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Assessment of uncertainties in life prediction of fatigue crack initiation and propagation in welded rails

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ABSTRACT

The risk for initiation of fatigue cracks in the rail head and web in the weld zone of a rail is studied. The interaction between the welding residual stress field and the stress field caused by service loads is simulated in a nonlinear finite element (FE) analysis where the welding residual stress distribution (shape) and magnitude, the service load magnitude and the material parameters used in the fatigue life estimation are varied. The initiation of fatigue cracks is assessed using the shear-stress-based multiaxial fatigue criterion proposed by Dang Van, and the propagation of fatigue cracks in the rail web is carried out using a Paris-type crack growth law. A discussion is presented of the interpretation of using the Dang Van criterion to assess crack initiation for stress–response load cycles with low shear stress amplitudes and high hydrostatic stress levels. In addition, the accuracy in the fatigue life assessment is evaluated by statistical uncertainty analysis where the variances according to the Gauss approximation formula are studied. The risk for fatigue crack initiation and propagation in the rail head and rail web, respectively, is enhanced due to the welding residual stress, and the uncertainty in load level dominates the uncertainty in the fatigue assessments.

1. Introduction

Modern rails are subject to a complex loading situation with high local stresses at the rail head during a wheel passage superposed with a global bending stress in the rail cross-section [1] . Hence, a material point near the rail's surface is subject to cyclic, fatigue loading with rotating principal stresses. Rolling contact fatigue (RCF) and wear of the rail head are technical problems of concern for the railway operators [1].

The manufacturing of rails may give rise to additional concern for fatigue cracks starting from defects in the weld zone. Failures at rail welds and growth of cracks starting in the weld zone have been studied in Mutton and Alvarez [2] and Desimone and Beretta [3]. A completed weld, a flash butt weld or a thermite weld, typically exhibits high tensile residual stresses in the web region, see Skyttebol and Josefson [4] and Fig. 1. These stresses may increase the risk for fatigue failure as they are relatively unaffected by the subsequent resulting high local stresses at the rail head during wheel passages [5], where growth of cracks in a rail butt weld is studied considering also the influence of the welding residual stress field.

In this paper, the influence of the tensile residual stress level relative to the service stress level with respect to both the risk for initiation of fatigue cracks in the rail head and the propagation of cracks near defects in the web in the weld zone of a rail is discussed. The interaction between the residual stress field and the stress field caused by service loads is simulated in a nonlinear finite element (FE) analysis, followed by fatigue analyses and statistical uncertainty analyses of fatigue crack initiation in the rail head and fatigue crack propagation in the rail web. In total, the following parameters are varied in the FE and statistical analyses:

- the welding residual stress distribution (shape) and magnitude,
- the service load magnitude,
- the material parameters used in the fatigue initiation and propagation estimations, and
- the size of a presumed crack/defect in the rail web zone.

The fatigue analysis of the initiation of fatigue cracks is assessed using the Dang Van criterion [6,7]. The effect and consequences of high hydrostatic stress and the validity of the Dang Van criterion are discussed in particular for the rail web region where high residual stresses exist from the welding operation. The fatigue crack propagation analysis is carried out considering both Mode I and Mode II crack growth using a Paris-type crack growth law. To evaluate the accuracies of the fatigue initiation and propagation predictions, statistical uncertainty analyses are carried out by studying variances according to the Gauss approximation formula [8].

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Nomenclature

A	extent of zone of tensile residual stress in the rail web
C	fatigue crack growth factor in a Paris-type crack growth law
I, II	subscripts I and II refer to Modes I and II, respectively
N	number of load cycles
R	nominal stress ratio, $R = \sigma_{min}/\sigma_{max}$
S_{eff}	effective stress range in Paris-type crack growth law
X	general notation for stochastic variable
a	crack length
a_0	initial crack length
a_c	final crack length
a_{DV}	material parameter in the Dang Van multiaxial fatigue criterion
d_y	distance from the rail foot to the position for fatigue analysis
m	fatigue crack growth exponent
p	service load; contact pressure
v	train velocity
x, y, z	coordinates of the rail's coordinate system (lateral, vertical and longitudinal)
Δ	symbol for "range"
ρ, ρ_{lim}	stress ratio on the critical plane; critical stress ratio on the critical plane
σ_A	(tensile) residual stress in the rail web
σ_h	hydrostatic stress
$\sigma_{n,max}$	maximum stress perpendicular to the critical plane
σ_x, σ_y, σ_z	normal stress components
τ_{xz}, τ_{yz}	shear stress components
$\sigma_{A\infty}$, $\tau_{A\infty}$	fatigue limit during fully reversed axial loading conditions and fully reversed torsion, respectively
τ_a	shear stress amplitude (deviation from midvalue during a stress cycle)
τ_e	fatigue limit during torsion

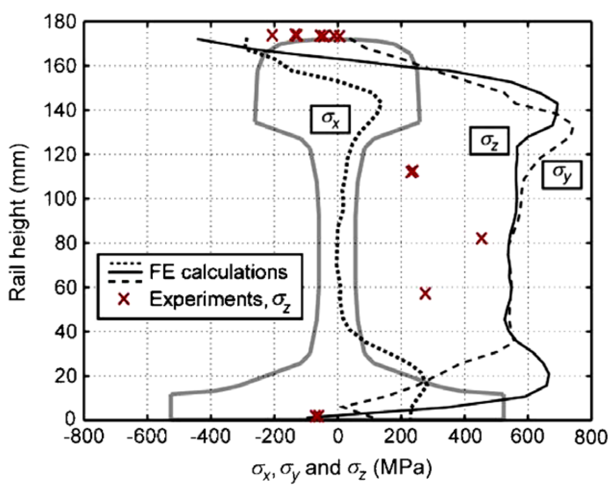

Fig. 1. Calculated (lines) and measured (cross marks) residual stresses in a rail after flash butt welding (x = lateral, y = vertical and z = longitudinal direction of the rail) [4,5].

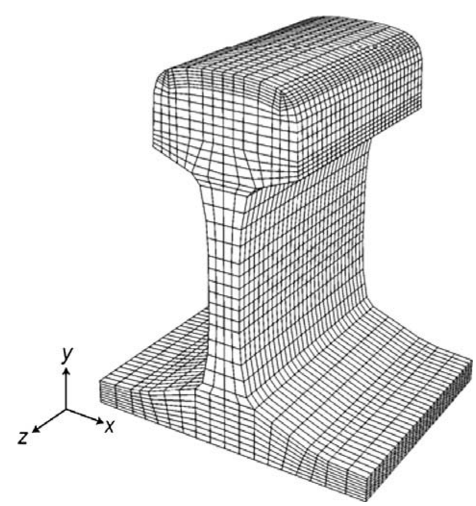

Fig. 2. The FE mesh of the rail model used in the FE tool.

2. Finite element model

In Ringsberg et al. [9] an FE tool was developed for the analysis of RCF of railway rails. It contains two FE models, for track and rail, which are coupled by time-dependent boundary conditions. This track and rail model FE tool was used in this study, and all FE modelling details and representation of contact loads are described in detail [9]. The FE analyses were carried out using the commercial FE code Abaqus version 6.5-1.

The rail model is a three-dimensional FE model where 8-node linear brick elements form the mesh; see Fig. 2 where the FE mesh of the UIC 60 rail profile (rail height: 172 mm) used for the rail model is shown. The material volume in the rail near the wheel–rail contact undergoes elasto-plastic material response. Hence, high mesh density was used in this region to resolve all the stress and strain gradients satisfactorily. The elasto-plastic material behaviour was modelled with the nonlinear kinematic hardening model described in Nielsen et al. [10], and the material used was the UIC grade 900A. This constitutive material model was deemed satisfactory for our investigation where the material response in the web region of the weld develops into elastic or elastic shakedown subsurface after some wheel–rail passages (load cycles).

The service load situation studied is a track curve of the heavy haul iron-ore line, Malmbanan, situated in Northern Sweden. The FE tool is used to calculate the stress field in the rail model for four combinations of axle load and train velocity, v, discussed in Nielsen et al. [10]: 5×10^3 kg at 70 km/h; 22.5×10^3 kg at 100 km/h; 25×10^3 kg at 50 km/h; and 30×10^3 kg at 60 km/h. Regions of stick and slip were disregarded here and the traction coefficients in the wheel–rail contact zone are 0.1 and 0.35 in the rail longitudinal and lateral directions, respectively. In Nielsen et al. [10], a parametric study was carried out where the traction coefficients were increased. The results confirmed that high traction coefficients affect the stress–strain response near the rail surface, while the stress response at the positions of interest in Fig. 8 was more or less unaffected. Table 1 presents a list of the parameters involved in the FE simulations. The magnitudes of the tensile residual stress σ_A in the web, and the extent of the tensile zone A, were chosen from studies by, among others, Tawfik [11]. The service load, p, is the maximum (Hertzian) contact pressure for the axle load under consideration. All combinations of these parameters were simulated which resulted in a total of 36 FE simulations.