RAIL LIFE PREDICTION FOR TRAMCARS UNDER FULL SLIP REGIME

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ABSTRACT

In a previous paper [1], a method to analyse the rolling contact fatigue damage on a tramcar rail section, starting from the dynamical simulations of it, has been proposed. In the present work, the referred method is applied to obtain the so-called 'ratchetting maps' i.e., the damage region, for a given number of cycles, of a rail section due to the accumulation of plastic flow. Also, the influence of the rail material strength, in terms of its yield shear stress, is analysed.

1 INTRODUCTION

Design criteria for tramcars are different form those of railway vehicles: the load per axle is less than 80kN, the vehicle speed is below 80km/h, usually independent wheels with small radii and low floor solutions are adopted and the track geometry is different (the curve radius may be as small as 15m and usually no super-elevation is adopted). This means that problems that occur on tramcar vehicles will usually not occur on railway vehicles and viceversa. In particular, in small radius curves (radius less than 50 m) the rolling/sliding condition of the wheel over the rails tends to be in the full slip regime, a condition which is rare for railway systems. Figure 1 shows, plotted onto the shakedown map, the simulated points for the tread and flangeback contacts for a fully loaded vehicle running on a right hand 50m radius curve at 25km/h considering a low level (according to ORE B176, [2]) of rail irregularity [1]. In these simulations the ratio *Ft/Fn* (*Ft* being the tangential force and *Fn* the normal force) becomes equal to the friction coefficient, showing full slip at the wheel rail interface.

In this context, it is important to analyse how are the surface and subsurface damages relates with load conditions and the rail material shear yield stress. Cross sections of rails show damage by a process known as ratchetting. The ratchetting process involves strain accumulation under cyclic directional loads. With each wheel pass the strain accumulated is of the order of elastic strain at yield, but over millions of cycles to which the rail material is subjected to, the accumulated strain becomes large. A material subjected to ratchetting fails either by low cycle fatigue or after accumulating a critical strain comparable to the strain to failure in a monotonic test (the so-called 'ratchetting' failure). These two failure modes may be treated as competitive so that the actual failure mode corresponds to the one that occurs first. Kapoor and co-workers [3], [4] have shown that materials of tribological surfaces usually fail due to the second mode, i.e. due to the accumulation of strain.

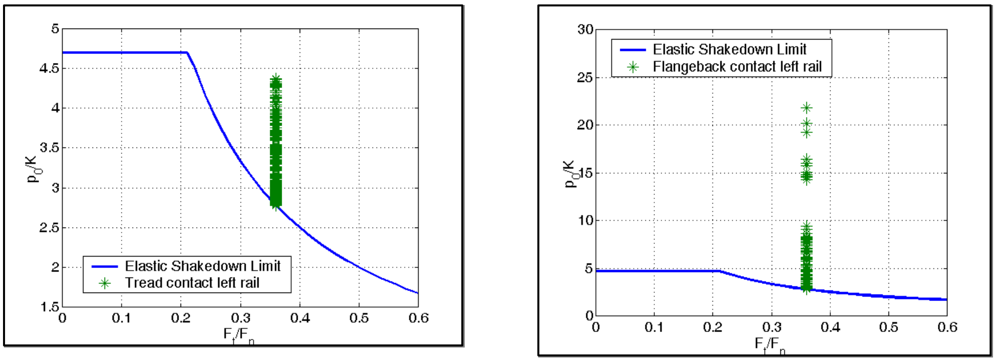
In previous work [5]-[7] it is assumed that ratcheting will occur at any point in the rail cross section where the following condition is met,

$$t > k_{eff} \tag{1}$$

where t stand for the applied shear stress and k_{eff} stands for the effective (current) shear yield stress. With this damage hypothesis, the Figure 2 shows the damage zones for a surface loaded with a three-dimensional, spherical contact pressure. Two values of p_o/k_{eff} (p_o representing the maximum normal pressure) are considered. The rolling direction is along x-axis and the depth is along z-axis. Figures *2a* and *2b* show the most severely loaded plane, i.e. the plane *y=0*. Dimensions are normalized with respect to the radius of the contact patch (*a*). Equations from the work of Sackfield et al. [8] have been used for computing shear stresses. The severity of damage accumulation per cycle, termed ratchetting load (RL), is computed by using equation (2) below, and the contour plots are shown in Figure 2.

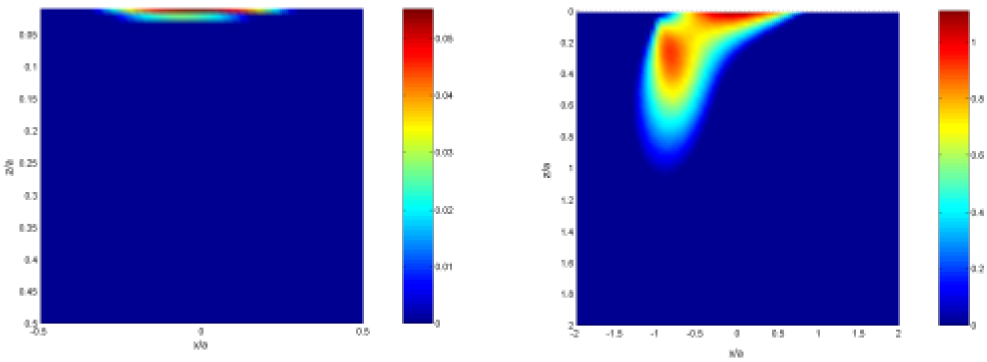
$$RL = \frac{t_{(x,0,z)} - k_{eff}}{k_{eff}} \tag{2}$$

It can be observed that for the smaller values of p_o/k_{eff} damage occurs close to the surface, while for the higher values, damage occurs in two regions (surface one and the subsurface). The presence of friction makes the damaged region unsymmetrical about the x=0 axis. In the current simulations involving high friction coefficient, full slip and high ratchetting loads, both surface and the subsurface regions are important and are considered.



(a) *(b)*

Figure 1. Shakedown maps: a) simulated points for a tread contact; b) simulated points for a flangeback contact. After Beretta et al. [1]. (Note: only the simulated points over the shakedown limit are displayed).



(a) *(b)*

Figure 2. Ratchetting damage zones for full slip regime (m=0.36): a) p_o/k_{eff}=3.0; b)p_o/k_{eff}=6.0 .

2. ANALYTICAL MODEL

2.1 Damage criterion: In order to determine the accumulation of strain for the simulated manoeuvres, a (local) 3D grid below each contact area is considered. At each node of this grid the stress tensor is calculated using Boussinesq-Cerruti equations (elastic half-spaces). As t_{yz} is of the same order of magnitude as t_{xz}, the accumulation of ratchetting is estimated considering the maximum shear stress on a plane parallel to the surface [9], by modifying equation (1) as,

$$t = \sqrt{{t_{xz}}^2 + {t_{yz}}^2} > k_{eff} \tag{3}$$

Under the assumption of quasi-stationary vehicle behaviour, one single rail section can be considered to analyse track damage phenomena: the contact forces acting on any rail section will act on the considered section with a probability of occurrence equal to the probability of occurrence along the track. It is therefore possible to reduce the (local) 3D grids below each contact area to a (global) 2D grid over the considered section.

2.2Damage accumulation: The rail damage due to the passage of a tramcar vehicle can be represented through two different graphs [1]: a first graph showing the probability $p_{(y,z)}$ of occurrence of ratchetting over the rail cross-section and a second graph showing how much the limit ratchetting condition has been exceeded (average ratchetting intensity, $<t/k_{eff}>$). The interested reader is referred to [1] for a full description of the method. Let recall here that the probability $p_{(y,z)}$ of occurrence of ratchetting over the rail cross-section is defined as:

$$p(y,z) = \frac{\sum_{i=1}^{N_{step}} R_i(y,z)}{N_{step}} \tag{4}$$

where $R_i(y,z)$ is an indicator function:

$$\begin{array}{lll} R_i(y,z) = 1 & if & t_i(y,z) > k_{eff} \\ R_i(y,z) = 0 & if & t_i(y,z) = k_{eff} \end{array} \tag{5}$$

and N_{step} is the number of simulated contact cases. Note that a value of $p_{(y,z)}$ equal to 1 means that, at this node of the (global) 2D grid, the limit ratchetting condition is reached whenever contact occurs in this position (tread, flange or flangeback). Instead, a value of $p_{(y,z)}$ equal to 0 means that ratchetting does not occur at this node. In turn, the average ratchetting intensity t/k_{eff} (indicated as $<t/k_{eff}>$), is determined by dividing the sum of the t/k_{eff} values by the number of contacts that occur in the considered position (tread, flange or flangeback):

$$< t / k_{eff} >_{(y,z)} = \frac{\sum_{i=1}^{N_{step}} R_i(y,z).(t(y,z)/k_{eff})}{p(y,z).N_{step}} \tag{6}$$

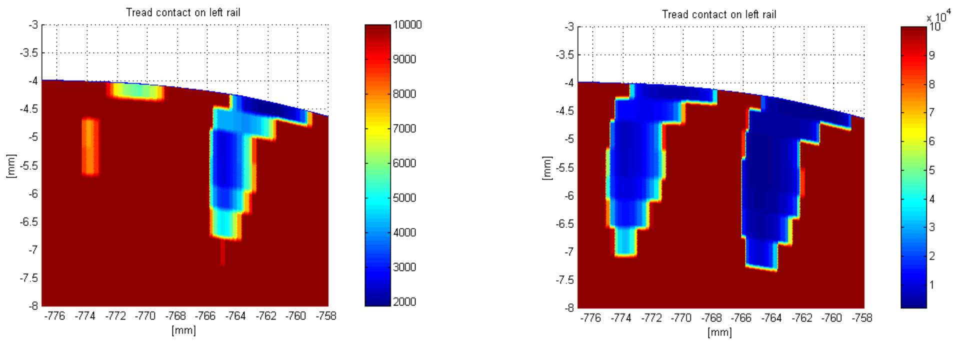
2.3Rail life prediction Knowing the probability of occurrence of ratchetting $p_{(yz)}$ and the average $t/k_{eff}>$ ratio, the number of cycles to failure for each discrete point (y,z) of the (global) 2D grid is given by:

$$N(y,z)=\frac{g_r}{C\left(\left\langle t/k_{eff}\right\rangle_{(y,z)}-1\right)\cdot p(y,z)} \qquad (7)$$

g_r being the shear strain to failure and C being an empirical constant independent of the stress. These two constants were taken from literature ([10]) and are related to BS11 steel: g_r = 11.5 and C = 0.00237. As a first approximation, in the present study k_{eff} is assumed to be a constant, i.e. the material does not strain harden. In accordance with an elastic-perfectly plastic material behaviour and a cyclic yield stress, k_{eff} is equal to $s_{cyc}/\sqrt{3}$, (s_{cyc} being the cyclic yield stress [11]).

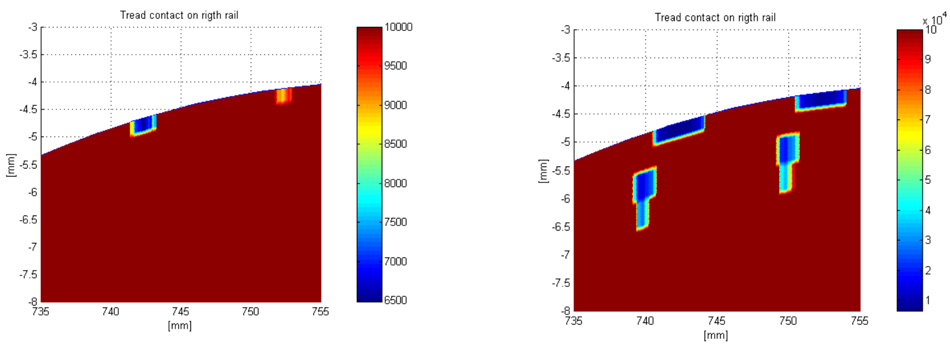
4 RESULTS

All the results presented here are referred to a fully loaded tramcar vehicle running on a 50m radius curve, 15km/h, and with low level of rail irregularity. The influence of k_{eff} has been analysed. Ratchetting maps are presented in Figures 3 to 7.



(a) Damage after 10^4 cycles (b) Damage after 10^5 cycles

Figure 3. K_{eff}=300 MPa. Damage on left tread

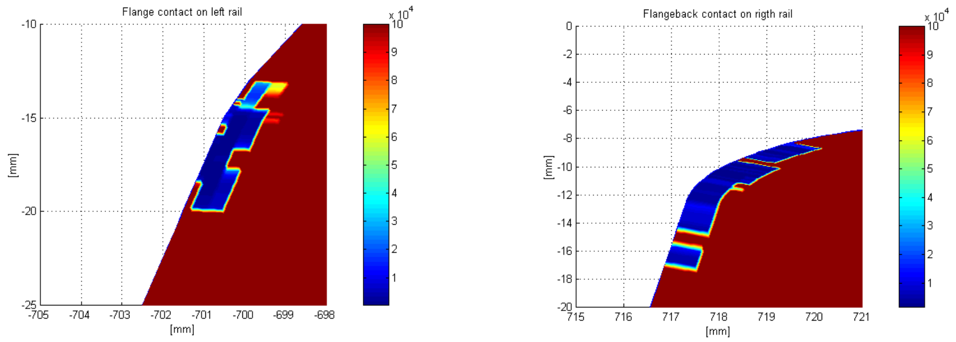


(a) Damage after 10^4 cycles (b) Damage after 10^5 cycles

Figure 4. K_{eff}=300 MPa. Damage on the right tread

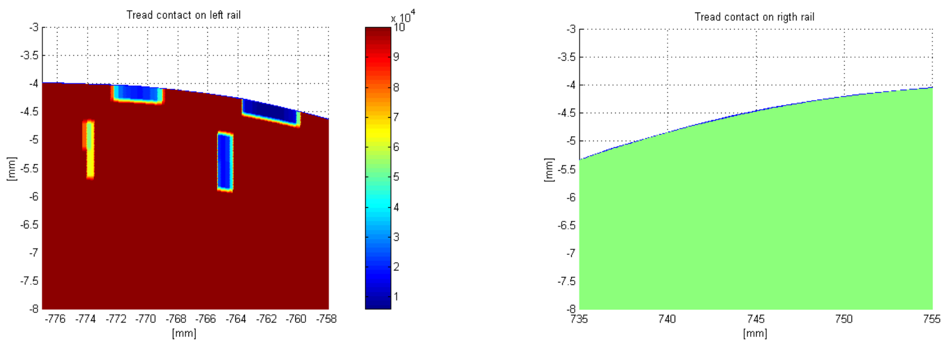
Figure 3a shows the damage region after 10^4 cycles. The colour bar shows the number of cycles to failure, computed with eq. (7). All the region filled with the colour corresponding to 10^4 cycles means that after these cycles not failure is evidenced in this zone, although it is possible that some kind of damage has been accumulated (i.e., it is possible that some regions have accumulated a permanent shear strain smaller than the shear strain to failure, g_r). When the number of cycles is increased up to 10^5, (Fig. 3b), it is possible to see how the damage region also is increased.

As it can be observed in Figures 3 to 7 the k_{eff} parameter has an strong influence on the ratchetting maps. For example, a 33% increase in the initial value (k_{eff}=300 MPa) results in no damage at all for the right tread. For the flangebacks, the damage is significantly reduced but it is not cancelled, even for a value of k_{eff}=500 MPa. Thus, it seem that for the flange/flangeback contact ratchetting damage continues even for a material with a very high cyclic shear yield stress. Table I summarises the results.



(a) Damage after 10^5 cycles (b) Damage after 10^5 cycles

Figure 5. K_{eff}=300 MPa. Damage produced by flange and flangeback contacts.



(a) Damage after 10^5 cycles, left tread (b) Damage after 10^5 cycles, right tread

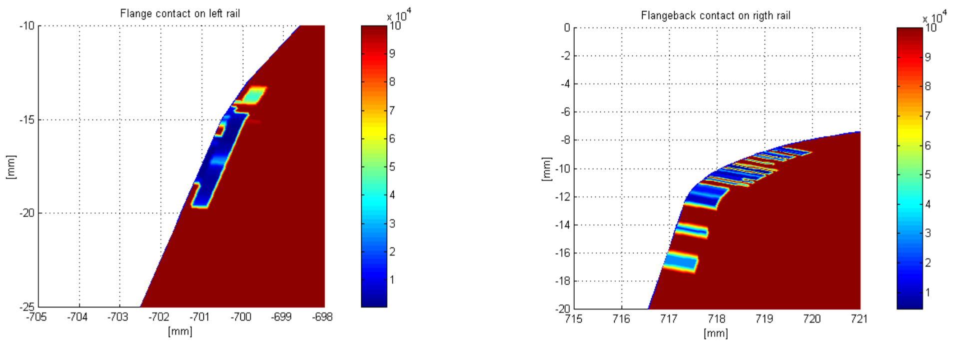
Figure 6. K_{eff}=400 MPa. Damage on right and left tread

k_{eff}	*Is Damage present after 10^5 cycles?*			
	Left Rail		Right Rail	
	Flange Contact	Tread Contact	Flangeback Contact	Tread Contact
300	YES	YES	YES	YES
400	YES	YES	YES	NO
500	YES	NO	YES	NO

Table I. Results in terms of presence or not of ratchetting damage after 10^5 cycles.

5 CONCLUDING REMARKS

The damage in terms of ratchetting has been analysed for a tramcar in conditions of full-slip regime. In this context, ratchetting maps, for a section of the rail have been proposed. The value of k_{eff} strongly affects the damage results. In the particular case simulated here, a higher damage is observed in the left tread than in the right tread. This is correlated with the different loads acting on each one in the curve (i.e, due to dynamic considerations, left tread is subjected to higher loads [1]). Also, it can be observed that for the flange and flangeback contacts, due to the very high loads (in a shakedown sense), damage is also present for $k_{eff}=500\ MPa$. Also, as it has been predicted in section 1, in many cases the subsurface damage region has higher dimension than the surface one.



(a) Damage after 10^5 cycles, left flange contact (b) Damage after 10^5 cycles, right flangeback contact

Figure 7. Damages due to flange/flangeback contacts for K_{eff}=500 MPa.

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