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2D fatigue crack propagation in rails taking into account actual plastic stresses

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ABSTRACT

Due to increase axle loads, repeated passages of the wheels, rolling contact fatigue cracks initiate in the surface or subsurface of the rails. These defects can propagate and lead to the rail failure. A two-scale frictional contact fatigue crack model developed within the X-FEM framework is used to address the cracked rail problem, calculate the stress intensity factors, perform crack propagation and fatigue life prediction. Actual plastic stresses, quantified through a dedicated software developed by SNCF within the consortium IDR2, are taken into account in the propagation simulation via projection of the asymptotic mechanical fields. The effects of those actual plastic stresses are investigated on the crack growth path and rate. Interactions between multiple cracks of a network are also analyzed.

1. Introduction

The repeated train traffic leads to crack initiation at the rail surface or within the subsurface, up to the development of very complex 3D crack network, like squats and head-checks. Rail failure may occur and potentially derailment too. Costly maintenance operations are deployed to avoid such a situation.

Rolling contact loading is a time-dependent, multi-axial and nonproportional loading. This cyclic loading leads to an asymptotic stress state within the rail that influences the crack behavior. The cracks are also submitted to large compressive stresses inducing crack face closure and frictional contact.

Previous works about fatigue crack growth in the rails are available in the literature. The role of liquid entrapment using finite element analysis [1–3] or boundary element method [4,5] was analyzed on the crack growth mechanism. The influence of different parameters, such as elastic foundation [3,6], the initial crack geometry or the crack face friction coefficient [3,5,7,8] was also investigated on the stress intensity factors (SIFs) or on the crack propagation path [9]. It is well known that the distribution of the residual stress field affects the crack propagation behavior [10–15], but most of previous studies use simplified techniques. This residual stress field is accounted as the addition of uniform tensile or compressive conditions at the boundary of the considered domain [8,16,17].

To improve the understanding of the crack initiation and propagation mechanisms, a global methodology has been developed thanks to a long-term collaboration between French railway organizations (SNCF, RATP, RFF), rail producer (Tata Steel)

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Nomenclature

$\boldsymbol{\epsilon}(0)$	initial elastic strain for the cracked structure problem
$\boldsymbol{\epsilon}_p$	initial plastic strain for the cracked structure problem
$\boldsymbol{\sigma}(0)$	initial elastic stresses for the cracked structure problem
$\boldsymbol{\sigma}_e$	elastic stress tensor
$\boldsymbol{\sigma}_{plastic}$	initial plastic stresses for the cracked structure problem
ϵ_e	elastic strain tensor
$\frac{da}{dN}$	crack growth rate
μ_{crack}	friction coefficient between the crack faces
$\mu_{wheel-rail}$	wheel-rail friction coeffcient
σ	Cauchy stress tensor
$\mathbf{K}$	hook tensor
$\mathbf{t}$	local traction field
$\mathbf{u}$	global displacement field in the structure
$\mathbf{w}$	local displacement field
θ	initial angle between the crack and the running surface
a	Hertzian contact semi-length
da	crack extension length
dN	cycle jump
k_1	mode I stress intensity factor at the tip of a virtual crack extension
k_2	mode II stress intensity factor at the tip of a virtual crack extension
K_{eq}	equivalent stress intensity factor at the actual crack tip
K_{II}	mode II stress intensity factor at the actual crack tip
K_I	mode I stress intensity factor at the actual crack tip
l	initial crack length
P_{max}	maximal Hertzian pressure
x_c	distance between the crack mouth and the maximal Hertzian pressure

and research institutes and universities (LaMCoS/INSA Lyon, LMS/Polytechnique, MECAMIX, IFSTTAR) within the consortium IDR2 (Initiative for Development and for Research on Rails) based on a theoretical, numerical and experimental approach. Concerning the numerical simulation, it starts from the train traffic to a fatigue life assessment [18].

- Step 1: a railway multi-body dynamics is performed, accounting for the actual rail and wheel geometries and load conditions, to determine contact conditions at the wheel-rail interface.
- Step 2: the stabilized cyclic mechanical state of the rail is calculated using a 3D elasto-plastic finite element simulation and an original, time–cost efficient direct stationary algorithm.
- Step 3: a fatigue analysis of the rail is performed according to Dang Van criterion to define the critical sites for crack initiation within the rail.
- Step 4: the crack (s) are considered and their behavior and growth are analyzed.

This paper focuses on this latter point. A two dimensional Extended Finite element model accounted for actual residual stresses and frictional contact between crack faces is combined with a mixed mode nonproportional crack propagation model previously developed. In Section 2, the theoretical basis of the two-scale XFEM strategy for cracked body problem with frictional contact at the interface accounting for actual residual stresses is presented. Then, in Section 3 the fatigue crack growth procedure is briefly introduced. Section 4 illustrates the reliability of the results. Parametric studies are then performed to analyze the influence of the tangential loading, the friction coefficient between the crack faces and the initial crack orientation on the crack growth path and rate. In the last part of this section, the actual residual stress influence is studied and the role of neighboring cracks in the crack propagation mechanism is emphasized.

2. Two-scale XFEM strategy for cracked body problem with frictional contact at the interface accounting for actual residual stresses

2.1. Two-scale strategy for cracked body problem with frictional contact at the interface

Different authors have proposed mixed weak formulation to take into account the contact and the friction between the crack faces (Fig. 1) within the X-FEM framework [19–22]. We here use the approach proposed in [20] and consider a cracked body $\Omega \in \mathbb{R}^3$. Contact and friction can occur along the crack faces Γ^+ and Γ^- (Fig. 2(a)). Under small displacement and small strain assumptions, the interface Γ ($\Gamma = \Gamma^+ \cup \Gamma^-$) is assumed as an autonomous entity with its own behavior possibly