

Research on Stress Distribution Characteristics in the Wheel-Seat Zone of railway wheelset

Xiaoling Shi, Ning Wang, Debao Hu

Department of Resources and Mechanical Engineering, Lyuliang University, Lvliang, China

Abstract: The wheel-seat zone is a high-risk area for fretting fatigue and wheel-axle loosening failure. During service, it simultaneously bears multi-field coupling effects including mechanical loads, rotational centrifugal force, emergency braking thermal loads, and track impact loads. The dynamic fluctuation of contact stress directly determines the operational safety of the running gear. Taking the EA4T hollow power axle as the research object, this paper adopts a fully coupled thermal-mechanical algorithm to carry out independent single-field simulations and multi-field superimposed combined-condition simulations respectively: 1) Simulate the entire emergency braking process at 200/300/400/500 km/h and the wheel-axle temperature conduction and contact stress transfer laws during the parking cooling stage; 2) Quantify the weakening effect of centrifugal force at different rotational speeds from 200 to 500 km/h on the interference fit interface stress, and analyze the disturbance of track defect impact on the contact field combined with line-measured impact load spectra; 3) According to four typical coupled conditions—static load, high-speed centrifugal load, single emergency braking, and multiple consecutive braking—systematically reveal the axial and circumferential stress and micro-slip distribution characteristics in the wheel-seat zone under multi-physical field superposition. The results show that the wheel-seat stress exhibits a "high at both ends, low in the middle" distribution along the axial direction, with significant stress gradients at the contact edges. Both centrifugal force and braking temperature rise reduce the average interface contact stress, with the thermal accumulation of consecutive braking having the most significant weakening effect. Impact loads only locally amplify the edge stress peaks without altering the overall distribution pattern. Under the four coupled conditions, the fatigue strength of the wheel-seat zone meets UIC standards, but the fatigue safety margin at the inner edge is relatively low. This research can provide simulation-based references for the selection of interference fit amounts in EMU wheel-axle press-fitting, operational control of braking conditions, and axle fatigue life extension.

Keywords: Axle, Wheel-seat zone, Multi-physical field coupling, Interference fit, Stress distribution.

1. Introduction

China's high-speed railway operating mileage ranks first in the world, and EMUs have long been undertaking high passenger flow and high-density operation tasks. As the core safety component that bears the full vehicle weight and transmits traction torque, the axle forms the wheelset with the wheel through an interference fit. The contact stress at the fit interface is the core control indicator for preventing wheel-axle loosening and suppressing fretting slip cracks. Numerous high-speed train derailment accidents both domestically and internationally have been traced back to fatigue fracture and wheel-axle separation in the wheel-seat zone: the Eschede ICE train in Germany, the TGV in France, and the ICE-3 derailment in Germany were all caused by the propagation of fretting fatigue cracks in the axle wheel-seat zone, proving that research on multi-field coupled stress in the wheel-seat zone is crucial to train operation safety.

The actual service of EMUs is a complex process involving multi-physical field coupling of temperature field, centrifugal force field, alternating mechanical loads, and impact field: vehicle dead weight and wheel-rail lateral forces form continuous bending loads; high-speed rotation generates radial centrifugal deformation, reducing the effective interference; emergency braking friction generates a large amount of heat conducted through the wheel web to the wheel-seat, and thermal expansion further reduces contact pressure; rail joints, tread bruises, and track irregularities bring instantaneous impact loads, aggravating edge stress concentration. Single mechanical simulation cannot reproduce the actual service stress state, and multi-field

coupled numerical simulation has become the core means of wheel-axle safety assessment.

Existing studies mostly analyze single factors such as centrifugal force or braking temperature in isolation, lacking comparison of combined conditions under the superposition of mechanical, thermal, centrifugal, and impact loads, and have not systematically distinguished the difference between single braking and consecutive braking thermal accumulation [1]. Relying on the measured load data from the Zheng-Xu railway line and the dual-standard load boundaries of EN 13104 and JIS-E4501, this paper constructs a thermo-mechanical coupled finite element model including the brake disc, hierarchically analyzes the laws of single-field action and the evolutionary characteristics of multi-field coupled stress, compensating for the shortcomings of existing research in multi-field superposition analysis, and providing theoretical support for the optimization of wheel-axle assembly processes and maintenance standards [2].

At the level of fundamental theory of wheel-axle interference contact, Li Yanghui et al used nonlinear finite element analysis to study the effects of interference amount and machining errors on assembly stress [3]. Yang Guangxue established a hollow axle model based on ABAQUS, verifying that increasing the interference amount can enhance the average interface contact stress and reduce micro-slip [4-7]; Pi Te et al. only studied the centrifugal effect within 350 km/h, without covering higher speeds and thermal load coupling conditions. In braking thermal research [8], Wei Lingyu used the friction power method to solve the brake disc temperature field but did not import the temperature field into the wheel-seat contact stress model; Shu Yiliang et al.

simulated wheel-disc braking heat transfer but did not combine it with the superposition of centrifugal and bending loads. In terms of centrifugal loads [9]. Shu Yiliang derived an analytical formula for interference attenuation under rotation but lacked comparative analysis of braking thermal coupling [10]. Existing research in the field of impact loads mostly focuses on wheel-rail contact and has not extended to the stress disturbance law of the wheel-seat interference interface. Overall, existing achievements are mostly single-field isolated studies, lacking a systematic comparison of typical conditions under the multi-physical field coupling of braking heat + high-speed centrifugal + dynamic bending + track impact. This paper takes this as its innovation point to carry out the research.

2. Multi-Field Coupled Finite Element Modeling of the Wheel-Axle

2.1. Geometric Structure and Material Parameters

The research object of this paper is a hollow power axle, made of EA4T alloy steel, with wheels and brake discs made of cast steel. The key dimensions of the complete wheelset are: wheel-seat fitting length 180 mm, axle inner diameter 100 mm, outer diameter 200 mm, wheel rolling radius 430 mm, and brake disc outer diameter 860 mm. The temperature-dependent thermodynamic parameters of the materials are shown in Table 1.

Table 1. Thermo-physical properties of EA4T and brake disc materials

Temperature / °C	Thermal conductivity / $W \cdot (m \cdot K)^{-1}$	Specific heat / $J \cdot (kg \cdot K)^{-1}$	Coefficient of thermal expansion $\times 10^{-5} / ^\circ C$	Density / $kg \cdot m^{-3}$
20	39.3	443	10.9	7200
200	44.1	520	11.6	7200
400	45.3	562	12.3	7200
600	46.2	565	13.5	7200

Other mechanical properties of the material: elastic modulus $E = 206$ GPa, Poisson's ratio $\nu = 0.3$, yield strength 340 MPa, tensile strength 630 MPa, and fatigue limit for 10^7 cycles 260 MPa. The standard assembly interference amount for the wheel-seat is 0.2 mm, with a friction coefficient of 0.3.

2.2. Finite Element Model Construction

A 1/4 axisymmetric simplified model is adopted to reduce the computational scale while accounting for the circumferentially symmetric force characteristics. The total number of elements is 325,412 with 523,415 nodes. Mesh refinement is applied to key regions: the minimum mesh size on the wheel-seat fitting surface is 1 mm, the brake disc friction zone is refined, and other regions are moderately coarsened to improve computational efficiency. The element type selected is C3D8RT, an eight-node thermally coupled hexahedral element that simultaneously supports displacement and temperature degrees of freedom, suitable for fully coupled thermo-mechanical analysis.

Contact settings: the inner surface of the wheel hub is defined as the master surface, and the wheel-seat is the slave surface. The small-sliding contact algorithm is selected with a contact gap tolerance of 0.045 mm. The interference amount is applied in steps (first step: 0.0001 mm pre-contact; second step: loading the true 0.2 mm interference) to avoid non-convergence. Thermal boundary conditions: initial ambient temperature 20 °C; heat flux is applied to the brake disc friction surface; convective heat transfer coefficients are set on all exposed surfaces of the wheelset—forced convection $h = 75 W \cdot (m^2 \cdot K)^{-1}$ during braking, and natural convection $h = 11.5 W \cdot (m^2 \cdot K)^{-1}$ during parking; contact thermal resistance is set between the wheel web and the brake disc and hub to simulate heat conduction loss.

2.3. Load Boundary Conditions

(1) Centrifugal Load

The rotational angular velocities corresponding to 200/300/400/500/600 km/h are calculated, and a global inertial centrifugal field is applied to simulate the radial expansion deformation of the wheel, hub, and axle.

(2) Braking Thermal Load

The energy conversion method is used to calculate the friction heat flux on the brake disc, with a fixed braking acceleration of $-1.3 m/s^2$ and heat absorption rate $\eta = 0.95$. Two types of braking conditions are defined: Condition I—single emergency braking followed by 2500 s of natural cooling; Condition II—three consecutive emergency braking events, with acceleration back to the initial speed between braking events and short cooling time, resulting in thermal accumulation.

(3) Track Impact Load

Based on the calibrated sixteen-level load spectrum from instrumented wheelsets, the maximum instantaneous vertical additional impact load is 30 kN, applied at the wheel-rail contact point to simulate instantaneous impacts from rail joints, tread defects, and track irregularities.

3. Stress Distribution Laws in the Wheel-Seat Zone Under Single Physical Fields

3.1. Effect of Emergency Braking Temperature Field on Stress

The temperature transfer sequence during single emergency braking (200-500 km/h) is consistent: the brake disc friction surface instantaneously heats up to 550-875 °C, and heat is slowly conducted through the web to the wheel hub. The temperature peak at the inner side of the hub (wheel-seat fitting zone) lags behind the braking end by approximately 1100 s. The higher the initial braking speed, the greater the peak temperature: at 300 km/h, the maximum hub temperature is 26.9 °C; at 400 km/h, it is 38.2 °C; and at 500 km/h, it reaches 59.3 °C.

Three consecutive braking events exhibit a significant thermal accumulation effect. Due to insufficient cooling between braking events, the disc surface temperature rises progressively, and the maximum hub temperature increases substantially: at 400 km/h, consecutive braking reaches 71.3 °C; at 500 km/h, it reaches 97.6 °C; and at 600 km/h, it can reach 159.2 °C. The temperature distribution along the axial direction of the wheel-seat is "high in the middle and

low at both ends," with edges having lower temperatures due to air convection cooling.

The temperature rise from single braking is limited, and the reduction in wheel-seat contact stress is minimal—the center stress drop during single braking at 200-500 km/h is less than 2 MPa. However, after thermal accumulation from consecutive braking, the weakening effect is significant: after three braking events at 500 km/h, the center contact stress decreases from 97.2 MPa to 82.0 MPa, and the edge stress

decreases from 257.3 MPa to 246.8 MPa. The stress reduction at the edge is greater than at the center of the fit. The main reason is that the radial thermal expansion of the hub is greater than that of the axle, reducing the effective interference and the normal contact pressure at the interface. The axial temperature gradient causes differential thermal deformation, aggravating the stress non-uniformity on both sides, with the outer edge of the wheel-seat experiencing greater attenuation. The results are shown in Figure 1 and Figure 2.

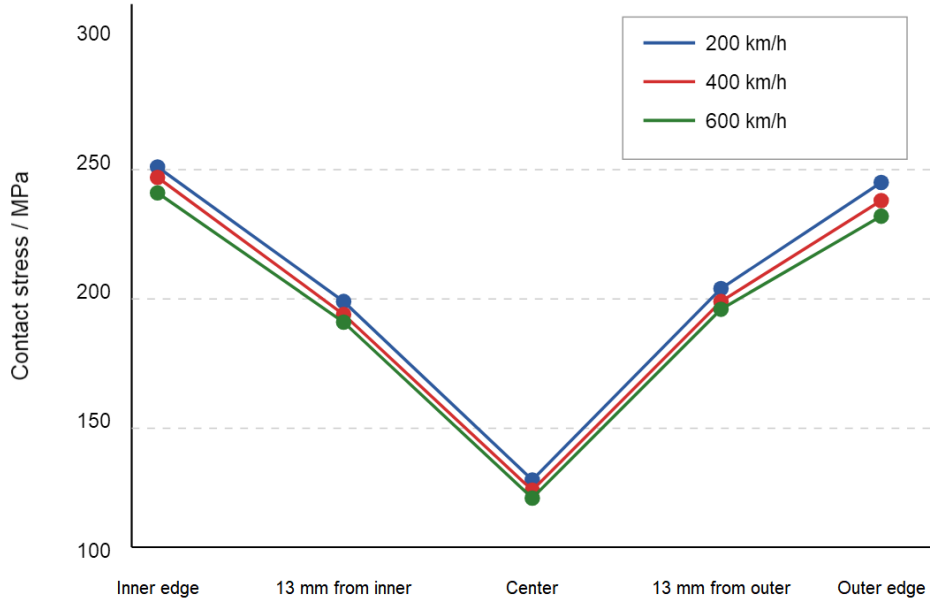


Figure 1. Axial contact stress distribution at different speeds

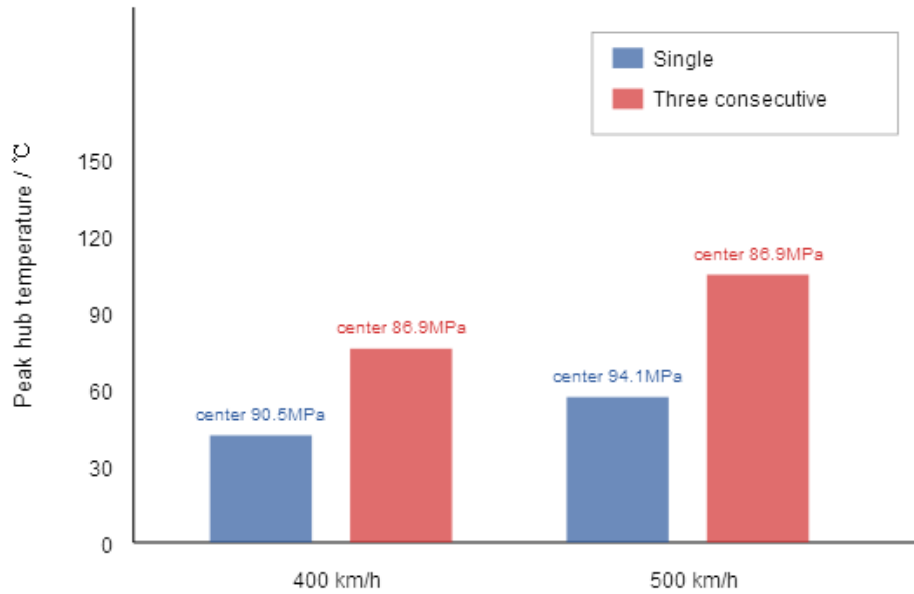


Figure 2. Comparison of thermal accumulation: single vs. three consecutive braking cycles

3.2. Effect of Rotational Centrifugal Force on Stress

Under the condition of applying only the centrifugal field without thermal loads, in the speed range of 200-600 km/h, the overall contact stress of the wheel-seat decreases linearly with increasing speed: at 200 km/h, the center stress is 103.2 MPa and the edge stress is 253.6 MPa; at 600 km/h, the center stress is 97.6 MPa and the edge stress is 243.5 MPa. The overall reduction at the center is 6.9%, and at the edge is 3.1%.

The main reason is that under high-speed rotation, the

radial expansion deformation of the hub (with a larger outer diameter) is greater than that of the hollow axle, increasing the radial clearance at the fit surface and reducing the equivalent interference. Since the hub mass is concentrated near the center of the fit, the centrifugal weakening effect in the center region is much greater than at both edges. The axial distribution pattern does not change with speed, consistently maintaining the "high stress at both ends, gentle at the center" characteristic, with only the overall stress level shifting downward.

Simultaneously, with the change in micro-slip, as rotational

speed increases and contact stress decreases, the interface friction force decreases. The maximum micro-slip increases slightly with increasing speed, with slip concentrated in the region within 18 mm from the edge—this area is the location prone to fretting fatigue.

3.3. Disturbance Effect of Track Impact Loads

When instantaneous impact loads (40 kN additional vertical force) are superimposed on the constant static load, the overall stress distribution trend of the wheel-seat remains unchanged, with only instantaneous stress peaks appearing at the contact edges: the inner edge peak increases by approximately 10.8%, while the center stress is almost unchanged. The impact duration is extremely short, producing only transient stress pulses without altering the average contact stress level.

At the same time, impact loads aggravate the axial micro-slip difference on both sides of the fit, with the amplitudes of positive slip on the left and negative slip on the right increasing simultaneously. Under impact, the maximum slip increases from 9.5 μm to 11.2 μm , an increase of 20.7%. Repeated track impacts will accelerate fretting wear on the wheel-seat surface and promote fatigue crack nucleation.

4. Stress Characteristics Under Typical Multi-Field Coupled Conditions

4.1. Definition of Four Typical Coupled Conditions

Combining the full service scenarios of EMUs, integrating static bending, centrifugal, braking thermal, and impact loads, four extreme typical coupled conditions are defined, covering the full spectrum of parking, high-speed cruising, single braking, and consecutive high-temperature braking:

Case 1 (Static Load Parking Condition): Only standard vertical + lateral static loads are applied, without centrifugal force or braking thermal loads—serving as the baseline reference condition.

Case 2 (High-Speed Condition): Static load + 550 km/h centrifugal field, without braking thermal loads—simulating long-distance high-speed constant-speed operation.

Case 3 (Single Emergency Braking Condition): Static load

and 550 km/h centrifugal field + single emergency braking at 500 km/h cooled to peak temperature.

Case 4 (Consecutive Multiple Braking Extreme Condition): Static load + 550 km/h centrifugal field + thermal accumulation from three consecutive braking events at 550 km/h (hub temperature 183.2 $^{\circ}\text{C}$), superimposed with the maximum line impact load—the most severe service condition.

Five key observation nodes are selected in the wheel-seat zone: inner edge, 13 mm from inner edge, center of fit, 13 mm from outer edge, and outer edge. Contact stress and slip data are extracted for each condition.

4.2. Contact Stress Distribution Under Multi-Field Coupling

(1) Common axial distribution characteristics: Under all four conditions, the contact stress in the wheel-seat zone exhibits a "high at both ends, gentle at the center" distribution, with significant stress gradients at both inner and outer edges. The stress at the inner edge is consistently higher than at the outer edge. The root cause is that the axle neck bending load generates tensile strain in the upper half of the axle, weakening the interference compression effect on the outer side, resulting in lower outer-side contact pressure.

(2) Overall stress attenuation ranking: The severity of operating conditions decreases progressively from Case 1 to Case 4.. Multi-field superposition exhibits an attenuation superposition effect: centrifugal force causes a small stress reduction, single braking adds a small additional attenuation, and the combination of consecutive braking thermal accumulation and impact loads reduces the contact stress to the lowest value across all conditions. In Case 4, the center fit stress is only 86.9 MPa, and the inner edge stress is 213.4 MPa—the minimum values among all conditions.

(3) Field coupling superposition effect: Centrifugal force and braking thermal loads have a superimposable weakening effect on contact stress, but it is not a simple linear superposition. The attenuation contribution from thermal accumulation is greater than that from centrifugal force. Impact loads only locally amplify instantaneous edge peaks without changing the average stress baseline.

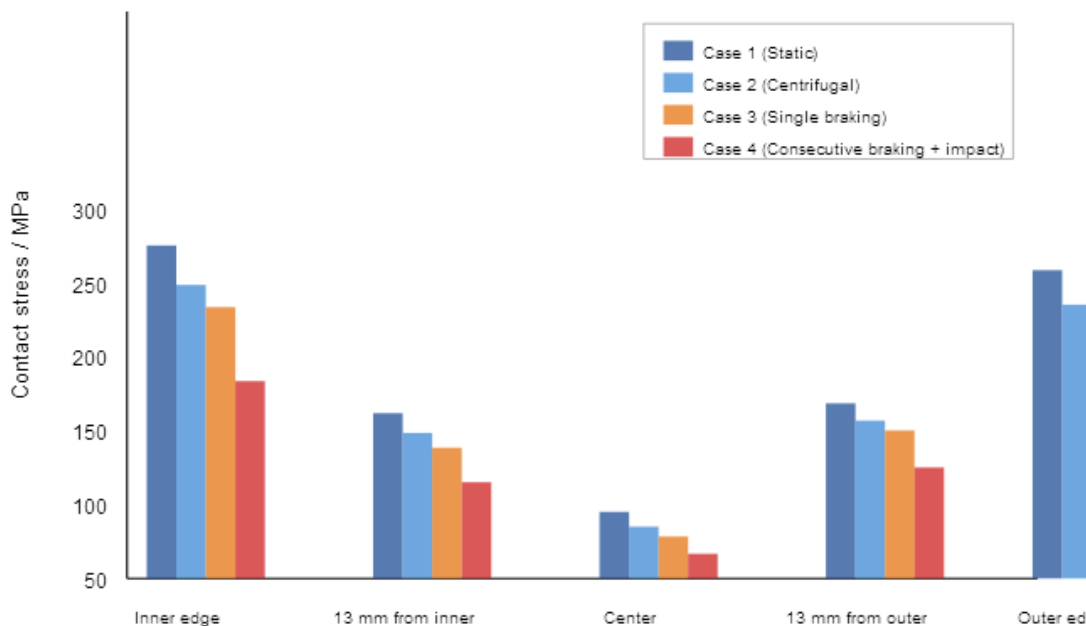


Figure 3. Axial contact stress distribution under four typical coupled load cases

4.3. Micro-Slip Evolution Under Multi-Field Coupling

The axial micro-slip distribution is consistent across all conditions: slip at the fit center approaches zero and increases continuously toward both edges, with the maximum slip concentrated in the region within 18 mm from the edge. On the left side of the center, the hub slides in the +x direction relative to the axle (positive value), and on the right side, in

the -x direction (negative value).

The ranking of slip amplitudes is: Cases 1 to 4 correspond to progressively aggravated operating conditions. Under Case 4 with multiple superimposed loads, the maximum micro-slip reaches 12.9 μm , an increase of 32.7% compared to the pure static load condition. Under a fixed friction coefficient of 0.3, the lower the contact stress, the smaller the interface friction force, and the more significantly the slip amplitude increases, with a corresponding increase in fretting damage risk.

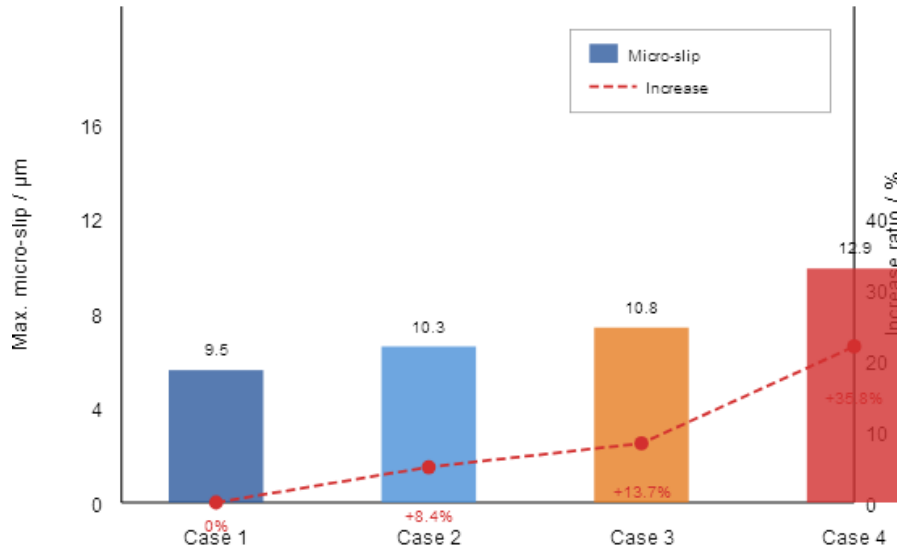


Figure 4. Maximum micro-slip and increase ratio under different load cases

4.4. Fatigue Strength Assessment of the Wheel-Seat Zone

The cyclic mean stress and stress amplitude at the five nodes under the four conditions are extracted. The results show that the stress cycle points of all nodes fall within the fatigue envelope, and the wheel-seat zone as a whole meets the 10^7 -cycle infinite life design requirements under all four conditions. However, the inner edge node under Case 4 approaches the envelope boundary closely, with insufficient fatigue safety margin, making it the weakest location of the entire vehicle. The main reason is that under the multiple coupling of high speed, consecutive braking, and track impacts, the alternating stress amplitude at the inner edge increases significantly. Under long-term high-frequency braking and frequent deceleration on long steep grades, fretting fatigue cracks are prone to occur, making this the key monitoring area for axle flaw detection.

5. Conclusions

(1) The inherent axial distribution pattern of wheel-seat contact stress is not affected by the type of load and consistently remains "high at both ends, low in the middle." There are significant stress gradients at both inner and outer edges, with the inner edge being the fatigue-critical point. Centrifugal force and braking thermal loads only reduce the overall stress baseline without altering the distribution trend.

(2) High-speed centrifugal force linearly weakens the wheel-seat contact stress with increasing speed. Compared with 200 km/h, the center stress at 550 km/h decreases by 6.3%. The temperature rise from single emergency braking has a negligible effect on stress, while consecutive multiple braking thermal accumulation significantly reduces the effective interference, with the stress attenuation effect being

greater than that of centrifugal force.

(3) Track impact loads only instantaneously amplify the stress peaks at the wheel-seat edges without changing the average contact stress. However, they significantly increase the interface micro-slip amplitude, accelerating fretting wear and crack initiation.

(4) Multi-physical fields exhibit an attenuation superposition effect. The extreme coupled condition of static load + 550 km/h centrifugal force + consecutive braking + impact produces the lowest contact stress and the largest slip. Although the fatigue strength meets the requirements under all conditions, the fatigue safety margin at the inner edge of the wheel-seat zone is relatively low.

(5) Temperature conduction exhibits a significant lag effect. The high temperature of the brake disc takes thousands of seconds to conduct to the wheel-seat. Consecutive braking thermal accumulation is the most unfavorable thermal load condition for wheel-axle fit failure.

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