The rolling contact research of three dimensional wheel-rail based on finite element analysis

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Abstract. In this paper, wheel-rail contact model was established and analyzed, some useful results were obtained. The results show that in the early stage of wheel-rail contact, the wheel-rail contact pressure increases gradually and the contact point shape changes from regular polygon to irregular polygon in the process of wheel approaching rail joint. The equivalent stress and elastic deformation trend of the rail are basically the same, both of which decrease rapidly and then slowly increase. The plastic deformation of the rail gradually increases and accumulates, and the stress concentration area occurs at the side of the rail joint. When the wheel starts rolling, the equivalent stress of the wheel gradually decreases at first, and then increase. The peak value of the maximum equivalent stress occurs at the joint where the wheel reaches the rail.

1. Introduction
With the increase of railway load-carrying capacity and speed, the research on wheel-rail contact is becoming more and more important [1]. The research methods of wheel-rail contact mainly include Hertz’s analytical method [2], Kalker’s programs, and Fastsim and CONTACT [3]. Document [4] used the finite element method to analyze the influence of axle weight, wheel transverse motion, elastic modulus and poisson’s ratio on the contact stress of wheel-rail. Document [5] compared the influence of different profile of wheel on the contact stress of wheel-rail under the static contact condition. Document [6-10] have used this method to obtain the optimized solutions for different wheel-rail interaction problems.

In this paper, three dimensional wheel-rail rolling contact model was established to analyze wheel-rail contact problems. The distribution of the wheel-rail contact pressure, equivalent stress, plastic strain and elastic strain during wheel rolling were obtained.

2. Establishment of the wheel-rail contact model
A commonly used 840 mm diameter elastic wheel and corresponding rail were created. The x-axis was the axial direction of the wheel, the y-axis was the vertical direction along the rail, and the z-axis was the running direction of the wheel. The slope of 1:20 was utilized, since it could be adjusted easily with sleepers’ slope. The rail’s length was 500 millimeter to simulate the initial stage of wheel-rail contact. It could be seen in figure 1. Friction coefficient 0.3 was used in this model.

The 3D geometric model was meshed with SOLID185, that was 8-noded hex elements as shown in figure 2. Where bi-linear kinematic Hardening elastic-plastic material was used for the wheel-rail rolling contact model, and the material properties were in table 1. It could give the stress-strain
relation of the material as shown in figure 3.

![Figure 1. Geometric model.](image1)

![Figure 2. The wheel-rail finite element contact model.](image2)

![Figure 3. Stress-strain relation of the material.](image3)

Table 1. The properties of the materials.

| Material | Modulus of elasticity (GPa) | Yield stress (MPa) | Modulus of plasticity (GPa) | Poisson’s ratio |
|----------|-----------------------------|-------------------|-----------------------------|----------------|
| Steel    | 210                         | 450               | 93                          | 0.3            |

Two load steps were applied for realizing wheel rolling on rail. In the first load step, the translation degree of the x, z direction was fixed, the translation degree of the y direction was free and the load \( F \) 10.5 \( t \) was applied in the negative y direction at pilot node. In the second load step, the rotational degree of the x direction was free and translation displacement of the z direction was 400 mm for wheel. All freedom degrees at the bottom of the rail were constrained. The final wheel-rail rolling contact model can be seen from figure 2.

According to the basic Hertz contact theory, the theory of the normal contact pressure for three-dimensional problem can be expressed as:

\[
P(x,y) = P_0 \left( \frac{1 - \frac{x^2}{a^2} - \frac{y^2}{b^2}}{2} \right)^{\frac{3}{2}}
\]

(1)

Where \( P(x, y) \) is the contact pressure at the contact point and \( P_0 \) is the maximum contact pressure of the wheel and rail. \( a \) represents the major semi axis of the contact point and \( b \) represents the minor semi axis of the contact point.

\[
P_0 = \frac{3Q}{2\pi ab}
\]

(2)

where the \( Q \) is the axle load.

3. Results and discussions

Extended Lagrange algorithm was used, the calculation time was set at 4 seconds, and the load steps were divided into 2000 substeps and contact pressure, stress and deformation were obtained. Total displacement for both wheel and rail at three different times was shown in figure 4. It can be seen from figure 4, with the increase of time, the wheel rolled from the left end of the rail to the right. when \( t=0.6 \) s, the maximum equivalent displacement is 117.671 at the top of the wheel rim. From 0.6 s to 4 s, The maximum equivalent displacement is 363.965, 606.324, 803.918 successively, the maximum equivalent displacement of the wheel-rail gradually increases, and the maximum value is always at the end of the wheel rim and gradually moves towards to the rolling direction of the wheel, this simulation is similar to the real wheel-rail rolling.
3.1. Discussion of the contact pressure

Figure 5 shows the pressure diagram of wheel-rail contact, the maximum contact pressure occurs at the contact spot, it’s position is marked with MX. The maximum contact pressure value is 1029.57 MPa. When the Q is 10.5t, a is 8.1 mm, b is 6 mm. According to the equation (2), the wheel-rail contact pressure is 1024 MPa. The numerical result of the wheel-rail contact pressure is consistent with the basic Hertz contact theory, the error between them is 0.5%, which verifies the accuracy of the wheel-rail contact simulation model.

It can also be seen from figure 5, with the wheel rolling, the area of the wheel-rail contact spot is
almost constant, but the shape of the contact spot has a slight change at different time. The initial regular polygon shape gradually evolves into an irregular polygon, this is due to the corrugation effect of the rail.

The curve of the wheel-rail contact pressure at 0.6s, 1.8s, 3s, 4s is presented in figure 6. It can be seen from figure 6, with the wheel rolling, the contact pressure rises dramatically at the beginning, and wheel gets closer to the rail joint, the wheel-rail contact pressure increase slowly, after 3s, the maximal contact pressure is stable around 1140 MPa. Therefore, the maximum value for wheel-rail rolling model at 4s is 89.19 MPa higher than that at initial time.

**Figure 6.** The contact pressure curve of the wheel-rail at different time.

**Figure 7.** The maximum equivalent stress distribution curve of the rail.

3.2. Discussion of the equivalent stress and elastic deformation for rail and wheel

Distribution curve of the rail maximum equivalent stress at different time is shown in figure 7, it can be seen that with the increase of time, the equivalent stress of the rail decreases sharply at beginning, and then increases relatively slowly. Till 3s, The wheel and track deformation tend to stabilize the maximum equivalent stress reaches the peak, and then it stable at 460 MPa. Till 4s, the wheel and rail contact point is close to the track edge, as the difference of bearing structure between track edge and middle rail, so the maximum equivalent stress distribution curve of the rail decreases.

Equivalent stress distribution of the rail at different time is plotted in figure 8. With the wheel rolling, the equivalent stress area moves toward to the rolling direction of the wheel, and the equivalent stress influence area gradually diffuse from the wheel-rail contact area to the surrounding area. It also can be seen that when the wheel is on the rail joint at 0s or 4s, the distribution of the equivalent stress is the approximate semicircle area connecting the rail upper and lower surface, and extending to the rail joint, which is easy to cause stress concentration and crush rail joint.

The elastic deformation distribution is roughly consistent with the equivalent stress distribution of the rail.
The equivalent stress distribution and the maximum equivalent stress distribution curve are plotted in figures 9 and 10. As can be seen from figure 9, with the wheel rolling, the maximum equivalent stress is 434 MPa, is lower than the yield limit of wheel material, so the plastic deformation of the wheel is not occur. The shape of the contact spot is relatively elliptic and the equivalent stress distribution is adjusted with the Hertz contact theory. It also can be seen from figure 10, as the wheel rolling, the maximal equivalent stress of the wheel gradually decreases at first, and then increase. When the wheel reaches to the rail joint, the maximum equivalent stress reaches the peak.
Figure 9. The equivalent stress distribution of the wheel. (a) t=0s, (b) t=0.6s, (c) t=1.8s, (d) t=3s and (e) t=4s.

The elastic deformation distribution and the maximum elastic deformation distribution curve of the wheel are shown in figures 11 and figure 12. It can be seen from figure 12, the maximal elastic deformation occurs at wheel-rail contact spot and its maximal elastic deformation fluctuates 0.002 mm with the wheel rolling. It also can be seen from figure 11, with the increase of time, the equivalent elastic deformation of the wheel decreases dramatically at first, and then increases relatively sharply. When the time is 4s, it reaches the peak.

Figure 10. The maximal equivalent stress distribution curve of the wheel,

Figure 11. The maximal elastic deformation distribution curve of the wheel.
3.3. Discussion of the plastic deformation of rail
When the wheel rolling only rail has plastic deformation and the plastic deformation occur at 0s, 3s, 4s. Equivalent plastic deformation for the rail is shown in figure 13, with the wheel rolling, the plastic deformation for the rail occurs on the surface of rail. As the wheel rolling slowly forward, the plastic deformation area of the rail increases. At 0s, the plastic deformation area occurs at the side of the rail joint, this trends to lead to resulting in crushing of the rail joint. Hence, accumulation of these plastic deformation with the time will result in permanent deformation and lead to its corrugation.

4. Conclusions
In this study, the rolling contact of wheel-rail system is used to investigate the contact pressure, equivalent stress, elastic deformation and plastic deformation. Some useful results are obtained. As the wheel rolling, the wheel-rail contact pressure gradually increases, and the initial regular polygon gradually evolves into an irregular polygon. With the change of time, the equivalent stress and elastic deformation trend of the rail are basically the same, both of which decrease rapidly and then gradually increase, and reach the peak value when the time is 3s. For the wheel, when the wheel reaches to the rail joint, the maximum equivalent stress reaches the peak. With the increase of time, the plastic deformation of the rail gradually increases and accumulates, and the stress concentration area occurs at the side of the rail joint.

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