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Load interaction effects in propagation lifetime and inspections of railway axles

S. Beretta [*], M. Carboni, D. Regazzi

Politecnico di Milano, Dipartimento di Meccanica, Via La Masa 1, 20156 Milano, Italy

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ABSTRACT

As well known, an interaction effect arises, on crack propagation, when a specimen or a component is subjected to variable amplitude fatigue loading. Depending on the applied load sequence, a certain amount of retardation or acceleration can then be observed, on the fatigue crack growth rate, with respect to the constant amplitude case. In the case of structural ductile materials, the interaction phenomenon is mainly addressed by the local plasticity at the crack tip and can be explained, from a global point of view, by adopting the crack closure concept. In the present research, load interaction effects in a medium strength steel for railway axles are experimentally analyzed by companion and full-scale specimens. The experimental outcomes show a significant retardation with respect to a simple no-interaction approach and the Strip-Yield model offers good, yet conservative, estimates of crack advance. The consequences of crack growth retardation on the inspection periodicity of railway axles are then discussed.

1. Introduction

Railway axles are usually designed against fatigue limit [1,2], but, due to their very long service life (30 years or even more on European lines) and to in-service damage like corrosion or ballast impacts, the approach has moved to damage tolerance [3–5]. From this point of view, the presence of cracks in axles is accepted and they must be periodically inspected using non-destructive techniques. The problem so moves to the determination of the appropriate maintenance inspection intervals, based on crack growth life predictions and the adopted non-destructive testing technique [6]. Considering the former aspect of inspection intervals, it is well known from the literature that an interaction effect on crack propagation arises when a specimen or a component is subjected to variable amplitude (VA) fatigue loading, like railway axles. Depending on the applied load sequence, a certain amount of retardation or acceleration in fatigue crack growth rate can then be observed if compared to the constant amplitude (CA) loading case. In the case of structural ductile materials, this interaction phenomenon is mainly addressed by the local plasticity at the crack tip and can be explained, from a global point of view, by adopting the 'plasticity-induced crack closure' concept [7,8].

In the case of railway axles, apart the numerical simulations in [9], the papers with experimental VA tests show that: (i) at relatively high stresses (higher that the ones adopted for axle design) there is absence of load retardation [10,11]; (ii) under realistic stress spectra, there is a significant retardation for both a normalized C45 steel grade [12] and a quenched and tempered 25CrMo4 grade and higher grades [11,13]. As for the axles, it has to be remarked than the present test apparatuses for full-scale axles (three point bending [10,12], cantilever bending [11,14] or wheel-roller [13]) do not allow to make tests with real stress histories, but they can only apply sequences of block loadings. The effect of this simplification has not been yet thoroughly investigated.

The present paper aims at complementing the previous results about VA effects onto crack propagation in railway axles by a series of analyses (experiments and simulations) on the standardized medium strength EA4T grade [15], a quenched and tempered 25CrMo4 grade. VA tests were performed on SE(T) companion specimens and crack propagation was experimentally measured considering the original in-service load time history and different equivalent block loading sequences defined from it. An experimental full-scale test under block loading was carried out, as well. Eventually, crack growth predictions, using both a simple no-interaction algorithm and a Strip-Yield model [16], were carried out for small-scale and full-scale specimens and compared to experimental evidence. The effect of the significant crack retardation onto inspection intervals of railway axles is then discussed.

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[*] Corresponding author.
E-mail address: stefano.beretta@polimi.it (S. Beretta).

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2. Experiments

2.1. Crack growth behavior of EA4T steel grade

A dedicated experimental campaign was carried out, for each batch, in order to investigate the crack propagation behavior of EA4T grade at constant amplitude loading. The near-threshold region was particularly investigated, because, typically, the life of a railway axle is mostly spent within such a region. The details about this campaign are reported in [17], while a summary is provided in the following. Eight traditional SE(B) specimens from batch A and twelve from batch B, all having a $12 \times 24\,\mathrm{mm}^2$ cross section and an 8 mm initial notch length obtained by electro-discharge machining (EDM), were tested. Each specimen was pre-cracked under compression. Crack propagation tests onto SE(B) specimens were then carried out using a Rumul Craktronic resonant plane bending facility having a capacity equal to 160 Nm and working at a frequency of about 130 Hz. Crack length was measured, on either side of the crack, using 10 mm crack-gages and a dedicated control unit, by the potential drop technique. Specimens were tested at different stress ratios ranging from $R = 0.7$ to $R = -2.5$.

2.2. Variable amplitude loading experiments on SE(T) companion specimens

A new type of SE(T) specimen (width equal to 50 mm, thickness equal to 20 mm and initial notch length equal to 6 mm, as in Fig. 1(a)), having the same crack tip 'constraint' of cracks in real axles, was adopted for variable amplitude loading experiments as a companion specimen of full-scale axles [18]. Tests were performed by a mono-axial servo-hydraulic Schenck facility with 250 kN maximum load. First, specimens were pre-cracked under compression, in order to obtain, similarly to small-scale SE(B) specimens, a non-propagating and naturally arrested fatigue crack characterized by no closure effects, as in the example of Fig. 1(b). After compression pre-cracking, each specimen was instrumented by two 20 mm crack-gages, one on either side, for real-time crack length monitoring by a potential drop technique. Moreover, before starting each test, eight strain gages were glued on each specimen in order to verify the correct alignment of the load axis: the SE(T) specimen equipped for tests is shown in Fig. 1(c).

The complete plan of VA experiments on SE(T) specimens is shown in Table 1. The first two SE(T) specimens (EA4T batch B steel grade) were tested with the aim to check the crack propagation behavior of the material subjected to a load-time history and to an equivalent block load sequence derived from the time history itself. These experiments were also performed because the typical fatigue test machines used for testing full-scale axles are not able to apply load time histories, but only block load sequences and the possible differences in the response could then be checked. The applied load-time history is representative of 57,000 km of service and was derived by in-service measurements onto a high-speed train. Fig. 2(a) shows the load spectrum of the load-time history and compares it to its equivalent block loads: the blocks were rearranged according to a Gassner sequence [19] typically adopted by some European railway operators for the homologation of axles and here defined as 'long blocks' sequence (Fig. 2(b)). The amplitudes of both the load-time history and the block load sequence were applied to specimens after being scaled so that their maximum ΔK_{max} at the beginning of each test was equal to the one at the tip of a 2.5 mm deep crack located in the most stressed section along the groove of a real axle.

2.3. Variable amplitude loading full-scale test

A full-scale railway axle was tested using the 'long blocks' sequence. The full-scale specimen, shown in Fig. 3(a) and made of EA4T batch B steel grade, was tested under three point rotating bending on a dedicated fatigue test machine, available at the Department Mechanical Engineering – Politecnico di Milano, having a capacity of 250 kNm and a rotational speed of about 9 Hz. The static scheme of the test machine is shown in Fig. 3(b). Two artificial notches were machined at the section highlighted in Fig. 3(a) by EDM, at 180 from each other, in order not to interfere during crack propagation. The notches had a semi-elliptical shape, with initial depth $a_0 = 1.5$ mm and aspect ratio $a/c = 0.67$, according to Fig. 3(c). The full-scale specimen was first subjected to 10 repetitions of the 'long blocks' sequence scaled to a maximum SIF value equal to the one applied to SE(T) specimens, in order to initiate a sharp crack out of the artificial notches. Then, other 90 repetitions were applied and, finally, since no significant crack advance was measured, to another 77 repetitions increasing the load levels of the 'long blocks' sequence by 25%.

3. Results

3.1. Constant amplitude loading tests

Fig. 4(a) shows the experimental CA crack growth curves obtained from each batch, along with their interpolation carried out applying the maximum likelihood method to Forman–Mettu's equation for crack growth rates [20]:

$$\frac{da}{dN} = C\left[\left(\frac{1-f}{1-R}\right)\Delta K\right]^{n} \frac{\left(1-\frac{\Delta K_{th}}{\Delta K}\right)^{p}}{\left(1-\frac{K_{max}}{K_c}\right)^{q}} \tag{1}$$

where C, n, p and q are the empirical constants, ΔK_{th} is the threshold SIF range, K_{max} and K_c are the maximum and the critical SIF values, respectively, R is the stress ratio and f is the 'Newman's closure function' [16] describing the plasticity-induced crack closure phenomenon:

$$f = \frac{S_{op}}{S_{max}} = \begin{cases} \max(R, A_0 + A_1 R + A_2 R^2 + A_3 R^3) & R \geqslant 0 \\ A_0 + A_1 R & -2 \leqslant R < 0 \end{cases} \tag{2}$$

where S_{op} is the opening stress. The involved coefficients are defined as [16]:

$$\begin{aligned} A_0 &= (0.825 - 0.34\alpha + 0.05\alpha^2)\left[\cos\left(\frac{\pi S_{max}}{2\sigma_y}\right)\right]^{\frac{1}{\alpha}} \\ A_1 &= (0.415 - 0.071\alpha)\frac{S_{max}}{\sigma_y} \\ A_2 &= 1 - A_0 - A_1 - A_3 \\ A_3 &= 2A_0 + A_1 - 1 \end{aligned} \tag{3}$$

being α the 'constraint factor' originally proposed [16] by Newman as the calibrating parameter of the Strip Yield model. $\frac{S_{max}}{\sigma_y}$ is, instead, the ratio between the maximum applied stress and the cyclic yield one.

In Fig. 4(a), data were normalized due to their proprietary nature. In spite of the big differences between the two experimental approaches considered for characterizing the threshold region, the two data sets are in good agreement in the linear region of the $da/dN - \Delta K$ diagram, as previously shown by the authors [21] for EA4T and EA1N steel grades.