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Probabilistic fatigue assessment for railway axles and derivation of a simple format for damage calculations

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ABSTRACT

This paper describes a procedure for the determination of railway axle risk of fatigue failure under service loading for a simple fatigue assessment compliant to modern structural recommendations.

After an initial review of reliability assessment under fatigue, a fully probabilistic approach is outlined, whose input data for the fatigue damage obtained with the EURAXLES project are briefly summarized. Then, a series of Montecarlo simulations was carried out in order to determine the maximum allowable stress for a given axle made of EA4T and EA1N under service conditions identified by different load spectra from the literature.

Results have been obtained in terms of a *safety factor* for damage calculations that allows designers to adopt a simple semi-probabilistic approach for designing axles for a target reliability against fatigue. The application of this procedure to a railway axle then shows how safety factors should be have to be further increased for taking into the prospective presence of impact damages.

1. Introduction

Railway axles are *primary safety components* designed for an *infinite life* and real their service life can last 30 years. The current design rules, now incorporated in `EN13103/13104` [1,2], date back to ERRI B136 report #11 [3], which stated the principles for designing the axle loads, the admissible fatigue limit stress for EA1N steel and the concepts for axle fatigue experiments. The current EN design rules do not consider any degradation of the axle surface due to the long service (accidental damages, impacts, corrosion), therefore it is needed that maintenance and inspections, whose periodicity has to be determined on damage tolerance principles (see [4,5]), should ensure the structural reliability of the axle. The consequence of both actions (design and inspections) is that axle reliability records are very good (see recent documents [6,7]) and they are already compliant to modern structural reliability requisites (see discussion in Section 3).

If on one side most of the recent literature about fatigue of axles has been devoted to damage tolerance concepts and tools, on the other hand only a few papers have dealt with fatigue design discussing that axles with the same safety against fatigue may have very different residual lifetime [8,9] and that an axle designed for *fatigue safe life* [10] can have a very short residual propagation lifetime [11]. These are the reasons why any actions for improving the reliability and design of axles would need to propose modern methods for the fatigue assessment based on probabilistic concepts.

This was the address of the research project EURAXLES, aimed at *minimizing the risk of fatigue failure of railway axles*. In particular, the results consist in new fatigue data for consolidating current design limits and new tools for modern design (FE analysis, fatigue assessment under service loads, damage calculations) and future design exploitations. In this paper, we start from a summary of the results about fatigue properties of full-scale axles obtained in EURAXLES for proposing a robust approach for designing railway axles with a target reliability.

1.1. Scope – Standards for fatigue assessment

The current standards `EN13103/13104` [1,2] are based onto simple calculations by Reuleaux [12] for identifying reference maximum axle loads for a given train wagon. Recent analyses carried out within EURAXLES have shown that the calculated local axle stresses correspond to a conservative estimation of the upper levels of the service stress spectrum [13]. A local fatigue assessment is then carried out, under the assumption of constant amplitude loading under those conservative axle loads, considering reference fatigue strengths divided by a minimum safety factor $\eta = 1.2$ for EA1N steel and $\eta = 1.33$ for EA4T steel.

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Nomenclature

a_0	initial crack size
C	parameter of the S–N diagram power equation
D	calculated fatigue damage
D_{crit}	critical value of the calculated damage
CV_X	coefficient of variation for the X variable
CV_S	coefficient of variation for the classes of the service spectrum
k	slope of the S–N diagram for $S > S_D$
k'	slope of the S–N diagram for damage calculation for $S < S_D$
j_D	safety factor for fatigue damage adopted by `FKM Guideline`
N_D	number of cycle for the knee of the S–N diagram
P_f	failure probability
$\hat{P}_f$	target failure probability
S_D	stress amplitude for the knee of the S–N diagram (fatigue strength)
$S_{D,char}$	characteristic value of fatigue strength for assessment
S_i	stress amplitude for the ith class of a service spectrum
S_L	single load condition for the assessment under constant amplitude
$S_{\max}$	maximum stress amplitude (or stress amplitude of the highest class) of a service spectrum
$S_{\max,perm}$	maximum permissible stress amplitude (or stress amplitude of the highest class) for obtaining a failure probability $P_f \leqslant \hat{P}_f$
UTS	ultimate tensile strength
β	safety margin for failure probability calculations
$\Delta K_{\max,o}$	initial SIF range calculated at the maximum stress of service spectrum for $\bar{a}_0$
η	safety factor for fatigue strength adopted by `EN13103/104`
η_D	safety factor for axle damage calculations adopting *FKM format*
γ_{Mf}	safety factor for fatigue damage adopted by `Eurocode 3`
λ	failure rate
μ_X	mean value for the X variable
$\bar{X}$	median for the X variable
Φ	normal standard cumulative distribution function
σ_X	standard deviation for the X variable

The limitations with EN Standards methods are: (i) it is not clear what are the levels of failure probability associated with these simple indications, firstly because the axle fatigue strength to be considered is not explicitly related to a prospective strength distribution; (ii) the design procedure does not consider the possibility of an analysis based on fatigue damage, while it is considered in other standards. In the following the prescriptions by `EUROCODE 3` [14] and *FKM Guidelines* [15] are illustrated.

1.1.1. Eurocode 3

According to `EUROCODE 3`, the fatigue assessment of a given structural details can be done considering the S–N *characteristic* curves for the different details. In particular, the design curves correspond to a $P_f = 5\%$ failure probability and they have the typical bi-linear shape suggested by Haibach, with slopes $k = 3$ and $k' = 2k - 1 = 5$ and a *knee* at $N_D = 5 \cdot 10^6$ cycles.

The assessment (both for constant amplitude and variable amplitude loading) is done considering a design curve which corresponds to the characteristic curve divided by an appropriate safety factor γ_{Mf}, reported in Table 1. Considering that a railway axle is a *safety critical* component, according to `EUROCODE 3` the safety factor should be in the range 1.15–1.35.

1.1.2. FKM Guideline

The *FKM Guideline* appears to follow the same approach (even if it is more detailed). In particular, it prescribes a characteristic curve, in terms of stress amplitude, corresponding to a $P_f = 2.5\%$ failure probability. The design curve is once again determined by applying a safety factor (named j_D, reported in Table 2) to the characteristic fatigue strength (see Fig. 1).

Table 1
Recommended values for partial safety factor γ_{Mf} [14].

Assessment method	Consequences of failure	
	Moderate consequences	Severe consequences
Damage tolerance	1.00	1.15
Safe life	1.15	1.35

Table 2
Recommended values for partial safety factor j_D according to *FKM Guideline* [15].

	Consequences of failure	
	Moderate consequences	Severe consequences
No regular inspection	$j_D = 1.30$	$j_D = 1.50$
Regular inspection	$j_D = 1.20$	$j_D = 1.35$

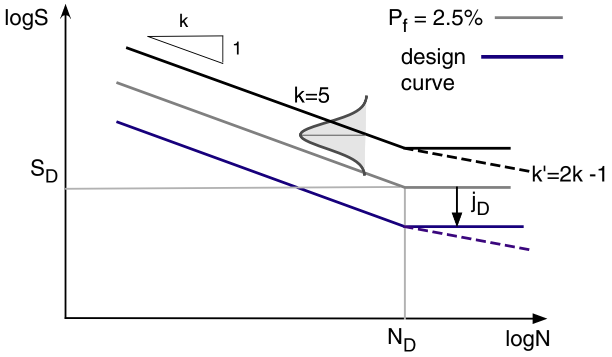

Fig. 1. S–N diagram for fatigue assessment by `FKM` [15].

The critical damage sum according to the *FKM Guideline* should be carried out according to *Miner Konzequent* – *MK* method and its critical value depends on the material: for steel components the values to be considered for damage calculations are $k = 5$ and $D_{crit} = 0.3$. A more simple alternative to the *MK method* is to consider the Haibach's bilinear approximation with a slope $2k - 1$ for stress cycles with $S_a < S_D$ (the calculation with Haibach's hypothesis is a conservative first approximation of the MK calculation).

The FKM approach appears to be more conservative than `EUROCODE 3` and it considers that, under variable amplitude loading, the typical damage sum is lower than 1 [16,17]. On the other hand, the problems of the FKM approach, in common with `EUROCODE 3`, are:

- the value of the safety factor does not appear to be related to the scatter of the load/stress, while it should depend on the dispersion of the stress;