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Comparison of crack growth behaviour between full-scale railway axle and scaled specimen

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ABSTRACT

There is an increasing demand for railway-axle damage tolerance analysis. However, few studies have focused on the correspondence between the theoretical crack growth behaviour and the observed results for railway axles under constant stress amplitude. This paper presents the results of crack propagation tests using full-scale axles conducted in accordance with the ASTM E 647 standard. The threshold stress intensity factor range is also evaluated using a full-scale axle. Moreover, the crack growth behaviour of the full-scale axles is compared to that exhibited by compact tension specimens, which is obtained in the same manner.

1. Introduction

Railway axle integrity is a critical aspect of railway system safety, because axle failure may cause serious accidents, including vehicle derailment. Axle design guidelines such as the European and Japanese standards [1,2] differ in terms of axle design procedures and fatigue criteria; however, they essentially prescribe an infinite life design based on fatigue strength. A number of studies have demonstrated that axle fatigue strengths must be higher than the standard requirements, based on fatigue test results using full-scale axles [3–8]. For example, Beretta and Regazzi [5] and Cervello et al. [6] have conducted fatigue testing to determine the fatigue strengths or failure probabilities of such axles. These findings have ensured the structural reliability of railway axles, so that axle failures are extremely rare. However, axle failure during service does occur, mainly as a result of surface or subsurface defects [9–11]. In axles with defects such as corrosion, ballast impacts, or non-metallic inclusions, fatigue cracks may initiate from those defects. Then, the initiated cracks may grow as a result of operational loading.

It is difficult to evaluate the reliability of axles containing such defects based on their Wöhler (*S*–*N*) curves or fatigue limits. In addition, an infinite life design does not allow quantitative evaluation of the inspection intervals, which are determined based on operating experience. Thus, there is an increasing demand for damage tolerance assessment for railway axles based on fracture mechanics, which would facilitate estimation of residual lifetimes or appropriate inspection intervals for railway axles. Zerbst et al. [12] have presented basic input parameters for such damage tolerance analysis, namely, the axle geometry, the fatigue crack extension characteristics, the location or shape of an initial crack (defect), the crack size detectable via non-destructive inspection (NDI), and the probability of crack detection (POD) via NDI. They have also investigated the influence of fatigue crack growth behaviour characteristics on the residual lifetimes of railway axles, such as the crack growth rate, $\mathrm{d}a/\mathrm{d}N$, as a function of the stress intensity factor range, ΔK, and the ΔK threshold value, ΔK_{th} [13]. In addition, several studies on POD have been reported [14–16]. For example, Hillmansen and Smith [14] and Carboni and Beretta [15] have evaluated the association between POD and NDI intervals and the probability of axle failure. Carboni and Cantini [16] have also suggested a POD curve based on consideration of the crack reflection area.

A number of reports have addressed railway-axle crack growth calculation based on crack propagation behaviour measured using compact or scaled specimens [17–23]. For example, Freitas and François [17] have evaluated the crack growth rate of a railway axle under a constant stress amplitude using the crack propagation curve obtained for middle-tension (MT) specimens and scaled axles. Further, Varfolomeev et al. [18] have investigated the effect of the specimen geometry on fatigue crack growth rates. Several articles have examined crack growth behaviour under variable stress amplitude for compact specimens [20,21,24]. It should be

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noted that the crack growth behaviour is influenced by effects such as crack closure, residual stresses in the crack tip plastic zone, and crack tip blunting, which are affected not only by the load sequence, but also by the component scale. In order to evaluate the effects of these factors on crack growth behaviour, crack propagation tests using full-scale axles under variable amplitude stress have also been conducted [25–28]. Beretta and Carboni [26] have investigated the application of crack growth predictive models and concluded that load-interaction effects in full-scale axles differ from those obtained for compact specimens because of constraint effects. Traupe et al. [27] and Mädler et al. [28] have experimentally evaluated residual lifetimes or appropriate inspection intervals of full-scale axles with a load spectrum derived from measurement data. Mädler et al. [28] have also indicated that crack growth calculations cannot precisely incorporate the complexity of crack propagation processes, which are caused by effects related to the scale or load sequence or time-dependent mechanisms. Despite this difficulty, few reports have focused on theoretical crack growth behaviour analysis adapted to full-scale axles under constant stress amplitude, in which the load sequence effect does not appear [24,29]. Beretta et al. [29] have conducted crack propagation tests using compact specimens and full-scale axles under constant stress amplitude to investigate the feasibility of fatigue crack growth algorithms; however, they did not clearly state the differences between the two sets of results. In addition, Carboni et al. [24] have reported correspondence between the crack growth curves obtained for compact specimens and full-scale axles under constant amplitude loading. However, the crack growth behaviours of these items in the vicinity of ΔK_{th} were not compared.

In addition, the crack aspect ratio $a/2c$, where a is the crack depth and $2c$ is the crack length (Fig. 1), is one of the most important factors determining the stress intensity factor K. Note that $2c$ represents the arc length along the axle surface, rather than the major axis of a semi-ellipse. Carpinteri et al. [30] have indicated via fatigue crack growth simulations that crack growth paths for different initial crack configurations under rotary and plane bending tend to converge to a nearly circular arc shape. Further, Madia et al. [31] have evaluated the K factors for various crack shapes and crack sites in railway-axle geometries. Traupe et al. [27] and Mädler et al. [28], when conducting fatigue tests of full-scale axles, have assumed $a/2c = 0.4$ as the starter artificial notch, based on fracture surface investigations of broken axles. Traupe et al. [27] have also reported that $a/2c$ remains almost constant during the test and the a value can be estimated rather reliably from $2c$. However, to the best of our knowledge, no studies have experimentally assessed crack shape development in full-scale axles subjected to rotary bending stress, except for cases involving starter notches of semi-circular or semi-elliptical shape.

The main objective of this paper is to evaluate the differences in the crack propagation rates between full-scale axles and compact specimens under constant stress amplitude through the inclusion of ΔK_{th}. Crack propagation tests using full-scale axles are conducted in accordance with ASTM E 647 requirement [32], in order to exclude the crack closure behaviour generated under variable amplitude loading. Further, full-scale axle test results are compared with those for compact specimens obtained in the same manner. In addition, the crack shape development from a non-circular starter notch and its convergence are validated experimentally, as a sub-objective.

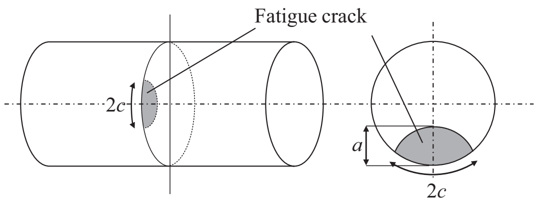

Fig. 1. Round bar with semi-elliptical surface crack. The crack aspect ratio is defined as $a/2c$, where a is the crack depth and $2c$ is the crack length.

2. Methodology of crack propagation tests for full-scale axles

2.1. Material properties

In the experiments discussed in this paper, quenched and tempered medium carbon steel, SFA640, was used as the test material. SFA640 is widely used in Japanese railway axles, except for high-speed trains [33]. The chemical composition and mechanical properties of the SFA640 used here are shown in Tables 1 and 2, respectively. The properties required by the Japanese Industrial Standard (JIS) for the considered steel are also shown in Tables 1 and 2. Note that the yield strength, σ_y, and the tensile strength, σ_B, of the tested material are relatively high compared to the JIS requirements. The JIS states minimum values only; however, there is a large difference between these requirements and the typical strength values for SFA640.

2.2. Fatigue testing rig and specimen geometries

Fatigue tests using in-service wheelsets can be very problematic, because a heavy load is required in order to apply a large stress, which causes damage to the axle bearings or wearing of the wheel tread. In this paper, the test rig shown in Fig. 2 was employed, which is designed to facilitate fatigue testing of full-scale axles under four-point rotary bending conditions. Note that these conditions are similar to those experienced by an in-service axle. The electro-hydraulic actuator controls the applied bending stress. As the distance between the supporting bearings is relatively large, a large bending moment and stress can be applied, even if the actuator load is relatively small. Therefore, this apparatus is suitable for crack propagation tests using full-scale axles, which require high cycles.

Fig. 3a illustrates the geometry of a full-scale axle. The bending moment between the inside bearings (the mid-span area with 145-mm diameter) was constant as a result of the four-point bending condition. The axle had a starter artificial notch at its centre, because the K solution procedure is simple for a crack propagating on the axle body, which has no stress concentration and exhibits a linear stress gradient in the radial direction. This is in contrast to the T-transition, which is subjected to stress concentration and a nonlinear stress gradient. The starter artificial notch, which was 1 mm in both length and depth ($a/2c = 1.0$), was electrical-discharge machined in each axle and the mid-span area was

Table 1
Chemical composition of SFA640 and JIS requirements (wt%).

	C	Si	Mn	P	S
Tested material	0.44	0.20	0.80	0.019	0.011
Standard requirement	–	–	–	<0.035	<0.040

Table 2
Mechanical properties of SFA640 and JIS requirements (σ_y: yield strength (MPa), σ_B: tensile strength (MPa), A: Elongation (%), Z: reduction of area (%)).

	σ_y	σ_B	A	Z
Tested material	465	743	26	61
Standard requirement	>345	>640	>23	>45