Dynamics of Rolling Stock Wheels and Track Interaction in Areas of Welded Rail Joints Crush

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Abstract. Finite element models of a rail crushed in a welded joint area and fixed on an elastic damping foundation and a car wheel have been developed. An algorithm has been developed to calculate quasistatic and impact forces during a wheel rolling at different speeds. Experimental studies have been carried out to determine vertical forces in the crushed area of the welded joint at a depth of 1.8 mm using the strain measurement method on the rail web neutral axis.

1. Introduction
In accordance with the Railway transport development strategy in the Russian Federation until 2030 [1], the task has been set to bring the technical and technological level of the infrastructure, its maintenance and repair to the best world standards. At the meeting chaired by the Minister of Industry and Trade of the Russian Federation, D.V. Manturov [2] it was decided to increase the track overhaul life to 2,000-2,500 million tons gross. According to the long-term development program of JSC “Russian Railways” until 2025 [3], the task has been set to increase the service life of rails to 1,500 million tons gross.

To increase the service life of rails from 700 to 1100 and further to 1,500 million tons gross in 2012–2013 a large-scale reconstruction of the rail production at JSC “EVRAZ ZSMK” [4] was carried out, a new rail-and-beam shop was built in PAO “Chelyabinskiy metallurgicheskij kombinat” (PAO “Mechel”) [5]. New equipment of the above-mentioned rail production allows to produce long (up to 100 m long) differentially heat-strengthened rails using rolling heat and new environmentally friendly cooling media.

The conducted certification tests of DT350 rails produced by JSC “EVRAZ ZSMK” and PAO “Chelyabinskiy metallurgicheskij kombinat” (PAO “Mechel”) showed high performance characteristics – 1,300 and 1,100 million tons gross, respectively, of the passed tonnage, with 80% γ-service life [6]. However, the operating experience of differentially heat-strengthened rails under the conditions of the Eastern operating domain with high working capacity, complex track profile and harsh climatic conditions showed, by a number of criteria, insufficient service durability that did not match the results of the field tests on the JSC “VNIIZhT” test loop.

In 2017, on the railways of Russia, 129 cases of destruction (fracture) of rails were fixed, it is 2.7 times more than in 2015. The same tendency is demonstrated by the change in the number of defective rails withdrawn according to the readings of the fault detectors.

About 30% of all fractures of both DT rails and OT rails are due to the destruction of welded joints. An increase of rail fractures at the welded joints is observed. If from 2007 to 2011 the tendency to a decrease of the number of fractures was observed (from 25 to 10 units), then from 2011 to 2017 their
number increased to 34 units. All this speaks to the relevance of issues related to the study of the service life capabilities of welded joint areas and the development of measures to increase their service life.

One of the reasons for the insufficient service life of welded joints of continuously welded rails is lower mechanical characteristics in the heat-affected area of the welded joint. This determines the metal crush in the area under consideration with the formation of a saddle, which determines the impact nature of the wheels and rails interaction, leading to increased dynamic forces.

2. Theoretical background
The process of impact interaction between a wheel and a rail with defects on the running surface is the most difficult to study, since it is necessary to simultaneously take into account contact and bending strains of the rail.

The values of contact strains and forces in the contact area are related by the nonlinear dependence. The first stage of the wheel and rail impact interaction causes significant elastic strains in the contact area, slightly bending the rail as a whole and slightly straining the rail base. At the second stage, the development of the rail bending strains and the growth of the elastic settlements of the rail base occur.

In [7–10] the problem of the interaction of a wheel with a defect on the tread surface, which is accompanied by a rail impact, is considered as a model that includes a number of masses connected by conventional “springs” and “dampers”, which allow the reproduction of stiffness characteristics and internal energy dissipation of individual elements of the track superstructure.

The second method for calculating the wheels and rails impact interaction is based on the integral equation describing a transverse impact on a beam of infinite length lying on the elasto-viscous base. G. Hertz [11] solved the nonlinear problem of establishing the relationship between the local compression and the contact force, S.P. Timoshenko [12] obtained the integral equation for determining the contact force and other force and kinematic characteristics of an impact.

The method of generation an integral equation for determining the main characteristics of an impact formed the basis of many subsequent works on impact for beams and rods, plates, shells, and other elastic bodies [13–15].

In relation to the railway track, this approach was applied to determine the response of the rail to the contact force effect under impulse action in the form of a δ-function [16–18]. At present, geometric (solid) and finite-element modeling technologies are widely used to study contact interaction problems using various multi-purpose software systems for strength analysis and stress-strain state determination, such as Abaqus, Ansys, etc. This approach simultaneously allows to determine the forces of impact interaction and the stress-strain state of the object under study, in particular, the rail [19–20].

3. Model construction
At the first stage, field measurements of the crushed area of welded joints at a length of 1 m were carried out symmetrically with respect to the axis of the welded joint using a Riftek portable laser range profilometer. The measurement of the transverse profiles of the rail welded joint area was performed in 10 mm increments, which made it possible to create a 3D model of the rail for further finite element analysis.

To study wheels and a rail dynamic interaction in the welded joint area, a finite-element model of the “wheel – rail” system has been developed, where the rail is geometrically constructed using the obtained experimental data and taking into account irregularities on the running surface that occur in the welded joint area.

In the “sleeper – rail” contact area, MPC-links simulating the rail fastening on the sleeper seat are modeled, and elastic and damping elements are introduced that simulate the total stiffness of the elastic pads of rail fasteners and the sleeper seat, as well as the characteristics of the embankment oscillations damping. This allowed to significantly reduce the volume of the model and the estimated time, as well as to quickly vary the track stiffness characteristics. A finite-element model of an elastic
wheel with the function of rolling along a rail at a set speed is installed on the rail. The forces of the contact interaction in the “wheel – rail” area were determined when the wheel load was 10 tons. Impact forces were calculated from the interaction of the unsprung mass brought to the freight car wheel – 0.93 t with the crushed area of the welded joint.

The finite-element 3D-model of a rail with a welded joint area connected to reinforced concrete sleepers was transformed into the finite-element “wheel – rail” model using elastic and damping elements (Figure 1).

![Finite-element model of the wheel-rail system using elastic and damping elements.](image-url)

**Figure 1.** The finite-element model of the wheel-rail system using elastic and damping elements.

The characteristics of the springs are chosen taking into account the elasticity modulus of the rail base, which is numerically equal to the distributed reactive base reaction that occurs on a unit length of the rail with the elastic settlement equal to 1 [21]. The track stiffness is numerically equal to the force of the wheel pressure on the rail, referred to the elastic deflection under force.

At the first stage of the calculation, the quasistatic wheel load on the rail is determined. At the second stage, the impact dynamic load is calculated as a result of the interaction of the unsprung mass of the freight car – 0.93 tons with the welded joint crushed area. Calculations of impact vertical forces were carried out for the case of a wheel model rolling along a rail at speeds of 20, 40, 60, 80 km/h. It has been established that the values of the impact forces change according to a dependence that is close to parabolic; they increase more intensively with the movement speed increasing.

Table 1 presents the calculated values of the impact forces from the movement speed arising in the “wheel – rail” contact area during the freight car running through the area of the welded joint. The analysis of the obtained data showed that the forces significant increase is observed with the movement speed increase up to 80 km/h. Thus, the values of the impact forces increased from 31 to 60 kN with the speed increase from 20 to 60 km/h, with the speed increase up to 80 km/h the value of the impact force rises to 119 kN.
4. Experimental studies

For verification of the model, the data of the experimental studies of vertical forces from the wheels of freight trains while passing through the welded joint crushed area were used. The experimental track section was laid on the I main track of the Nepetsino – Ratmirovo section of the Moscow railway. For the continuous recording of vertical forces in the welded joint area, the force method proposed by prof. N.N. Kudryavtsev [8] was used.

The analysis of the vertical forces from the passing of freight train wheels showed that when the loaded freight cars were running along an even section, the levels of the vertical forces varied from 100 to 125 kN. When running over a joint irregularity, the vertical forces decreased from 100 to 78–80 kN for 0.2 s, then increased to 145–160 kN for 0.01 s, after which unloading took place for 0.006 s to 110–112 kN, then the vertical forces for 0.003–0.004 s again impulsive increased to 150–170 kN. The behavior of the calculated oscillograms (Figure 2) was somewhat different. During the initial period, there was a phase of unloading, typical for the wheel turning relative to the front point of the profile change, which led to the decrease of the vertical forces to 50–70 kN, depending on the speed of movement. After the interaction of the wheel with the surface of the welded joint crushed area, a jump of the vertical forces to 135–158 kN was observed at speeds of 45–60 km/h. After the passage of the peak value the magnitude of the vertical forces dropped to 58–80 kN for 0.1 s, after which the forces magnitude restored for 0.15 s to the initial 100 kN. The comparative analysis of the average values of experimental and calculated values of impact forces at a speed of 45 km/h showed that the degree of discrepancy between experimental and calculated data did not exceed 7.8%. The obtained result can be considered sufficient to perform practical calculations.

Using a verified finite-element model of a railway track with defects in the form of a crush in the area of welded joints of continuously welded rails, it is planned to carry out calculations and determine dependences of the stress-strain state of rails in the areas of welded joints on the depth and length of the crushed area, the rolling stock speed, and the stiffness of the rail base depending on the track design and time of year.

### Table 1. The maximum impact force of the “wheel – rail” contact $F_{\text{max}}$ in the area of the welded joint with the crush depth of 1.8 mm at different car speeds.

| Movement speed, km/h | 20  | 40  | 60  | 80  |
|----------------------|-----|-----|-----|-----|
| Impact forces, $F_{\text{max}}$, kN | 31.75 | 53.70 | 59.70 | 119.00 |
5. Conclusion

1. The area of the welded joint lowering determines the impact interaction of the rolling stock wheels and the track. A joint irregularity in the form of the welded joint lowering with the depth up to 1.8 mm on the basis of 1 m determines the values of the impact forces from the wheels of loaded freight cars at a speed of 45 km/h in the range of 35–45 kN, or 30–38% of the static load.

2. The results of the calculated values of impact forces at a speed of 20–80 km/h had values of 31–119 kN. The comparative analysis of the experimental and calculated values of the impact forces at a speed of 45 km/h showed that the degree of discrepancy between the experimental and calculated data is 7.8%. The obtained result can be considered acceptable for practical calculations.

3. The developed finite-element “wheel – rail” model with a “crushing” defect will allow to predict the change of forces occurring at the wheel and rail contact in the welded joint area depending on the length and depth of the joint crush, the stiffness of the rail base, and the rolling stock speed.

6. References

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