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Crack closure and retardation effects – experiments and modelling

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Abstract

The design of cyclically loaded components is in many cases carried out on the basis of experiments on small-scale laboratory specimens. In this approach, many effects such as load ratio, residual stresses and short crack growth are taken into account and described in a computational crack growth model. However, it can be seen that the prediction of the actual component lifetime with such models often is clearly too conservative. The reason for this behaviour can be found in occurring load sequence effects during operation, which are often not dealt with in the context of small-scale experiments.

This paper attempts to examine such variations of applied load stresses as they may occur during operation. On the basis of cyclically loaded single edge bending (SEB) specimens, crack retardation effects are investigated in detail. It will be shown that residual stresses and overloads as well as extended operation times under small loads can lead to a significant extension of the lifetime of a component.

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Keywords: crack retardation, crack closure, residual stresses, overloads, small loads

1. Introduction

For damage tolerant design of cyclically loaded components such as railway axles, a detailed knowledge of the crack propagation behavior is essential. Therefore a few years ago the project *'Safe and economic operation of running gears' (Eisenbahnfahrwerke 2, EBFW2)* was realized (Lütkepohl et al. (2009), Luke et al. (2010) and

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Luke et al. (2011)). Within EBFW2 a computational method for determining the residual life and/or inspection intervals of railway axles by means of fatigue crack growth calculations was developed. Although even various residual stress states can be considered in this computational model, non-negligible differences between computation and tests on full-scale components have been observed, with the full-scale components consistently exhibiting longer lifetimes than predicted. The computational method was developed using fracture mechanics material parameters derived from laboratory specimens. Provided that there exists no size effect between laboratory specimens and full-scale component tests, further effects or mechanism are expected to be responsible for the occurring differences. To clarify these differences, the project *'Probabilistic fracture mechanics concept for the assessment of railway wheelsets' (Eisenbahnfahrwerke 3, EBFW3)* was started.

The computational model developed in Lütkepohl et al. (2009) was based on the NASGRO fatigue crack growth equation. The NASGRO equation is able to describe the crack propagation rate for long cracks. Maierhofer et al. (2014a) modified the NASGRO equation slightly to consider also the behavior of short cracks. Also the growth of cracks emanating from deep sharp notches is not considered in the common NASGRO equation (Maierhofer et al. (2015)). This means that, considering the current state of knowledge (Maierhofer et al. (2014a, 2015)), the computational model will lead to even higher differences between prediction and full-scale tests. Hence, there must exist some additional mechanisms which are responsible for the deceleration of the crack propagation rate in full-scale tests in comparison to standard laboratory testing. Within the project EBFW3 the following main reasons for differences between constant load tests on small-scale fracture mechanics specimens and block program testing on full-scale test axles were found to be potentially responsible for crack retardation effects:

- Compressive residual stresses
- Overloads
- Small loads near the fatigue crack growth threshold

In the present contribution, the influence of these mechanisms on the fatigue crack propagation rate is investigated in detail.

Nomenclature

a_0	notch depth
$\mathrm{d}a/\mathrm{d}N$	crack propagation rate
Δa	crack extension
ΔK	stress intensity factor range
ΔK_0	crack growth threshold at R=0
ΔK_{ox}	stress intensity factor range
$\Delta K_{\mathrm{th,ox}}$	stress intensity factor range for building up an oxide layer
K_{max}	maximum stress intensity factor during one load cycle
K_{min}	minimum stress intensity factor during one load cycle
$K_{\mathrm{max,OL}}$	maximum stress intensity factor during an overload
K_{ox}	model parameter for oxide induced retardation
K_{res}	fictitious residual stress intensity factor due to overloads
L_{OL}	model parameter for overload induced retardation
L_{ox}	model parameter for oxide induced retardation
N_{ox}	number of applied small load cycles
m_{ox}	model parameter for oxide induced retardation
Φ	Gallagher's retardation factor
p_{OL}	model parameter for overload induced retardation
p_{ox}	model parameter for oxide induced retardation
q_{ox}	model parameter for oxide induced retardation
r_{ox}	model parameter for oxide induced retardation