Predicting Crack Growth and Risks of Rail Breaks due to Wheelflat Impacts in Heavy Haul Operations

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Summary: The risk for rail breaks is investigated from a mechanical and statistical point of view. In particular the influence of impact loads from flatted wheels is investigated in the current paper. The risk for fracture due to a wheel flat impact depending on the impact position of the flat and the position and size of a rail crack is assessed. Further, the growth of a rail crack until fracture is studied, and in particular the influence of wheel flat impact loads on crack growth rates.

Index terms: Out-of-round wheels, rail breaks, rail cracks, risk analysis, fracture mechanics, crack growth

1. BACKGROUND

Rail breaks are highly undesired in railway operations. Further, mitigating actions such as crack detection and rail replacements are costly and there is a large potential in optimizing these actions. In the current paper, the risk of rail breaks is assessed by numerical simulations. To this end, vehicle and track characteristics corresponding to heavy haul traffic on the Iron Ore line between Kiruna and Luleå in Sweden are employed. In particular, a bogie with 30 tonnes axle load operating a track with UIC60 rail is considered.

Surface initiated rolling contact fatigue rail cracks are initiated due to frictional loading of the railhead. This causes plastic deformation of the rail head material. When the deformation exceeds the fracture strain of the rail material a surface crack is initiated. The small crack is initially propagated in a shallow angle to the rail surface. As the crack continues to grow, the direction deviates transversally. The deviation is promoted by bending of the rail and by the tensile stress that exists during wintertime in all-welded rails, cf. [1]. Final fracture typically occurs when the fatigue crack has propagated through most of the railhead. It is manifested as a brittle transversal propagation through the web and foot of the rail, see Figure 1. In the current paper, the transversal growth and final fracture of a relatively long crack is studied. Previous studies with different focus may be found in the literature e.g. in references [2] and [3].

![Figure 1 Typical appearance of a head-check rail crack propagated to failure.](image)

It is considered that the novelty of the present paper lies in the strong coupling between analysis of dynamic train–track interaction and fatigue crack growth, and in the statistical analysis.
2. FORMULATION OF THE PROBLEM

In the current paper, the risk for rail breaks is assessed. An (out-of-round) wheel, that passes a rail section with a pre-existing crack, imposes the loading. A single rail crack is considered. The crack orientation is transversal with a shape approximated from deviated head check cracks found in operation on the Iron Ore line, see Figure 1. The size of the crack is varied in the simulations. The load due to the passing wheel creates a bending moment that loads the crack in mode I. In addition, there may be a tensile stress in the rail due to temperature loading, see Figure 2. Further, residual stresses will influence the crack propagation, however this influence is not considered in the current study.

The current formulation presumes that the influence of nearby cracks is negligible and that the crack grows predominantly due to rail bending and thermal loading. This is fulfilled if a relatively large crack, with a diameter (in the transverse direction) larger than some five to ten millimetres, is considered.

2.1 Simulation of dynamic train–track interaction

The current study features a loaded bogie with 30 (metric) tonnes axle load and a bogie wheelbase of 1.8 m, travelling at a speed of 60 km/h on a tangent track. The wheel diameter is 0.9 m and the wheel pair mass (incl. axle and bearings) is 1100 kg. The rail is an unworn UIC 60 profile resting on concrete sleepers with mass 250 kg and 0.6 m centre distances. Some vital track parameters are given in Table 1. A full description of employed parameters is given in [2].

<table>
<thead>
<tr>
<th>Ballast Pads</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Stiffness [MN/m]</td>
<td>140</td>
</tr>
<tr>
<td>Damping [kNs/m]</td>
<td>165</td>
</tr>
</tbody>
</table>

Table 1 Selected track parameters.

To evaluate the dynamic train–track interaction, the in-house code DIFF [4] is used. The code is capable of accounting for the contribution from high frequency excitations, which is vital for the current application where impact loads are considered. The rail wheel interaction is modelled with a 2-degrees-of-freedom system that, apart from the wheel mass, includes a smaller mass, a spring and damper to match the wheelset receptance. This interaction model accounts for loss of contact between rail and wheel.

Out-of-round wheels in the form of wheels with wheel flats are introduced in the simulations. The size of the wheel flat is defined as the length of the rounded flat, \( l \). Following [2], the geometry of the wheel flat is defined by an irregularity

\[
D_{\text{irr}} = \frac{d}{2} \left[ 1 + \cos \left( \frac{2 \pi x}{l} \right) \right] - \frac{l}{2} \leq x \leq \frac{l}{2}
\]

which can be pictured as a lack of material of a perfectly rounded wheel. The depth of the flat, \( d \) is given by

\[
d = R - \sqrt{R^2 - \frac{l_0^2}{4}}
\]

where \( l_0 \) is the fresh flat length corresponding to the length of a chord of a circle with the wheel radius \( R \). Fresh flats, caused by sliding, quickly become rounded. From observations of flatted wheels in operation, the relation between the fresh flat length and the rounded flat length is estimated as

\[
l = 1.5 \cdot l_0.
\]

In the simulations the flat is always positioned on the leading wheel in the bogie. The impact position of the wheel flat, \( \xi \), in relation to a reference sleeper (at \( \xi = 0 \)) is defined in Figure

![Figure 2 An out-of-round wheel passing a cracked rail section.](image)
3. Notice that the wheel base distance (1.8 meters) happens to be exactly three sleeper distances.

![Diagram of wheel base distance](image1)

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The repair criterion for wheel flats in Sweden [5] states that visually detected wheel flats of lengths in the range 40–60 mm must be taken to nearest workshop for repair if the temperature is below –10 °C. For higher temperatures, the only restriction is to avoid operation at speeds in the interval 15–45 km/h. For wheel flats longer than 60 mm, the train must head for the nearest manned station at a maximum speed of 10 km/h.

A wheel flat of a defined length can be related to the maximum wheel–rail contact force using numerical simulations by DIFF. An example corresponding to conditions at the Iron Ore line is given in Figure 4. During the winter 2002–2003, wheel impact load detectors (WILD), at Krokvik and Harrträsk, along the Iron Ore line detected load impacts exceeding 290 kN at a rate of one in 21 000 and one in 13 000 axle passages, respectively [2].

![Graph of contact force vs. flat length](image2)

Figure 4 Simulated maximum wheel–rail contact force as caused by a flat of varying length under conditions prevailing on the Iron Ore line.

### 2.2 Fracture mechanics analysis

Crack growth rates and risks for rail breaks are assessed using linear elastic fracture mechanics (LEFM). To this end, the evaluated bending moment in the rail at the position of a presumed crack is combined with the crack geometry to evaluate the stress intensity factor (SIF) of a transversally propagating head check crack. It should be noted that only global bending and longitudinal thermal stress in the rail are accounted for. This excludes e.g. residual and contact stresses. However, this simplification is deemed acceptable for the current study of a large, transversally propagating crack.

Presuming linear elastic fracture mechanics conditions and mode I loading, the stress intensity factor may be expressed as

\[ K_I = f(a) \cdot \sigma \sqrt{\pi a} \]  

(4)

Here \( f(a) \) is a geometry factor, \( \sigma \) the nominal stress and \( a \) the crack size cf. Figure 5.

![Diagram of crack geometry](image3)

Figure 5 Definition of crack geometry.
As mentioned above, the nominal stress is composed of bending and thermal stresses for the studied case, cf Figure 2. Magnitudes of $K_I$ for varying crack sizes are derived from the $J$-integral computed in FE-simulations featuring ABAQUS/Standard v6.5 [6] in a procedure outlined in [7].

The FE-simulations allow for an approximate establishment of the geometry factor $f(a)$ in equation (4) for bending and temperature loading as

$$f_b(a) = c_{b,0} + c_{b,1}a + c_{b,2}a^2$$  \hspace{1cm} (5) \\
$$f_T(a) = c_{T,0} + c_{T,1}a + c_{T,2}a^2$$  \hspace{1cm} (6) \\

The influence of crack size, $a$, is approximated by curve fitting of the FE-solutions for crack sizes $a = 2.5, 5, 20, 30, 40$ mm. Coefficients, $c$, are given in Table 2.

<table>
<thead>
<tr>
<th></th>
<th>$c_0$</th>
<th>$c_1$ [m$^{-1}$]</th>
<th>$c_2$ [m$^{-2}$]</th>
</tr>
</thead>
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<tr>
<td>bending</td>
<td>0.696</td>
<td>-13.46</td>
<td>510</td>
</tr>
<tr>
<td>temperature</td>
<td>0.721</td>
<td>-2.30</td>
<td>274</td>
</tr>
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</table>

Table 2 Magnitudes and dimensions for coefficients in the approximate expression of geometry factors, $f(a)$, according to equations (5), (6).

The nominal stress in equation (4) is defined as

$$\sigma_b(a) = \frac{M_b}{I} \cdot h$$  \hspace{1cm} (7) \\
$$\sigma_T(a) = \alpha \cdot E \cdot \Delta T$$  \hspace{1cm} (8) \\

Here, $M_b$ is the vertical bending moment of the rail, $I$ the corresponding moment of inertia, $h$ the distance from the neutral axis to the top of the rail head, $\alpha$ the thermal expansion coefficient, $E$ the elasticity modulus and $\Delta T$ the decrease in temperature below the stress free temperature. In the current study values according to Table 3 have been employed.

<table>
<thead>
<tr>
<th>$I$ [m$^4$]</th>
<th>$h$ [m]</th>
<th>$\alpha$ [°C$^{-1}$]</th>
<th>$E$ [Pa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>30.55$\times$10$^{-6}$</td>
<td>91$\times$10$^{-3}$</td>
<td>11.5$\times$10$^{-6}$</td>
<td>210$\times$10$^9$</td>
</tr>
</tbody>
</table>

Table 3 Employed rail parameters.

To account for varying load magnitudes and interaction between bending and temperature loading, the LEFM presumption (together with the fact that both bending and temperature impose mode I loading) allows for scaling and addition of stress intensity factors.

### 3. RISKS OF RAIL BREAKS DUE TO A PASSING BOGIE

The risk of rail breaks, i.e. final fracture of a cracked rail due to an overload, is assessed. The fracture criterion is defined as

$$K_I \geq K_{lc}$$  \hspace{1cm} (9) \\

where $K_I$ is the mode I stress intensity factor of the rail and $K_{lc}$ the fracture toughness of the rail material. Consequently, for a given temperature, and crack geometry, and location (and also state of residual stress, which is ignored in the current analysis), the onset of final fracture is governed by the maximum bending moment, corresponding to a tensile stress in the rail head, during a bogie passage.

#### 3.1 The influence of wheel flat impact and rail crack position

In Figure 6 are the maximum (during a passage of the bogie) rail bending moments at nine equally spaced positions in a sleeper bay are presented as function of the impact position of the wheel-flat of length $l = 150$ mm (which is a very large wheel flat). It should be noted that algebraic values are considered and that a positive bending moment corresponds to tension in the rail-head. It is seen that for all impact positions, the most severely loaded rail section is above a sleeper (i.e. positions $0/8$ and $8/8$ in Figure 6). Further, for these positions, the maximum bending moment occurs for impact positions $\xi = 1.5$ and $\xi = 2.5$, respectively. That is, the highest bending moment occurs at a position on the rail located 1.5 sleeper distances behind the flat impact position. The reason that $\xi = -1.5$ (and $\xi = -2.5$) do not induce equally high bending moments is that the wheel base distance is 3 sleeper distances and consequently, an impact position of $\xi = -1.5$ (and $\xi = -2.5$) do not induce equally high bending moments that the wheel base distance is 3 sleeper distances and consequently, an impact position of $\xi = 1.5$ corresponds to a symmetric loading with respect to the studied sleeper at position 0 (and an impact position of $\xi = 2.5$ to a symmetric loading with respect to the sleeper at position 8/8=1), see Figure 6.
Based on the analysis above, only a crack located above a sleeper (i.e. in the most severely stressed rail section) will be considered in the following. This can be motivated by the presumption that cracks in different locations of a sleeper bay are initiated with a reasonably similar probability. However, when the cracks deviate to transverse growth (as studied here), cracks located above sleepers will grow more rapidly than cracks in mid-bay. It can be noted that operational cracks that have caused rail breaks, as the one shown in Figure 1, typically are located above, or close to, sleepers. Also note that in the DIFF simulations, the sleeper width is not explicitly modelled (although the rotational stiffness due to fastening, etc is included).

3.2 The influence of wheel-flat size

The wheel flat size will have an influence on the induced maximum bending moment in the rail. In Figure 7 maximum bending moments at position 0 in Figure 3 are plotted as a function of size, \( l \), and impact position of a wheel-flat.

3.3 Probability of rail break

To assess the risk of rail fracture, the magnitude of the maximum bending moment above a sleeper can be formulated as a function of the impact position of the wheel flat. This is illustrated in Figure 8 where, for each impact position, also the bending moment corresponding to the previous (for positive impact distances) and subsequent impact position are indicated by the dashed line. This is due to the fact that flat impacts occur in periods of one wheel circumference. Consequently, any considered rail section will experience bending moments induced by several impacts. However, impact positions more than half the wheel circumference away from the studied section corresponds to low load magnitudes.
The impact position of the wheel-flat can be considered as a stochastic parameter. It is understood that the impact position must have a uniform distribution along one arbitrary wheel circumference. From this distribution and a prescribed flat length, the distribution of the maximum bending moment is given. In addition, for a certain set of fixed crack size and $\Delta T$, a critical bending moment, $M_c$, causing fracture is identified from equation (9) as the bending moment that induces a stress magnitude causing the fracture criterion $K > K_{Ic}$ to be fulfilled.

The probability of final fracture is then given by the probability that the stochastic bending moment exceeds $M_c$. In Figure 9 probabilities of fracture are given for various crack sizes, $a$, temperatures, $\Delta T$, and flat lengths, $l$, in the form of level curves. The fracture toughness is set to 40 MPam$^{1/2}$ [8].

From the bending moment ranges, corresponding stress intensity ranges $\Delta K$ are evaluated (for a presumed $\Delta T$) using equations 4, 5 and 6. Crack growth is now predicted by integrating Paris law

$$\frac{da}{dN} = C \cdot \Delta K^n$$

with $C = 2.47 \cdot 10^{-9}$ and $n = 3.33$ (growth rate in mm/cycle and stress in MPa) [8]. It is presumed that one in every one hundred bogies contains a wheel with a flat with $l = 150$ mm. No threshold
or history effects are considered, and $\Delta K$ is defined as

$$\Delta K = K_{I,max} - \max\{0, K_{I,min}\} \quad (11)$$

where $K_{I,max}$ and $K_{I,min}$ are taken for each load cycle.

![Figure 10 Rail bending moment evolution at a position 0 (above a sleeper) due to a wheel with a 150 mm wheel flat impacting at a position 1.5 (1.5 sleeper distances from position 0), non-defect bogie (dashed line)](image)

- a) Overview
- b) Zoom-in of boxed part

![Figure 11 The ten largest cycles of the bending moment in Figure 10 as identified through rain-flow counting.](image)

![Figure 12 Crack growth as predicted for different temperatures.](image)

It is seen from Figure 12 that for $\Delta T = 10 ^\circ C$ the predicted crack growth rate is low. During 4 million bogie passages, the crack grows from the initial crack length of 2.5 mm to 3.7 mm. Crack growth rates will increase with $\Delta T$, but for $\Delta T = 30 ^\circ C$ and $\Delta T = 40 ^\circ C$ crack growth rates are equal even though lower temperatures result in higher $K_I$ magnitudes. This is due to the fact that the cracks remain open during the entire bogie passage. Consequently a further temperature decrease will not influence $\Delta K_I$ and thus the crack growth rate. The decreased temperature will however increase $K_{I,max}$, which will promote final fracture. For $\Delta T = 30 ^\circ C$ and
\(\Delta T = 40 \, ^\circ C\), fracture occurs after roughly 3.5 million bogie passages. This corresponds to 875 000 loaded wagons or some 13 000 trains, corresponding to roughly 3 years of operational traffic. Note that all except the flatted wheels are presumed to be perfectly round and non-loaded trains are not accounted for. It should here be noted that temperature loading is only considered as a static load, whereas in reality temperature fluctuations (during a 24 hour period and during a year) will impose additional load cycles. Further it can be noted that the initial crack length of 2.5 mm is so small that its initial growth will most likely also be influenced by the contact stress as the wheels pass.

In Figure 13, crack growth for operations with only perfectly round wheels is compared to a scenario where one percent of the bogies have a flatted wheel (\(l = 150 \, \text{mm}\)). The temperature is taken as \(\Delta T = 40 \, ^\circ C\). It is seen that for the studied conditions, the contribution of the flatted wheels to the total crack growth is minor.

In Figure 14 stress intensity factor ranges are given for a non-damaged wheel (lower solid line) and for wheels with a wheel flat (\(l = 150 \, \text{mm}\)), with \(\Delta T = 40 \, ^\circ C\). The scattered appearance of \(\Delta K\) for the flatted wheel is due to the fact that every dot is represents the passage of a flatted wheel with a stochastic impact position (\(\xi\)). It is seen that if the wheel flat impacts in a critical position, the increase in \(\Delta K\) may be close to 100%. However, few flats impact in this position and it is presumed that only one in 100 bogies have a flatted wheel.

Further, since crack growth rates are high close to final fracture (and bear and mind that these are evaluated using Paris law which underestimates crack growth rates close to final fracture), the crack will rapidly grow to a size where also a non-damaged wheel will cause a fracture. For the case of a 150 mm flat and \(\Delta T = 40 \, ^\circ C\), an additional 130 000 bogie passages (from the instant when a flatted wheel causes rail fracture) are required to make non-damaged wheels critical. The crack lengths corresponding to final fracture due to loading of perfectly round and flatted wheels are 35 mm and 28 mm respectively. Note that the latter value will vary between simulations depending on the (random) impact position of the wheel flat causing the final failure.

5 CONCLUDING REMARKS

The influence of operations featuring flatted wheels on the risk for rail breaks on the Iron Ore line has been analysed. The risk for final fracture
has been assessed for varying temperatures, wheel flat lengths and crack sizes.

The results from these simulations indicate the major influence of temperature. A conclusion is that the current Swedish practice of different criteria for allowed wheel defects depending on operational temperatures is well founded from a mechanical perspective.

Further, the influence of wheel flats on crack growth and rail life has been investigated. It was concluded that even though the considered wheel flat gives a massive increase in contact forces, the influence on fatigue crack growth is minor since not all impact position will correspond to a similar increase in rail bending (and thus crack loading). In the simulations one out of every one-hundred bogies were presumed to contain a wheel with a very large flat. Though both frequency and flat length are chosen as very conservative, the influence on total fatigue life was small.

This leads to the conclusion that large flats are not of major concern regarding crack growth, in contrast they are of major concern regarding final fracture. Future studies will investigate the influence of less severe out-of-roundness. These types of defects will cause less increases in impact load magnitudes. On the other hand their influence is less dependent on the impact position. Further they are more frequent and each wheel passage is likely to cause several load cycles due to the dynamic effects of the rough surface, cf [11, 12].

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