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Experimental validation of inspection intervals for railway axles accompanying the engineering process

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ABSTRACT

In the paper an example of successful cooperation between an operator, a vehicle manufacturer, a wheelset supplier and a research institute is presented demonstrating the current state of a design procedure which aims at meeting wheelset specification requirements recently adopted by the Deutsche Bahn (DB). Different from the conventional praxis, these requirements incorporate the fracture mechanics approach for determining inspection intervals of railway axles. The procedure includes the wheelset dimensioning based on current railway standards, fracture mechanics considerations to assess subcritical crack propagation starting from a crack size just below the detection limit, and crack propagation tests on full-scale axles under load spectrum representative of in-service conditions. The paper describes different steps of the procedure, while mainly focusing on fracture mechanics – both computational and experimental – issues.

1. Introduction

For several decades, wheelsets have been designed according to guidelines which have meanwhile become a European standard [1]. The latter basically comprises classical fatigue criteria by comparing a design stress level with the material fatigue strength (endurance limit). Besides the dimensioning aspects [1], the technological product requirements [2] and since 2010 maintenance activities [3] are subjects of the current standardization program. This system of standards has grown empirically and is further continuously adapted to the state-of-the-art. Taking into consideration the overall number of wheelsets in operation and the annual fleet mileages, axle fracture can be judged as an extremely rare event [4].

With the fatigue fracture of an ICE 3 powered axle in July 2008 at Cologne Main Station [5], the discussion around the determination of sufficiently safe non-destructive testing (NDT) intervals reached a new dimension. As a consequence, the NDT intervals determined heretofore empirically were challenged, and thus their reconsideration and/or new requirements had to be established. To help resolve this problem, merely theoretical fracture mechanics models [6–10] were available at the time of the damage event addressed above, whereas approved normative guidelines for estimating in-service inspection intervals of wheelsets were and are still lacking. As a consequence for existing designs, the NDT intervals for wheelsets of German high speed trains have in many cases been drastically shortened, which had caused severe problems with the availability of vehicles and considerably increased the maintenance costs. In order to counteract this situation, especially in view of new vehicles procurement and design, Deutsche Bahn (DB) as the biggest railway operator in Germany has extended their performance specifications for wheelsets by the requirement of demonstrating a sufficient residual lifetime of axles by means of fatigue crack growth analyses, assuming initial cracks of a specified size. Depending on particular application, the requested remaining lifetime may vary, however being in the order of magnitude of about 500,000 km. Due to the lack of experimental validation for the most theoretical studies of fatigue crack growth in railway axles, one of the main targets within the approach adopted by DB is an experimental validation of computational results by a limited number of full-scale axle tests.

In what follows, this approach is demonstrated on an example of a current vehicle project in which the authors and their companies were involved.

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2. Wheelset description

The results presented in this study were derived within the Coradia LINT and the Coradia Continental vehicle projects of railway manufacturer ALSTOM Transport Deutschland. Those vehicles are provided with driven and non-driven wheelsets. The wheelsets of Coradia LINT are produced by Gutehoffnungshütte Radsatz, those of the Coradia Continental by Bonatrans Group. The material used for the axles in both projects is EA4T (quenched and tempered steel 25CrMo4).

Fig. 1 shows the trailer wheelset of the Coradia LINT project with a schematic indication of the assessment location between the seats of the wheel and axle-mounted brake disc. This assessment location is considered as the most critical with respect to fatigue crack propagation due to a combination of a relatively high bending moment, a local stress concentration in the transition radius and high stresses due to press fitting. Different from the Coradia LINT, the wheelset of the Coradia Continental is equipped with wheel brake discs, which feature affects stresses acting in the transition from the axle to the wheel seat, both due to press fitting and bending, whereas the critical assessment location is nearly the same as for the Coradia LINT. Generally, the respective stresses have to be determined taking into account the particular wheelset design. For the sake of brevity, the results of stress analyses reported in the following section are confined to the Coradia LINT axle.

3. Fracture mechanics assessment

The goal of theoretical analyses for the axle under consideration is to estimate the crack growth behaviour in the subsequent experimental investigations and thus minimize the risk of an unsuccessful test. Moreover, the results of crack growth calculations provide some valuable information which is employed in establishing test specifications. It is out of scope of this study to judge to which extent the current status of the theoretical crack growth prediction matches results of full-scale axle tests. However, it is worth noting that theoretical and experimental investigations reported in [7,8] and performed for a limited amount of full-scale axles with semi-elliptical surface cracks suggest that the computational framework adopted in those studies underestimates the axle residual life, so that a considerable safety margin between the estimated and real fatigue lives is likely to be expected. The related issue of the transferability of fatigue crack growth curves derived by the standard method [11] on small standard specimens to the assessment of full-scale axles is discussed elsewhere, see e.g. [12], and is not addressed in this paper.

Fatigue crack growth calculations performed in this study follow the framework established in [7,8]. This employs following information:

i. Fatigue crack growth curves derived by testing M(T) specimens at $R = -1$ and $R = 0.1$ [7,8], as well as their smooth curve fitting by a NASGRO type equation. The R value is defined as the ratio of the minimum to maximum stress intensity factor in a load cycle, $R = K_{min}/K_{max}$. The respective effect has to be considered due to the superposition of rotary bending stresses with residual (mean) stresses resulting from press fitting, see e.g. [7,13]. No crack closure effects are included in the fatigue crack growth model.
ii. In-service loading defined as a load spectrum, in terms of the nominal stress amplitude, measured or estimated at a representative location at the axle surface.
iii. Axial stress distributions resulting from both external bending load and press fitting (assembly of the wheels and other parts, e.g. brake discs). The both stress distributions are determined separately from finite-element analyses, for those axle cross-sections which are regarded to be most critical with respect to crack propagation behaviour. The stresses due to press fitting are then considered during the whole axle lifetime as constant residual stresses acting as a mean stress, whereas stresses from rotary bending are to be scaled according to the load spectrum.
iv. Analytical crack growth calculations at superimposed bending and residual stresses, starting from a pre-defined initial crack size until some significant crack size is reached.

In numerical stress calculations for the axle without crack, several parameters as well as uncertainties in their definition should be considered. One of those parameters is the fitting interference, i.e. the difference between the axle and wheel diameters. Numerous analyses have revealed that the larger fitting interference the higher stresses due press fitting and thus the shorter residual lifetime are to be expected for the axle. For this reason, the maximum fitting interference according to EN13260 [2], as the utmost severe assumption, is employed in the finite-element calculations throughout this study. For instance, the interference values of 0.31 mm and 0.304 mm are adopted when modelling the wheel and brake disc press fits, respectively. Another influencing parameter is the coefficient of friction (COF) which is considered to increase from a relatively low initial value just after press fitting

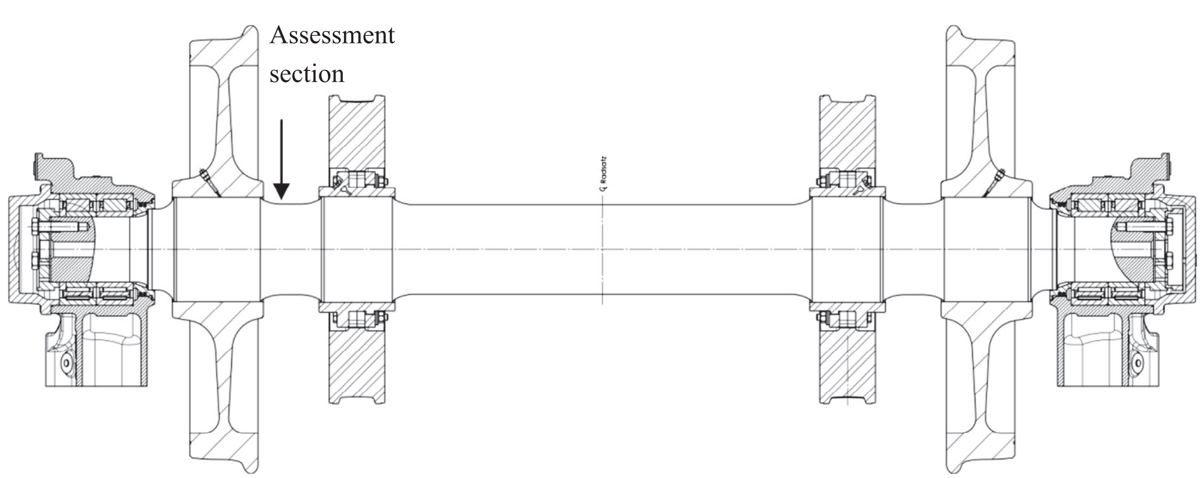

Fig. 1. Drawing of the non-driven wheelset of the Coradia LINT vehicle.