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ScienceDirect

Procedia Structural Integrity 8 (2018) 610–617

Structural Integrity Procedia

www.elsevier.com/locate/procedia

AIAS 2017 International Conference on Stress Analysis, AIAS 2017, 6–9 September 2017, Pisa, Italy

Comparison of SIF solutions for cracks under rotating bending and their impact upon propagation lifetime of railway axles

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Abstract

The stress intensity factor (SIF) is a crucial input parameter for the definition of the inspection intervals based on the damage tolerance approach. In the present work the applicability and precision of existing analytical stress intensity factor solutions for the cracks in railway axle geometries,subjected to rotary bending and residual stresses is discussed, by comparison with a reference set of solutions obtained from finite element (FE) analyses. Both the SIFs and the crack shape evolution are considered, comparing the predicted crack shape growth, from FE and analytical solutions, with a series of experimental data from the literature. Finally, the effect of the different approximations for the propagation lifetime and non-destructive tests (NDT) reliability of railway axles is discussed.

Peer-review under responsibility of the Scientific Committee of AIAS 2017 International Conference on Stress Analysis

Keywords: railway axles; stress intensity factor comparison; residual stresses; residual lifetime

1. Introduction

Railway axles are designed to have an infinite life-time. Even if this is accepted as adequate, the fact remains that occasional failures have been and are observed in service. Hillmansen and Smith [1] recently cited 37 failures during a period of 27 years (1975 - 2002) for a total number of 170 000 axles circulating in UK. Similar figures have been observed all around Europe in other references [2]. The typical failure positions are the press- fits for wheels, gears, and brakes or the axle body close to notches and transitions[2]. Such failures always occur as fatigue crack propagation whose nucleation can be due to different causes. In the case of railway axles, the presence of widespread corrosion or the possible damage due to the ballast impacts [3] may constitute such causes.

This kind of failures is usually tackled by employing the 'damage tolerance' methodology, whose philosophy consists in determining the most opportune inspection interval given the 'probability of detection' (POD) of the

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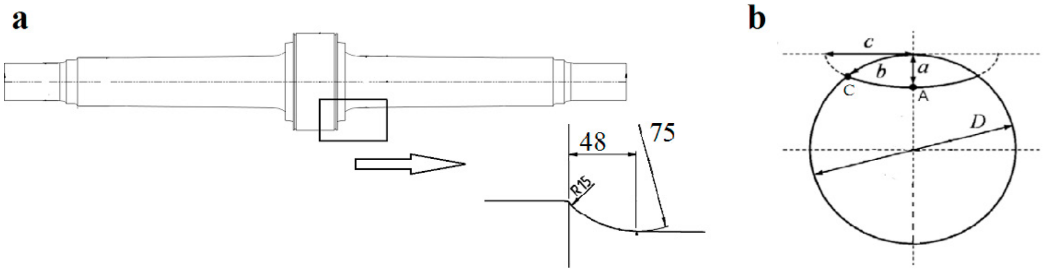

Fig. 1. geometry of the axle: a) dimensions at the T-notch b) crack configuration

adopted non-destructive testing (NDT) technique or, alternatively, in defining the needed NDT specifications given a programmed inspection interval. The knowledge of several factors is essential for a accurate calculation regarding to the damage tolerance analysis including: Initial crack dimensions, the acting load spectra during the service life the axle, the crack growth behavior of the adopted steel grade, which describes fatigue crack propagation rate in each cycle and evaluation of stress intensity factor along the crack front.

In order to have precise prediction of crack propagation rate and consequently residual lifetime, it is necessary to have accurate estimation of driving forces on the cracked component ΔK. Usually FE analyses are performed to calculate the SIFs along the crack front, which gives precise results, but the computational effort, due to the fact that several crack configurations needs to modeled, is very high. Moreover, the FE methodology is not flexible: apart from the analyzed cracks and geometries, the results cannot be easily extended.

Besides the FE analyses for K factors, there is also a need for less expensive analytical solutions, which allow at least an approximate estimation of the parameter. Currently there are wide range of analytical SIF solution available in literature [4], involving different loading conditions, crack location, crack shape and cracked component shape. The SIF solutions are mainly evaluated adopting two kind of approaches. One base on the FE modeling of the cracked component, which results from FE evaluations, considering several crack shapes and dimensions, are usually interpolated or used for generating set of equations in order to obtain an analytical solution for the SIF of a developing crack, the other one onto an analytical approach adopting the so-called weight function [5]. The weight function depends only on geometrical and boundary conditions, so by determining the weight function for a given geometry it is possible to predict the SIF for any stress field acting on the crack plane for the same geometry.

The analytical SIF solutions were adopted for the T-notch and axle body of two different railway axles as representative for freight and high speed passenger train applications and the results were compared with the obtained FE solution, then the impact of estimated SIFs were investigate on residual lifetime and crack shape evaluation, however for the sake of brevity only the corresponding analysis for the freight axle is presented in this paper. Four important aspects regards to damage tolerance analysis of railway axles were considered in this research as following: the stress intensity factor prediction, rotary bending and residual stress, the choice of the initial crack shape and load spectra.

2. Finite element analysis

The FE analysis were carried out on the adopted full-scale specimens, shown in Fig. 1a, specially designed according to relevant standards [6], for the three point rotary bending facility available in LucchiniRs, *R&D* laboratories. Fatigue cracks in railway axles tends to have semi-elliptical shapes(see Fig. 1b). For analyzing crack propagation, it is necessary to perform separate analyses for the surface point and for the deepest point in crack front, because it will allow the crack to grow in depth to length ratio as it does in real case. Since there were no specific analytical SIF solution available for the given geometry, several crack configurations were considered in the assessment locations. In particular five different crack depth a (1,3,5,7 and 9 mm) and five aspect ratios a/c (0.2,0.4,0.6,0.8,1.0), with c being the semi-surface length, were consider in the present study.

SIFs were obtained on the basis of J-integral determination using the method of virtual crack extension and domain integrals. As it shown in Fig. 2 The most suitable approach for this purpose is to have reasonably refine and structural mesh in the global model, where the stresses had to be carefully measured, and then defining a sub-model for the local