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A Transient Finite Element Model to Simulate the Physical Mechanisms of High-speed Wheel/rail Rolling Contact on a Rail Welding Joint

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In order to study the influences of defective rail welding joints on wheel/rail interaction, a transient finite element model of a high-speed train passing over rail welding joints is presented on the basis of field measurements. Focusing on the physical mechanisms differences of wheel/rail rolling contact on welding joints with varying rail straightness at rolling speeds of up to 400 km/h, this model takes vehicle/track system dynamics and wheel/rail elastic–plastic deformations into account. The defective thermite welding joint with short wave irregularity easily leads to rail nucleus flaw with residual stress. When the running speed is over 250km/h,, the maximum value of wheel/rail vertical force at welding joint has a basic trend of a bilinear increase with the increase of running speed and the unevenness of the welding joint. There is a phase difference between the maximum contact force and the peak joint irregularity. When the high-speed railway operation management standard is 250~350km/h, the short wave irregularity at rail welding joint with over 0.3mm straightness should be grinded.

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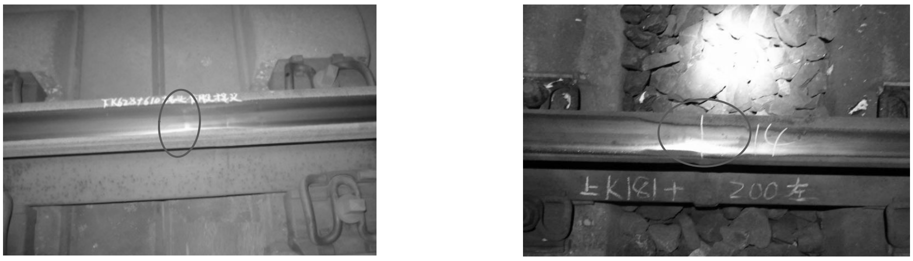
1. Introduction

The continuously-welded rail (CWR) is the best choice to realize the technology of high-speed running and heavy-duty track structure. Rail welding is the key technology of the CWR. The quality of the rail welding influences train speeds and service life of track components. At the welding joint of the CWR, due to the differences between the parent metal and the welding, the uneven abrasion on the top of welding rail will increase the interaction between wheel and rail. With the increase of railway operation speed and axle load, the damage of rail welding joint becomes serious, which will lead to high railway operation cost and directly affects the safety of railway transportation. Fig. 1 shows the defective thermite welding.



(a) (b)

Figure 1: Rail welding: (a) Ballastless track; (b) Ballast track

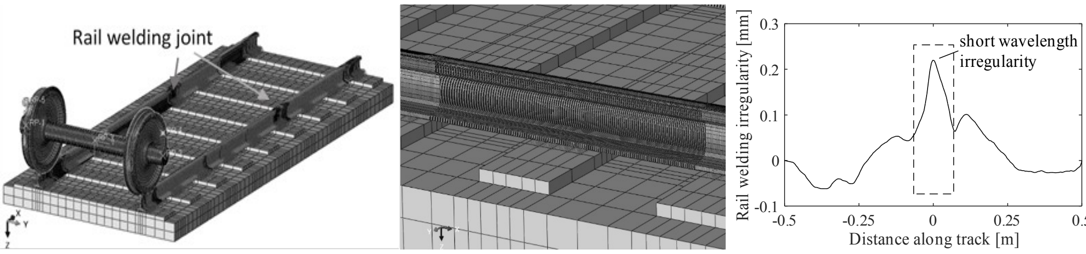
Rail joint modeling by solid elements has been implemented in FE models. Some studies simplified the rail structure and replaced it with beam elements. E.Kabo studied the relationship between insulated rail joints and the high-frequency dynamic train/track interaction through the numerical simulations [1]. Xiao Guangwen investigated the effect of rail welding on the track dynamic behavior and a Timoshenko beam was used to model the rails which were discretely supported by sleepers [2]. Wen Zefeng used the finite element program ANSYS/LS-DYNA to calculate the contact impact between wheel and rail at rail joint region considering the influences of axle-loads and train speeds [3]. Molodova established a 3D finite element model to simulate the axle-box acceleration at the thermite welding and investigated the quantitative relation between short wave track defects and the axle-box acceleration [4]. The other mainly study multi-body dynamics. Sun Yanquan established a 3D vehicle/track interaction dynamics model to determine the track vertical dynamic forces due to rail joints[5].

The vehicle/track coupling dynamics at rail welding is the key to analyze the impact that wheels have on welding joint. However, there are few published studies on vehicle/track coupling dynamic interaction in rail joint regions. Taking into account the primary suspension system and the wheel/rail elastic–plastic deformations, this paper describes a 3D transient finite element model to simulate high-speed wheel/rail rolling contact on a rail welding joint based on the field measurements. ABAQUS is used in the simulation of vehicle/track impact process focusing on the physical mechanisms differences of wheel/rail rolling contact on welding joints with varying rail straightness at rolling speeds of up to 400 km/h.

2. Dynamic Finite Element Model

2.1 Wheel/Rail Dynamic Finite Element Model

The vehicle/track coupling finite element model includes one three-dimensional wheelset and the primary suspension system and the ballastless track with defective thermite weldings (Fig. 2a-b). A high-speed line with rail welding irregularities is selected and Fig. 2c shows its actual straightness. The rail welding, about 0.22mm higher than the rail surface, exceeds high-speed railway grinding requirement. The rail welding center mileage is set to 0. The rail (CN60 profile, 1:40 inclination) and the wheel (LMA profile) are modeled using elastic-plastic material with 3D solid elements. The welding material is different from the rail parent material. The yield strength is about 80％～90％ of the rail parent ones in China [6]. The wheel radius is 0.43m and the track is about 10m long. A dynamic relaxation of track with about 2.75m long is designed for the system to relax oscillation. The smallest element size on the contact surfaces is about 1.5mm and the total number of the finite element nodes is about 10^6. The model parameters are normal values of high-speed railway (Table 1). The rail joint mainly causes the high frequency vibration of vehicle/track coupling system and the vehicle vibration frequency above the primary suspension system is low, therefore the structure above the primary suspension is set as load mass of about 7 tons.



(a) (b) (c)

Figure 2: Finite Element Model: (a) Vehicle/track model; (b) Rail welding joint; (c) Rail welding joint irregularity

Component		**Value**	**Component**		**Value**
Friction coefficient		0.3	Ballast Material	Young's modulus	35GPa
Lumped sprung mass		7000kg		Poisson's ratio	0.2
Wheel diameter		0.86m		Mass density	2500kg/m^3
Primary suspension	Stiffness	1.176MN/m	Wheel and rail Material	Young's modulus	206GPa
	Damping	10kN•s/m		Poisson's ratio	0.3
Rail fastening	Stiffness	50MN/m		Mass density	7850kg/m^3
	Damping	70kN•s/m		Yield stress	0.8GPa

Table 1: Parameters of the Model

2.2 Numerical Simulation Method based on Explicit Integration

Explicit integration method was adopted to simulate a high-speed train passing over a rail welding joint. Based on the explicit method for solving contact problems, a two-step central difference method can be adopted. ABAQUS/Explicit is used in the simulation of impact contact of vehicle and rail welding joints. At time *t*, the beginning of the increment step, the program solves the dynamic equilibrium equation [7]. Nodal acceleration is:

$$\ddot{u}_{(i)} = (M)^{-1}\left(P_{(i)} - I_{(i)}\right) \tag{2.1}$$

where the subscript *i* is the increment number, *M* is nodal mass matrix, *P* is the external force and *I* is internal force. The speed at the midpoint of the current increment step is as follows:

$$\dot{u}_{\left(i+\frac{\Delta i}{2}\right)} = \dot{u}_{\left(i-\frac{\Delta i}{2}\right)} + \frac{\left(\Delta t_{(i+\Delta i)} + \Delta t_{(i)}\right)}{2}\ddot{u}_i \tag{2.2}$$

The displacement at the beginning of the increment step is added to the velocity integral in time domain for determining the displacement at the end of the increment step as follows:

$$u_{(i+\Delta i)} = u_{(i)} + \Delta t_{(i+\Delta i)} \dot{u}_{\left(i+\frac{\Delta i}{2}\right)} \tag{2.3}$$

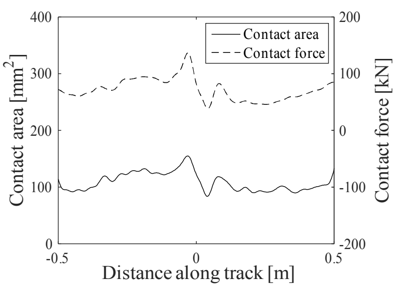
According to the strain rate, the element strain increment $d\varepsilon$ is calculated. The stress σ is calculated according to the constitutive relation as follows:

$$\sigma_{(i+\Delta i)} = f\left(\sigma_{(i)}, d\varepsilon\right) \tag{2.4}$$

The nodal forces $I_{(i+\Delta i)}$ are integrated. Then, i is set to $i+\Delta i$ and returns to step Eq. (2.1).

2.3 Calculation Result Analysis

With vehicle/track system finite element model, Fig. 3 shows wheel/rail interaction between contact area and contact force when a high-speed train passed over a rail welding joint at 330km/h. Fig. 4 and Table 2 show wheel/rail Von Mises stresses at different positions along track.



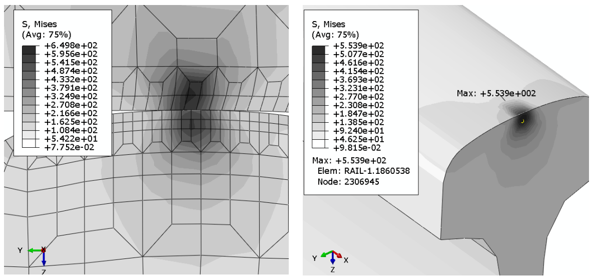
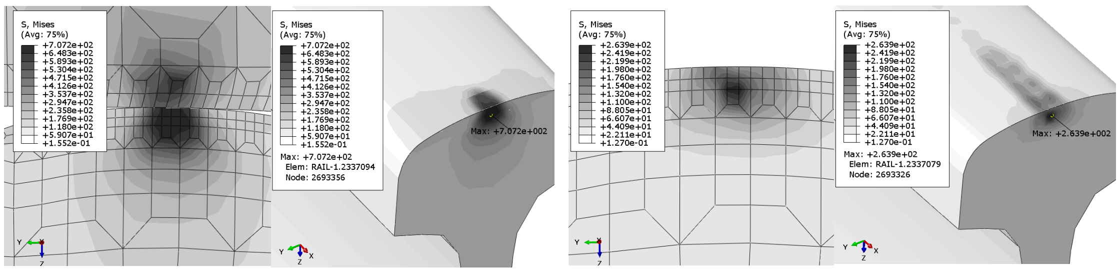


Figure 3: Wheel/rail Interaction at the Welding Joint (a)



(b) (c)

Figure 4: Wheel/rail Von Mises Stress: (a) No joint; (b) Joint; (c) Residual stress

Position of wheel/rail contact	The maximum Von Mises stress	The maximum Von Mises stress location
Before the joint regoin	649.8MPa	On the wheel
During the joint regoin	707.2MPa	On the rail
After the joint regoin	263.9MPa	On the rail (residual stress)

Table 2: The maximum Von Mises stress of the wheel/rail contact

In rail welding joint region, owing to the change of the rail longitudinal geometry and material, wheel/rail interaction appears fluctuation. The maximum value of wheel/rail contact force is about 137kN about 2 times of the axle-load and is not at the rail welding center mileage. The maximum value appears at about -0.03m and the minimum value appears at about 0.03m. There is a phase difference between the maximum contact and the peak welding joint irregularity. It may shorten the short wavelength and deteriorate the short wave irregularities at welding joint. When the welding joint irregularity exceeds the standard grinding value, it needs grinding in time. Fig.4a shows the wheel/rail Von Mises stress in the region without rail irregularity. Before the train reaches the joint, the maximum Von Mises stress on the wheel is about 649.8MPa and on the rail is about 553.9MPa. The maximum Von Mises stress of the wheel/rail contact appears on the wheel rather than the rail. When the train passes over the joint, the maximum value increases and appears at about 2~3mm below the surface of the rail. It exceeds the yield strength of welding joint material and makes rail plastic deformation. Hence, the defective thermite welding will cause more damage to the rail than the wheel (Fig.4b). After the train passesover the joint, there is residual stress on the rail welding joint with the maximum Von Mises stress of about 263.9MPa and it easily leads to rail nucleus flaw.

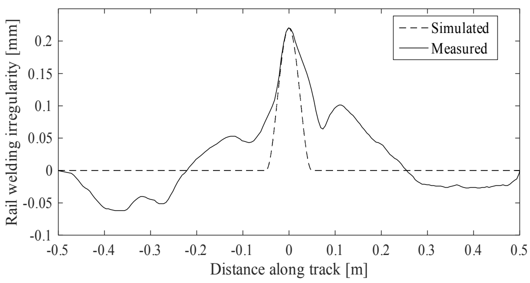
3. Parameters Analysis

3.1 Dynamic Results of the Model

According to the statistics of railways, a type of convexity irregularity which consists of three curved segments widely exists on the surfaces of rail welding [3] and can be described as,

$$Z_0(t) = \begin{cases} \frac{1}{2}\delta_1\left(1 - \cos 2\pi v t\right) & 0 \le t \le \frac{1-\lambda}{2v} \\ \frac{1}{2}\delta_2\left[1 - \cos\frac{2\pi v}{\lambda}\left(t - \frac{1-\lambda}{2v}\right)\right] + \frac{1}{2}\delta_1\left[1 - \cos \pi\left(1 - \lambda\right)\right] & \frac{1-\lambda}{2v} \le t \le \frac{1+\lambda}{2v} \\ \frac{1}{2}\delta_1\left(1 - \cos 2\pi v t\right) & \frac{1+\lambda}{2v} \le t \le \frac{1}{v} \end{cases} \tag{3.1}$$

where δ_1 and δ_2 are the depths of long and short wave irregularity, respectively. The long and the short wavelengths are, respectively, 1m and λ, and t is the time. This paper focus on the short wave track irregularity so that δ_1 is 0 and λ is set as 0.1 m. The dashed line is the short wave of the rail welding joint obtained by using the formula (3.1) (Fig. 5). The dashed line data was used in the finite element model of the vehicle/track system to make further research.



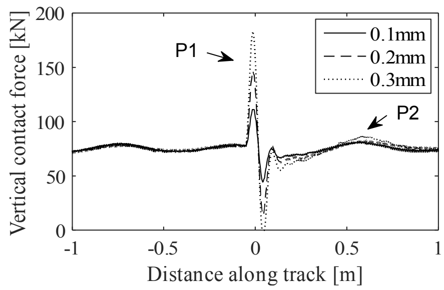


Figure 5: Rail welding straightness **Figure 6:** Comparison charts with different straightnesses

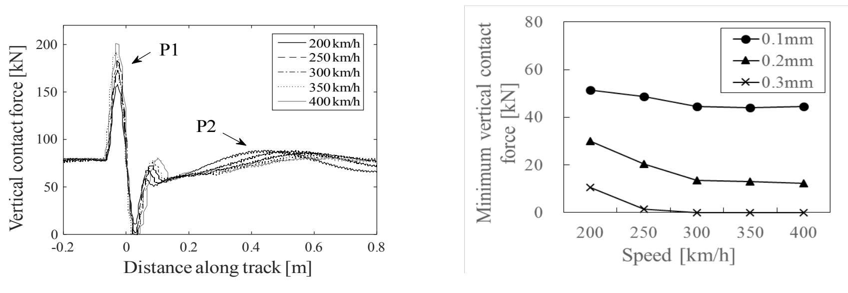
3.2 Comparison of the Results for Different Rail Welding Joint Straightness

The vehicle/track system finite element model is established by selecting different uneven amplitude of rail weldings. High-speed railway operation management standards are divided into 200~250km/h and 250~350km/h. Different speeds during 200~400km/h were selected as a comparative analysis with the rail welding irregularity as 0.1mm, 0.2mm and 0.3mm.

When the speed was 300km/h, wheel/rail vertical force under different welding irregularities was shown in Fig.6 The position of the maximum wheel/rail vertical force is within the range of -0.05 ~ 0m, indicating that the wheel has a large impact force P1 on the welding joint before reaching the amplitude of the rail welding. Then the wheel/rail vertical force appears the minimum. The vertical vibration of the wheel/rail force is gradually attenuated by a series of damping including the primary suspension system and fastening system, and the maximum value P2 appears at about 0.6m. The high frequency vibration of P1 force is caused by the short wave irregularities of the rail welding joint and P2 is the medium frequency force when the rail reaches the maximum displacement under the dynamic effect of the unsprung mass. The conclusion is consistent with the literature [6]. With the increase of the welding unevenness by 0.1mm, the maximum value of wheel/rail vertical force P1 at welding will increase about 36kN. When the welding is 0.3mm higher than the rail surface, the wheel/rail vertical force is 0, that is, the wheel has instantaneous beating. High-speed railway should avoid the occurrence of the situation, otherwise it will affect the train traffic safety.

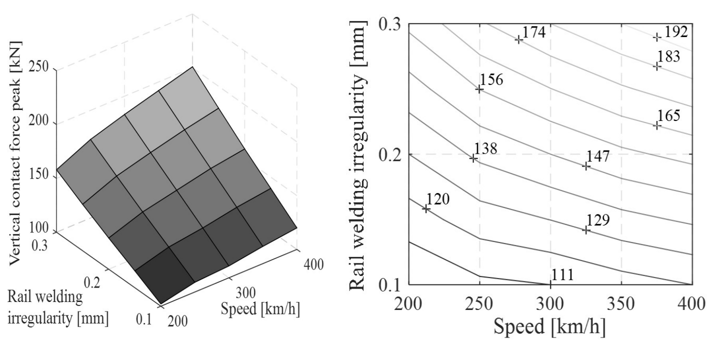
3.3 Comparison of the Results for Different Running Velocities

When the rail welding joint short wave irregularity was 0.3mm, the wheel/rail vertical contact forces under different speeds were shown in Fig.7a, compared with the straightness of 0.1mm and 0.2mm (Fig.7b). Fig.8 summarizes the combined effects of both rail welding irregularity and running speed on the dynamic contact force.



(a) (b)

Figure 7: Comparison charts with different speeds: (a) Vertical contact force; (b) Minimum vertical contact force



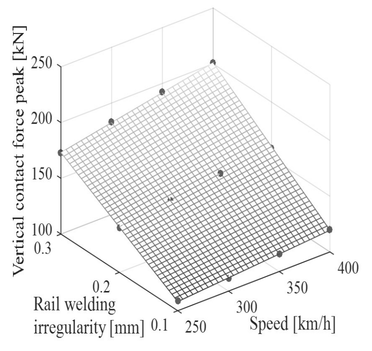


Figure 8: Wheel-rail vertical force contour plot **Figure 9:** 3D curved surface

With the increase of running speed by 50km/h, the maximum value of wheel/rail vertical force P1 at welding will increases about 10kN. However, P2 force decreases slightly with the phase delaying. This illustrates the phase of P2 force is clearly influenced by the series of damping including the primary suspension system and fastening system. When the running speed is not less than 300km/h, the wheel/rail vertical force minimum value is 0 and the wheel has a momentary beating. When the welding short wave irregularity is not more than 0.2mm, the wheel will not appear instantaneous beating phenomenon with the running speed below 400km/h. It can be seen from Fig. 8 that when the speed is over 250km/h, with the increase of the running speed and the unevenness of the welding joint, the contour plot of the maximum wheel/rail vertical force at the rail welding distribute evenly, indicating that it has a basic trend of a bilinear increase. The fitting bilinear formula is as follow:

$$F_{max}=70.6667+187.5D+0.02V+0.55DV \tag{3.2}$$

where F_{max} is the maximum wheel/rail vertical force, D is the unevenness of the welding joint and V is the running speed. It can be calculated that the correlation coefficient is 0.9996. Fig.9 shows the fitting three-dimension curved surface.

4. Conclusion

In order to study the influences of the defective rail welding joints on the wheel/rail interaction, a transient finite element model based on the explicit integration method is built. Compared with the physical mechanisms differences of high-speed wheel/rail interaction with different speeds under varyingjoint rail irregularities, the following conclusions are drawn:

(1) In the joint region, the maximum Von Mises stress of the wheel/rail contact appears on the rail. The defective thermite welding with short wave irregularity will cause more damage to the rail than the wheel and it easily leads to rail nucleus flaw with the residual stress.

(2) When the running speed is over 250km/h, with the increase of running speed and the unevenness of the welding, the maximum value of wheel/rail vertical force at welding joint has a basic trend of bilinear increase.

(3) There is a phase difference between the maximum contact force and the peak joint irregularity. When the speed is not less than 300km/h and the welding short wave irregularity is over 0.3mm, the wheel/rail vertical force minimum value is 0 and the wheel has a momentary beating. Hence, when the high-speed railway operation management standard is 250~350km/h, the welding short wave irregularity with over 0.3mm straightness should be grinded.

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