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Contents lists available at ScienceDirect

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journal homepage: www.elsevier.com/locate/wear

Numerical procedure for fatigue life prediction for railway turnout crossings using explicit finite element approach

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ARTICLE INFO

Article history:
Received 9 October 2015
Received in revised form
12 April 2016
Accepted 18 April 2016

Keywords:
Turnout crossing
Rolling contact fatigue
Crack initiation
Life prediction

ABSTRACT

In this paper a numerical procedure for analysis of rolling contact fatigue crack initiation and fatigue life prediction for the railway turnout crossing is presented. To analyse wheel–rail interaction, a three-dimensional explicit finite element (FE) model of a wheelset passing a turnout crossing is developed to obtain the dynamic responses such as the contact forces, displacements and accelerations as well as the stresses and strain in the crossing nose. The material model accounting for elastic–plastic isotropic and kinematic hardening effects in rails is adopted. The fatigue life of the rails is defined as the time to rolling contact fatigue crack initiation. In predicting the fatigue life Jiang and Sehitoglu model is used, which is based on the critical plane approach. Using the FE simulation results the ten critical locations on the crossing nose susceptible to crack initiation are determined first. Then, using the fatigue model the critical planes in these locations are obtained and the number of cycles to fatigue crack initiation is calculated for each location, based on which the most decisive location and the crossing life is determined. The results of the numerical simulations are presented and discussed.

1. Introduction

Turnouts are important elements in the railway infrastructure as they provide guidance to the rail traffic. A typical turnout consists of a switch panel, a closure panel and a crossing panel. In contrast to a normal track wherein the rail profiles remain constant, the rail cross-section is changing in the crossing section of a turnout. The rails in the crossing consist of two wing rails and crossing nose. During the wheel passage over the turnout crossing (in the facing direction) the wheel load is to be transferred from the wing rail to the crossing nose. Due to rail discontinuity (between the wing rail and the crossing nose) high impact forces can be generated in the crossing nose. Moreover, since the crossing profiles are gradually changing from its tip to the normal rail, the small width and radius of the railhead in the beginning of the crossing nose, which makes it the one of the weakest points in the crossing structure and is prone to break. Therefore, the high impact forces and crossing geometry together result in severe rolling contact fatigue (RCF) damage in the crossing.

In the Netherlands, RCF in the crossing nose is a severe problem that causes most of the operation disturbance of the turnout. It was observed that 6% of the trains delayed due to turnouts (30 times) in 2010 were responsible for 55% of the total disruption time. The impact of the broken crossings was 28% of the mentioned 55% of the disruption time. During the last 6 years the RCF damage on track was significantly decreased (more than 50%), however this reduction was not noticeable at the turnouts. There has even been an increase in the last two years. There are around 400 crossings replaced per year and two crossings per week are urgently to be repaired. The replacement budget reaches 6.4 million per year [1]. Therefore, solutions for the RCF related problems in the turnout crossings are urgently needed.

In Fig. 1 the typical defects in the turnout are shown. It can be seen that in the switch blade and the wing rail, large amount of wear were observed. In the curved rail and stock rail head checks and squats are normally found. However, in the crossing nose shelling is observed that nowadays can rarely be found on the normal lines. Generally, shelling is a subsurface defect that occurs at the gauge corner of the high rail in curves of railways with a high axle load and can crack at any level [2]. In the crossings it is more likely to obtain such kind of damage due to the impact of the wheel (Fig. 1b). According to the field observations, crossing nose experiences severe cyclic plastic deformation due to the high impact load and the subsurface cracks may occur over there, which becomes shelling at the later stage. In this study, only the crossing nose is considered and the fatigue crack initiation that later may form shelling of the crossing is studied. Here the crack size of 0.5 mm is considered in the fatigue analysis according to [3].

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http://dx.doi.org/10.1016/j.wear.2016.04.016
0043-1648/

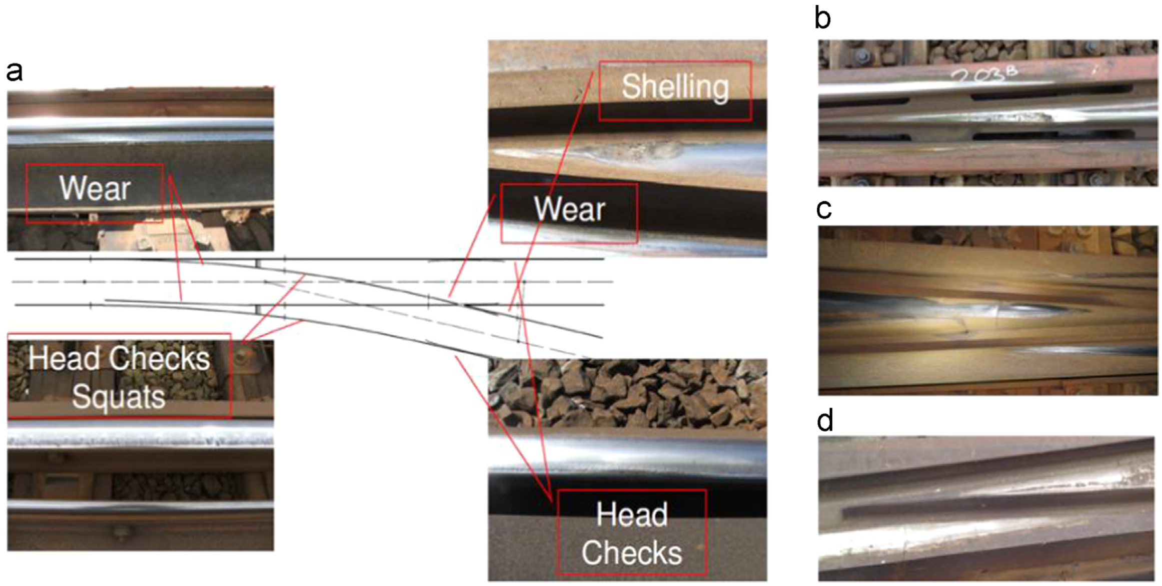

Fig. 1. Damage in the turnout.

Recently, several studies on damage of the turnout crossing have been conducted. In [4] the dynamic forces in a turnout crossing were analysed using the two-dimensional (2D) finite element (FE) model. By optimizing the track stiffness for a given rail geometry, the dynamic forces were reduced. The FE analysis of the cyclic deformation of a crossing nose was performed and the early revolution of damage was predicted in [5]. A three-dimensional (3D) FE model for the process of a wheel passing the crossing panel was presented in [6], where the frictional work, microslip and the equivalent plastic strain of the crossing were obtained for damage evaluation. In [7] the impact damage was estimated taking into account the wheel profiles and wheel lateral displacements. Three damage criteria including energy dissipation, normal contact pressure and force were considered to investigate the influencing parameters on turnout performance in [8]. In [9] the index FI_{surf} based on the contact forces was used to identify the surface initiated RCF defects of the turnout. Multi-scale FE approach was used to study RCF of three crossing nose materials [10], in which the crack development and growth of three materials were obtained and compared. However, these studies do not take the different stress types and stress directions into account to predict fatigue life of the crossings. Also, due to the variable crossing geometry, the possible damage in different locations should be considered separately.

In [3] fatigue life prediction procedure for RCF crack initiation on a normal track was propose, which combines the static FE analyses with fatigue crack initiation model and damage accumulation rule. In this paper, a procedure similar to the one presented in [3] applied to railway crossing is used. The 3D explicit FE model of a wheelset passing the crossing has been developed to provide the stress and strain responses to the fatigue model. The model is capable of the wheelset lateral movement as well as the further variation of the initial wheel–crossing contact conditions, compared to the previous models such as in [6]. It is used to identify the most possible area of damage in the crossing based on the stress/strain distributions at the different positions throughout the crossing. Then Jiang and Sehitoglu (J–S) fatigue model for determining the fatigue crack initiation of the crossing is used to predict the fatigue crack initiation plane and the number of cycles to fatigue crack initiation of the crossing nose was calculated. The fatigue life prediction procedure, numerical results and discussion are presented below.

2. Fatigue life analysis

As for fatigue life analysis various approaches have been proposed including stress-life models used at high cycle fatigue (HCF), strain-life models for low-cycle fatigue (LCF) and stress/strain-life models, in which a strain energy quantity is adpoted for both HCF and LCF [11]. For this model Smith et al. [12] advocated that the product of $\sigma_{max}\varepsilon_a$ (SWT parameter) controls the fatigue life to crack initiation, which is given as

$$\sigma_{max}\varepsilon_a = f(2N_f) = \frac{\sigma_f'2}{E}(2N_f)^{2b} + \varepsilon_f'\sigma_f'(2N_f)^{b+c} \quad (1)$$

where in σ_{max} is the maximum tensile stress and ε_a is the total strain amplitude, $N_f$is the number of cycles to failure, σ_f' is the fatugue strength coefficient, ε_f' is the fatigue ductility coefficient, b/c is the fatigue strength/ductility exponent. However, for cyclic loading that involves relatively large compressive mean stress, the stress/strain-life models might be non-conservative. Therefore, several modifications of the SWT parameter have been proposed, which are summarized in [11].

Moreover, regarding to the SWT parameter, tests of a 304 sainless steel under both proportional and non-proportional loading were conducted in [13] and in [14] correlations between the ratios, $\Delta\tau_1/\sigma_{1,max}$ ($\Delta\tau_1$– shear stress range, $\sigma_{1,max}$ – maximum principal stress),$\Delta\gamma_1/\varepsilon_{1,max}$ ($\Delta\gamma_1$ – shear strain range,$\varepsilon_{1,max}$ – maximum principal strain range), and the non-proportional loading factor are discussed (Fig. 2). It can be seen from this figure that $\Delta\tau_1/\sigma_{1,max}$ and $\Delta\gamma_1/\varepsilon_{1,max}$ on the maximum principal strain range plane become larger by increasing the non-proportional factor. This tendency means that the contributions of shear components to damage on the maximum principal strain range plane are more and more significant by increasing the non-proportional degree. However, in the SWT parameter only the normal components are considered [14]. Therefore, during non-proportional loadings, SWT model may give unconservative fatigue life predictions. Thus in this paper shear components should also be taken into account, which is later shown in Eq. (3).

It is known that in wheel/rail rolling contact problems the rails are subject to multi-axial and non-proportional loadings, which result in the variations of the stress directions and strain range during the wheel passage. Therefore, to predict the life of the rails a multiaxial criterion including non-proportional loading is