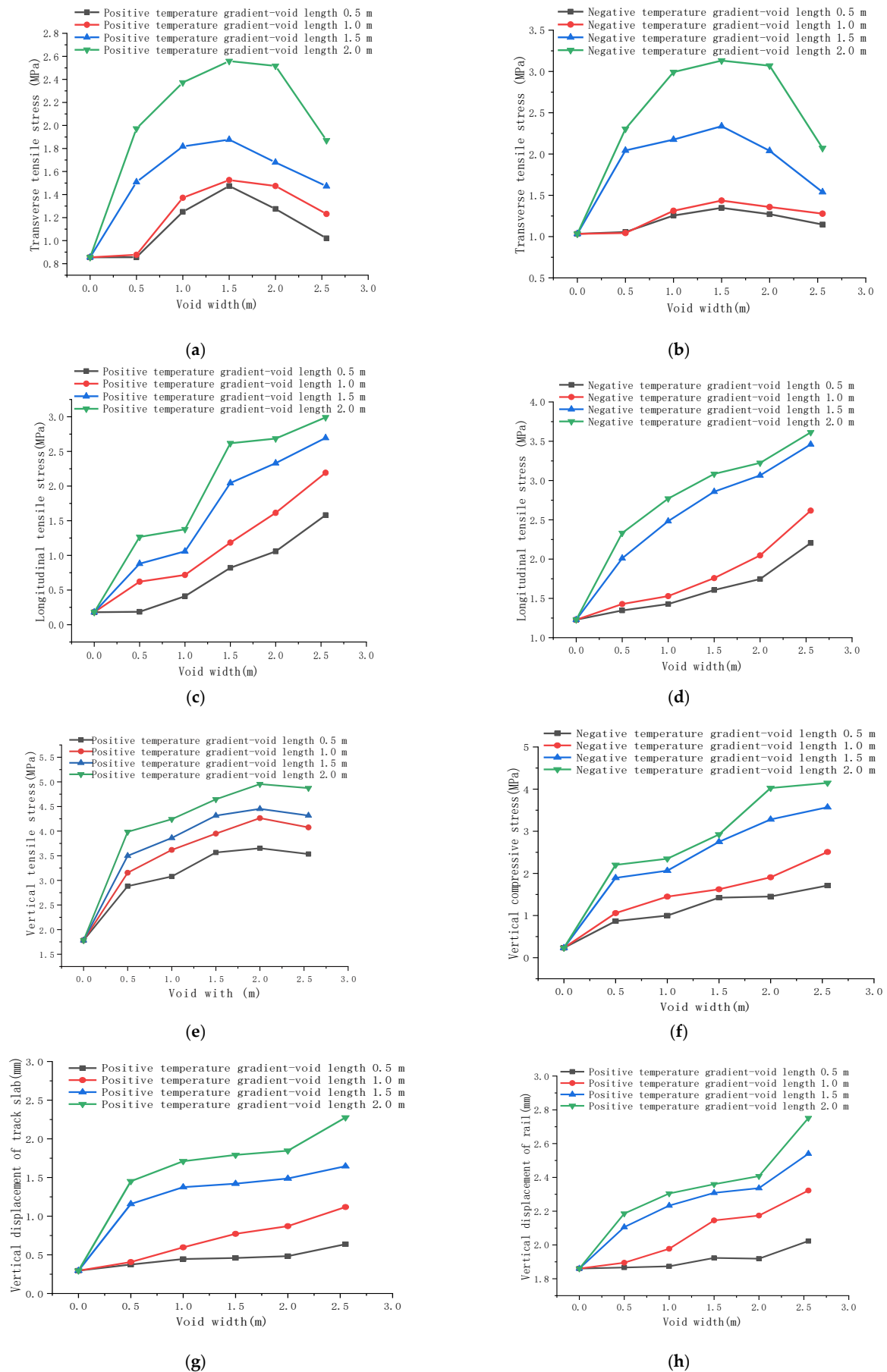


Figure 11. Cont.

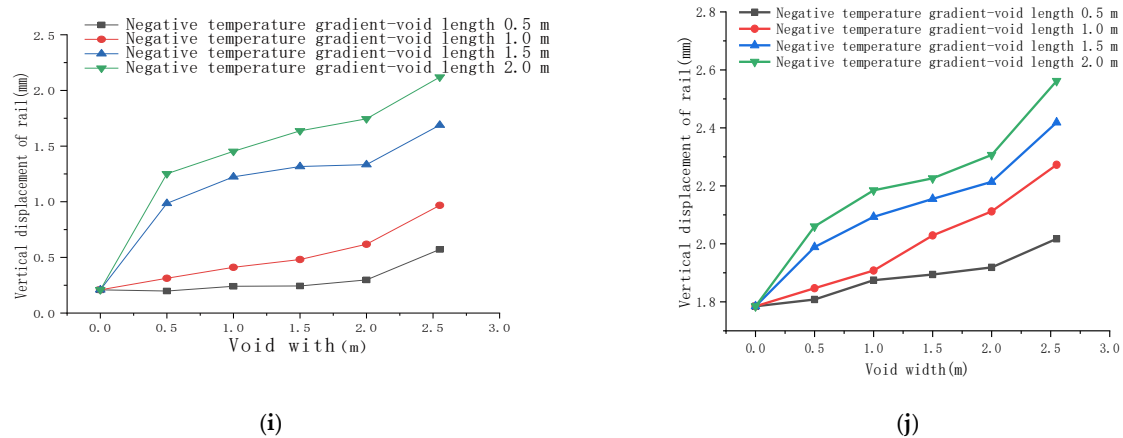


Figure 11. Variation of basic parameters under the rail with the void width under temperature gradient. (a) Transverse tensile stress of track slab under positive temperature gradient; (b) Transverse tensile stress of track slab under negative temperature gradient; (c) Longitudinal tensile stress of track slab under positive temperature gradient; (d) Longitudinal tensile stress of track slab under negative temperature gradient; (e) Vertical tensile stress of mortar layer with positive temperature gradient; (f) Vertical tensile stress of mortar layer with negative temperature gradient; (g) Vertical displacement of track slab with positive temperature gradient; (h) Vertical displacement of rail with positive temperature gradient; (i) Vertical displacement of track slab with negative temperature gradient; (j) Vertical displacement of track slab with negative temperature gradient.

Table 7. The influence of the clearance height on the displacement of the track system.

Void Height (mm)	Vertical Displacement of Track Slab					Vertical Displacement of Rail			
	Void Length	Void Length	Void Length	Void Length	Void Length	Void Length	Void Length	Void Length	Void Length
	0.5 m	1.0 m	1.5 m	2.0 m	0.5 m	1.0 m	1.5 m	2.0 m	
positive temperature gradient	5	0.614	1.170	1.787	2.651	1.820	2.027	2.430	3.032
	10	0.616	1.174	1.788	2.655	1.821	2.029	2.433	3.035
	15	0.619	1.177	1.788	2.657	1.823	2.031	2.435	3.037
	20	0.620	1.179	1.789	2.657	1.824	2.032	2.436	3.038
	25	0.622	1.181	1.791	2.656	1.285	2.034	2.437	3.038
	30	0.619	1.187	1.792	2.599	1.824	2.042	2.433	2.997
negative temperature gradient	5	0.458	1.208	1.747	2.140	2.012	2.330	2.572	3.154
	10	0.458	1.211	1.751	2.142	2.013	2.331	2.575	3.157
	15	0.459	1.212	1.754	2.145	2.013	2.332	2.576	3.16
	20	0.460	1.213	1.756	2.152	2.012	2.332	2.577	3.161
	25	0.461	1.214	1.758	2.156	2.012	2.333	2.578	3.161
	30	0.463	0.968	1.759	2.153	2.015	2.335	2.582	3.162

Obviously, under the same void length, the impact of the void height of the mortar layer on the rail and the track slab is relatively small. Under the positive and negative temperature gradient loads, the negative temperature gradient makes a huge impact on the tensile stress of the track slab.

The mortar layer's vertical compressive stress is subject to variations in void dimensions, as depicted in Figure 12. This graphic illustrates the nuanced impact of void height on the track system under contrasting thermal gradients. Specifically, it reveals a gradual reduction in mortar layer's vertical compressive stress with escalating void height, with a more pronounced sensitivity to positive temperature gradients. This underscores the heightened influence of positive thermal gradients on mitigating the compressive stress within the mortar layer when voids expand.

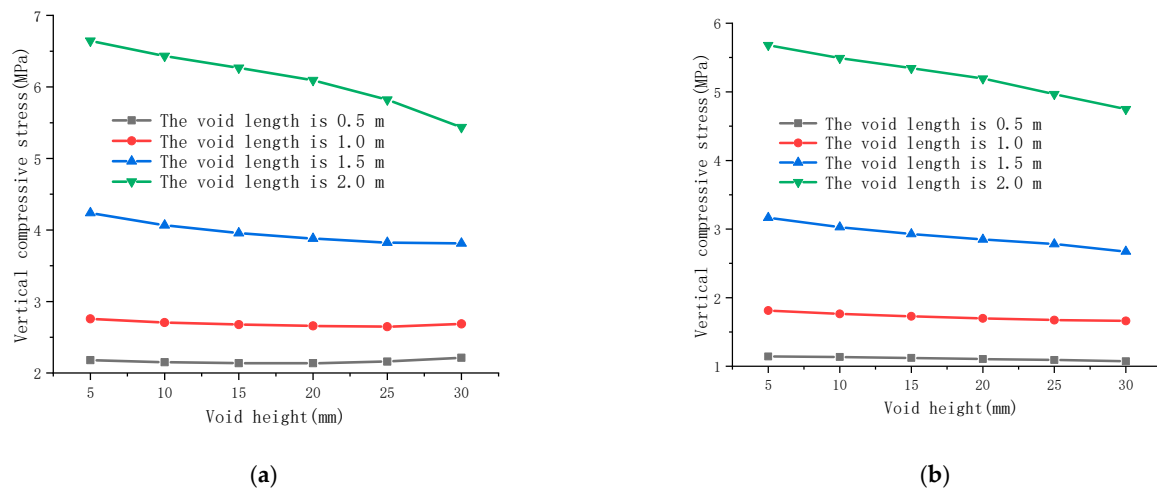


Figure 12. Vertical compressive stress of mortar layer. (a) Vertical compressive stress of mortar layer under positive temperature gradient; (b) Vertical compressive stress of mortar layer under negative temperature gradient.

4. Discussion

This study delves into key factors influencing the performance of track systems, specifically focusing on the track slab temperature, fastener stiffness, and mortar layer voiding. While Zhu [9] confines analysis to deformation and stress under varying temperature gradients, this research broadens the scope to encompass both the track system's overall temperature fluctuations and the specific gradient changes within the slab, offering a holistic assessment of stress and deformation under diverse thermal scenarios in ballastless tracks.

The analysis of the influence of the temperature field on the track system shows that a 20 °C decrease in temperature will cause the lateral tensile stress to exceed the concrete strength. This vulnerability to cooling aligns with the thermal sensitivity observed by Lou and Sun [11] in tunnel environments; however, our study reveals a critical distinction: open-air negative gradients pose a significantly more severe risk of cracking. Given this heightened risk, it is imperative that preventive inspections and crack sealing work are prioritized before the arrival of winter in cold regions to effectively mitigate damage caused by such drastic temperature changes.

In the realm of fastener stiffness, this work comprehensively examines the impact on track slab stress, mortar layer stress, and the displacement of both the slab and rail, demonstrating a positive correlation with increasing stiffness, aligning with established findings [13]. Concerning mortar layer stiffness, a comparative analysis with Dai's study [15] on CRTS I slabs, in which a 50% modulus reduction led to specific changes, serves to validate our findings for CRTS II slabs. Specifically, we report a 1.84% increase in slab displacement and a 16.01% decrease in mortar compressive stress. Building on this understanding of stiffness sensitivity, our findings further resonate with Sadeghi et al. [32], who emphasized the pivotal role of fastening system non-linearity in stress distribution. Our results confirm that even under quasi-static assumptions, such stiffness variations significantly alter the structural load path, thereby necessitating precise stiffness management to prevent premature deterioration.

The research results on the mortar layer voids show that under the combined action of the train and temperature gradient loads, when the void length exceeds 1.5 m, it will cause the longitudinal tensile stress to exceed the tensile strength of C60 concrete. This indicates that there is a critical threshold for initiating non-destructive testing and considering remedial measures, such as grouting. Similarly, when the void width exceeds 1.5 m,

peak transverse tensile stress will be generated in the track slab, meaning that when such defects are detected during on-site inspection, local repair or replacement of the track slab is required. Crucially, this geometric finding aligns with Zhang et al. [33], who noted that inter-layer debonding fundamentally alters CRTS II track mechanics. Our 1.5 m threshold quantifies the specific critical point where the system decouples, leading to rapid stress escalation, thereby validating their theoretical conclusions. Extending the analysis beyond geometric discontinuities, our simulation underscores the severity of material degradation: specifically, a reduction in the elastic layer's modulus to 50% of its design value (<350 GPa) precipitates a sharp transverse tensile stress surge exceeding 33%, concurrent with substantial vertical displacement amplification. We regard this as a maintenance trigger indicator based on elasticity and suggest that elasticity assessment should be conducted regularly, especially in areas with extremely harsh environmental conditions.

Addressing mortar layer voiding, akin to prior research [19], this study examines the voids' influence under temperature gradients and train loads, revealing that void expansion significantly impacts track slab stress, potentially leading to stress levels exceeding the slab's tensile strength threshold.

Through the comprehensive numerical investigation conducted in this study, the analysis conclusion is consistent with the existing research and is of significant importance for clarifying the influence patterns of factors such as temperature, stiffness and voids. Specifically, the finding that temperature gradients are the primary driver for inducing critical tensile stress corroborates the work of Walubita et al. [10] on CRTS III slabs, who similarly identified thermal loading as the dominant factor for interface shear stress initiation. Furthermore, regarding void propagation, our identification of the 1.5 m critical length threshold offers a geometric stress criterion that complements the hydrodynamic pressure models proposed by Zhao et al. [16], providing a dual-perspective validation of void damage mechanisms. Additionally, the observed stress transfer due to fastener stiffness aligns with the safety analysis by Xu et al. [12], reinforcing that excessive support stiffness accelerates stress concentration in the substructure.

Nevertheless, several limitations of this study must be acknowledged. This study conducts numerical simulations based on deterministic material parameters and widely adopted modeling methods. However, constitutive material behavior in actual engineering exhibits significant non-linearity and variability. Second, the current model employs simplified quasi-static loads and cannot capture high-frequency dynamic impact effects and vibration-induced fatigue. Additionally, the temperature dependence and long-term aging effects of CA mortar and fasteners will also affect the performance of the track.

Therefore, future research can further examine the influence of material uncertainty and environmental-load coupling on the long-term mechanical behavior of the track through on-site monitoring data and probability analysis methods. This will enhance the prediction accuracy of the model under real conditions and provide a more solid basis for the forward-looking and reliability of track design and maintenance.

This paper selectively explores fundamental track defects, with a particular emphasis on the compounded effects of voiding under temperature gradient loads. For a more comprehensive understanding, future studies could incorporate the synergistic effects of multiple defects, tailored to real-world conditions, thereby enhancing the applicability of findings to ballastless track maintenance and preservation strategies, providing a robust foundation for informed decision-making in infrastructure upkeep.

5. Conclusions

This study set out with the primary objective of quantitatively evaluating the individual and coupled influences of key environmental and structural factors—temperature

fields, fastener stiffness, CA mortar layer properties, and geometrically defined voids—on the mechanical performance of the CRTS II slab ballastless track system. The main findings, their novelty, and their implications are summarized as follows:

(1) Both uniform temperature decreases and negative thermal gradients were found to be primary drivers for inducing critical tensile stresses in the track slab, with a 20 °C decrease sufficient to exceed the tensile strength of C60 concrete, highlighting a major risk for transverse cracking.

(2) Increases in fastener stiffness predominantly govern rail vertical displacement and stress redistribution in the slab, while reductions in CA mortar layer stiffness significantly amplify transverse tensile stress within the slab, up to 33.7% increase for a 50% modulus reduction.

(3) The length and width of voids is critical parameters. Voids longer than 1.5 m precipitate longitudinal tensile stresses exceeding concrete strength, while a void width of 1.5 m was identified as a critical threshold generating peak transverse tensile stress—a novel insight attributable to the study’s explicit geometric modeling of partial debonding conditions.

Hence, targeted maintenance and remedial actions are crucial to addressing these underlying issues, thereby extending the operational lifespan of the track infrastructure effectively.

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