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Fatigue strength assessment of railway axles considering small-scale tests and damage calculations

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Abstract

Small scale fatigue tests aimed at determining the S-N diagram and the Miner Index to be adopted for fatigue damage assessment of railway axles were carried out within the frame of the frame of the research activities of EU funded EURAXLES project. Fatigue tests performed on steel grades EA4T and EA1N adopted by the European EN13103/13104 standards with both constant and variable amplitude loading are reported. The variable amplitude loading fatigue tests were carried out by using loading spectra derived from actual load measurements of fatigue bending moment in railway axles under significant service conditions. The consistent version of Miner's rule (according to the FKM-Guideline) with an allowable damage sum $D_{crit} = 0.3$ adopted in combination with 2.5% percentile (p2.5%) of the S-N curve derived experimentally with small specimens proved to be adequate as design criterion, thus enabling the transferability of small scale fatigue tests to full scale railway axles that would lead to improved fatigue resistance of railway axles with new designs.

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Keywords: S-N diagram, Fatigue damage, variable amplitude, Miner Index, railway axles

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1. Introduction

To maintain and to further increase its competitive advantage in the globalised market, the European railway industry requires new and improved methods for the design of railway axes, allowing higher and improved levels of safety and reliability. Currently, the fatigue assessment of railway axles according to EN 13103 and/or EN 13104 standards is usually based on a constant amplitude fatigue assessment under extreme load conditions. However, in order to increase the level of reliability of new and improved designs, the European railway industry is more and more frequently required to perform fatigue assessments with increased level of details based on measured stress spectra. In addition to that, designers require new and improve methods, allowing the transferability of fatigue test results obtained with laboratory specimens to actual components, as it's been shown, among others, by Gänser et al. (2016) and by Zerbst et al. (2013).

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The EU funded project EURAXLES has been successful at introducing revised axles design concepts by taking into account of actual service loading conditions and of the experimentally determined fatigue limits, including new materials and methods in order to predict the ‘failure probability’. Within the frame of Euraxles project, see Unife (2010), a fatigue test campaign on the steel grades EA1N and EA4T according to EN 13261 has been carried out with both constant and variable amplitude loading. The variable amplitude loading spectra were derived by loading spectra measured during service by one of the partners of the Euraxles project and made available for the scope of generating fatigue tests results that could allow transferability of the test results to actual railway axle fatigue strength assessment. In the present paper, the results of the fatigue tests under constant and variable amplitude loading of the steel grades EA4T and EA1N are given, complemented by an in-depth analysis of the fatigue test results aiming at identifying the allowable (or critical) damage sum leading to conservative fatigue assessment.

Nomenclature

k	slope of the S-N diagram
k'	slope of the S-N diagram for $S \leq S_D$ according to Haibach ($k' = 2k - 1$)
N	number of cycles to failure
N_D	position of the knee of the S-N diagram under constant amplitude stresses
S	applied stress
S_D	fatigue endurance strength

2. Constant amplitude fatigue tests

2.1. Axles cut-up plan and specimen preparation

In the Euraxles project, the fatigue behavior of two railway axle steels, EA1N and EA4T according to the definition of the EN standards, was investigated. The nominal monotonic (tensile) properties of the materials according to EN 13261 are reported in Tab. 1.

Grade	R_e (N/mm^2)	R_m (N/mm^2)	A_5 %
EA4T	≥ 420	650–800	≥ 18
EA1N	≥ 320	550–650	≥ 22

Table 1. Nominal tensile properties of EA4T and EA1N axle steels according to EN 13261.

Fatigue specimens were designed so that tension-compression axial fatigue tests could be carried out by employing the resonance fatigue test equipment Rumul Testronic 100 (Russenberger Prüfmachinen AG) available in the laboratories of both Politecnico di Milano and Fraunhofer IWM. Specimens were extracted from segments of railway axles that were cut in large pieces for the purpose of obtaining specimens for the research activities of the Euraxles project, see Unife (2010). In Fig. 1 the geometry of the specimens and the cut-up of a segment of an axles with the positions of the specimens is also shown. As it may be observed in Fig. 1, specimens for conducting the fatigue tests in the finite life regime with higher loading amplitudes were also taken out of the axles and manufactured with cylindrical ends and with an identical shape of the central gauge section, so that they could be tested with a MTS 810 servohydraulic test systems. In Fig. 1(c), specimens with a shape suitable for strain controlled low-cycle fatigue (LCF) tests are also shown, even if those LCF tests will not be discussed in this paper.

Segments of railway axles manufactured by 3 different European producers, partners of the Euraxles project, were used for the production of the fatigue specimens. Politecnico di Milano carried out fatigue tests with EA4T specimens of all three producers (in the following, due to confidentiality issues, they are referred to as Producer A, B, C), while Fraunhofer IWM performed fatigue tests with specimens extracted from the axles manufactured by producer A on both EA4T and EA1N steels.

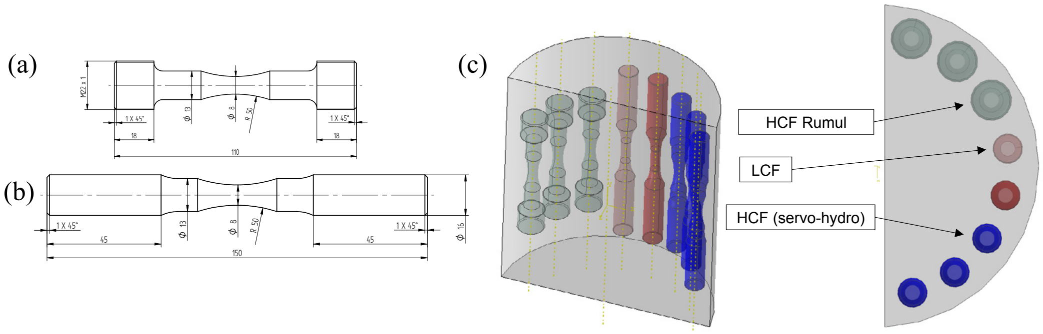

Fig. 1. Details of fatigue experiments: a), b) shape and dimension of HCF specimens; c) positions of the specimens in the railway axles segments.

2.2. Fatigue test results

Constant amplitude (load controlled) high cycle fatigue tests were performed with same equipment (Rumul Testronic 100 kN), available both at Politecnico di Milano and at Fraunhofer IWM. This type of fatigue test equipment allows to achieve loading frequencies of about 100 s^{-1} for obtaining fatigue test results in a relatively short time. All fatigue tests were conducted with pure alternating sinusoidal loading with a loading ratio $R = S_{\min}/S_{\max} = -1$. The number of cycles of runout test was fixed at 10^7 cycles. Fatigue tests were carried out according to the staircase procedure ISO 12107.

As for the higher applied stress amplitudes some plasticity is to be expected, causing a temperature increase of the specimens in the final portion of the fatigue tests due to a non-linear (hysteretic) response of the material in the upper stress range, some fatigue tests with higher stress amplitudes in the finite life regime of the Wöhler diagram were also conducted in a servo-hydraulic test machine (in load control) working at 25 s^{-1}, in order to cross check the validity of the fatigue test results obtained with the Rumul resonance fatigue testing system.

Initially, a separate analysis of the fatigue limits obtained from the staircase sequences for each producer was carried out by adopting ML analysis under the assumption that:

$$\log(S_D) \sim N(\mu, \sigma^2) = N(\log S_D, \sigma^2_{\log S}) \tag{1}$$

However, by carrying out a LR-test it's been observed that the mean values are not significantly different and so all the data were analysed together.

A common S-N diagram for three specimens series was the obtained by implementing a statistical model based on the concept of *uniform scatter band*, according to Haibach and Matschke (1982); Haibach (2006), see Fig.2.

In details, the fatigue life is assumed to be described by a lognormal distribution:

$$\log(N) \sim N(\mu, \sigma^2_{\log N}) \tag{2}$$

where:

$$\mu = \log N_D - k \cdot (\log S - \log S_D), \tag{3}$$

$$\sigma_{\log N} = k \cdot \sigma_{\log S} \tag{4}$$

In this way the entire S-N diagram is described by four parameters (N_D, S_D, k, $\sigma_{\log S}$).

The parameters describing the fatigue curve was evaluated in two separate steps: initially, the estimate of the fatigue endurance strength at 10^7 cycles (fatigue limit S_D) has been derived, considering the staircase sequence, by a maximum log-likelihood method. Then, the slope (k), the standard deviation (in the N direction) and the N_D (the number of cycles identifying the knee point in the Wöhler curve) parameters from a modified maximum log-likelihood method, where N_D is also considered as a function of the standard deviation.

The whole analysis of the fatigue data have been carried out with the ML method, reported in details by Beretta and Regazzi (2014). The results of the analysis of the fatigue data under constant amplitude loading for the two axle steels are reported in Tab. 2 and Figs. 3-4.

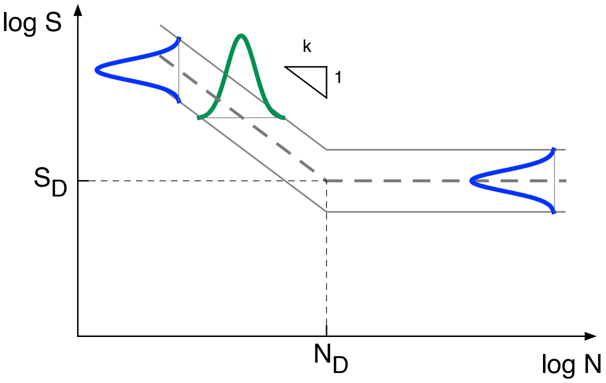

Fig. 2. Schematic of the SN diagram with a *uniform scatter band*.

Steel grade	S_D MPa	N_D cycles	k	$\sigma_{\log S}$
EA4T	373.19	1133300	15.05	0.020966
EA1N	251.6	2230000	18.80	0.01588

Table 2. Parameters for the SN curve and the fatigue endurance strength of EA4T and EA1N steels estimated by the ML method (small scale specimens, constant amplitude loading).

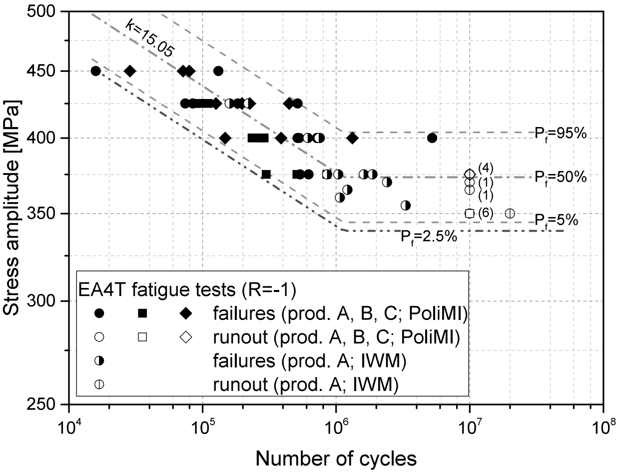

Fig. 3. SN curve of small specimens of EA4T steel.

3. Variable amplitude fatigue tests

3.1. *From measured spectrum to test spectrum*

For the fatigue tests with variable amplitude loading, a measured service loading spectrum that was made available by Trenitalia within the Euraxles project was chosen as a basis for deriving a test spectrum that could be employed in laboratory tests. This in-service loading spectrum was measured, in terms of bending moment occurrences, on the 2 front axles (front bogie wheelsets) of a locomotive of a intercity train hauling 8 wagons (1 laboratory coach + 7 lug-

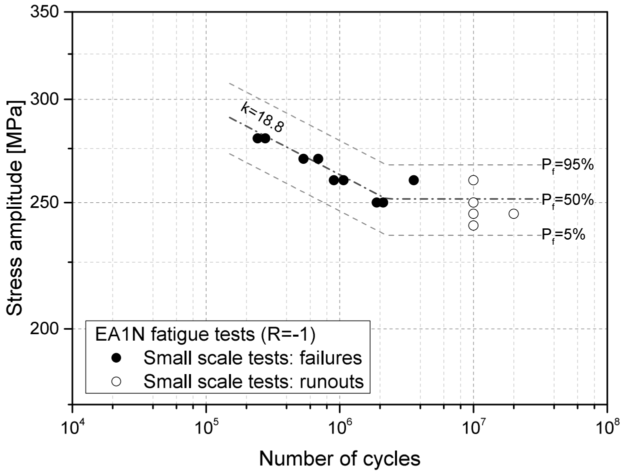

Fig. 4. SN curve of small specimens of EA1N steel.

gage wagons) and a control trailer at the end of the train. This measured in-service loading spectrum is representative of about 600 km, with a mixture of straight rails, large curves, small curves and very small curves (as it happens when approaching a railway station). The in-service loading spectrum was normalized by the maximum bending moment amplitude, and discretized in blocks, with steps of 0.05 (5%) in the observed amplitudes. In Fig. **??**, the comparison between the continuous and discretized loading spectrum is shown. At this stage of the service spectrum analysis, amplitudes below 45% of the maximum amplitude have been omitted already, as shown in Fig. **??**, as they represent a high number of load (bending moment) occurrences with amplitudes that will fall well below the fatigue endurance strength of the railway axle materials and they'll contribute to extend the total duration of the VA loading fatigue tests with little or negligible contribution to the fatigue damage. For the purpose of deriving a test spectrum, omission of small amplitudes becomes a necessity for obtaining tests results (failures) in a reasonable amount of time. The obtained spectrum was randomised in the block sequence and amplified up to the wanted maximum stress for the purpose of performing the variable amplitude fatigue tests.

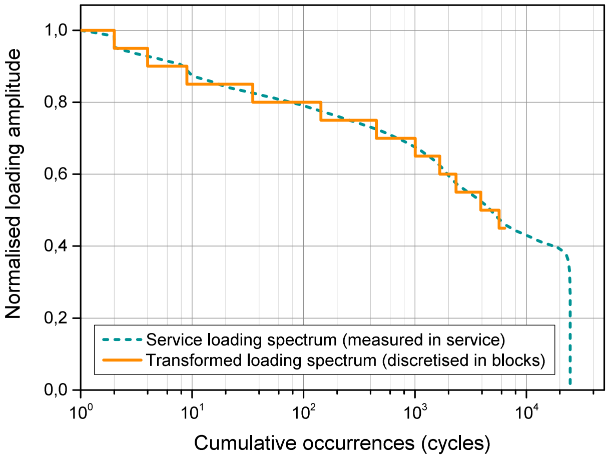

Fig. 5. From the loading spectrum measured in service to the shortened (accelerated) spectrum to be used in the fatigue tests with variable amplitudes with small specimens.

As the specimens for VA testing were tested on a resonant facility at about 100Hz, it was needed to increase the minimum number of cycles of each step in order not to miss the amplitudes. Thus, the number of cycles was multiplied by a factor of 500, thus obtaining a final loading sequence that was used at both laboratories for the variable amplitude fatigue tests.

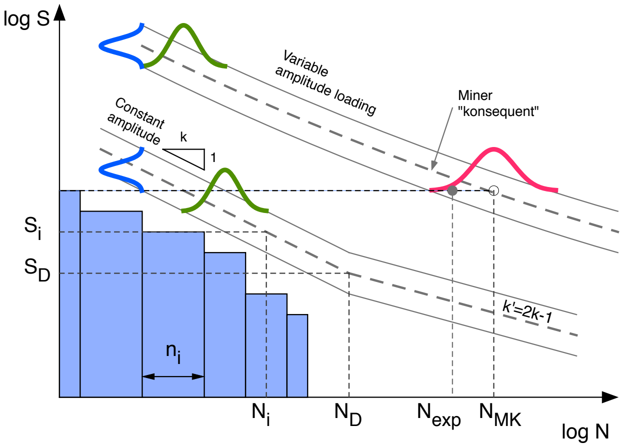

Fig. 6. Application of the Miner consistent (“konsequent”) rule to the fatigue test spectrum for deriving the allowable damage sum.

3.2. Damage calculation

Damage for the test spectrum and for a given maximum amplitude is calculated by adopting the S-N curve parameters for steel grade EA4T with two alternative methods:

- modified Miner’s rule (2 slopes), according to Haibach (1970, 2006);
- “Miner konsequent” (consistent Miner’s rule), according to FKM (2003).

The first method by Haibach provides a good approximations of the life estimates that could be obtained with “Miner konsequent” method as illustrated in FKM (2003) and it is much simpler to apply, since the damage can be calculated as:

$$D = \frac{1}{S_D^k \cdot N_D} \cdot \sum_{S_i \geq S_D} n_i \cdot S_i^k + \frac{1}{S_D^{k'} \cdot N_D} \cdot \sum_{S_i < S_D} n_i \cdot S_i^{k'} \qquad (5)$$

where $k' = 2k - 1$, according to Haibach (1970, 2006).

The second method, known as Miner “konsequent” and whose details can be found in FKM (2003), allows to calculate a fatigue life N_{MK} under the hypotheses that: i) the stresses above the fatigue limit cause a reduction of the fatigue limit for the subsequent cycles; ii) the reduction of fatigue strength can be simply calculated starting from the largest stress amplitude; iii) failure occurs when the damage reaches a value D_m.

The so-called consistent (“konsequent” in German) version of Miner’s rule was originally developed by Haibach (2006). The main aim of this modified version of the Miner’s rule is to take into account of the contribution to fatigue damage of loading (stress) amplitudes below the fatigue limit. The consistent version of Miner’s rule allows for the fact that the component fatigue limit will decrease as the damage sum progressively increases due to the application of fatigue loading. A simplified version allowing for the decrease of the fatigue limit (2 slopes: slope k in the finite life regime, for stress amplitudes above the fatigue limit and slope $k' = (2k - 1)$ for amplitudes below the fatigue limit) was proposed already by Haibach (1970) and became known as the modified version or the Haibach method of Miner’s rule, e.g. see Lee et al. (2012). The “konsequent” (consistent) Miner’s rule for assessing the fatigue damage under variable amplitude loading is also contained in the FKM Guidelines for the assessment of fatigue strength in mechanical components, see FKM (2003).

Considering all the tests, the *critical Miner Index* (the Miner index at failure) has been calculated considering the S-N curves with 50% failure probability. The critical damage sums D_{crit} have been calculated with Eq.(2) for Haibach's rule, while for the ”Miner konsequent” D_{crit} has been calculated as:

$$D_{crit} : N_{MK} = N_{\text{exp}} \tag{6}$$

where N_{MK} is the fatigue life calculated with the “Miner konsequent” method and N_{exp} is the experimental lifetime, see Fig. 6.

As it is shown in Fig. 7, the average critical damage D_{crit} is lower than 1 (as it's commonly and in most cases wrongly assumed) and there is no dependence on the maximum stress level of the spectrum. Moreover, the values of D_{crit} calculated with both the Haibach's modified Miner rule and Miner konsequent method are very similar and they follow a log-normal distribution (in accordance with discussion by Beretta and Regazzi (2016)).

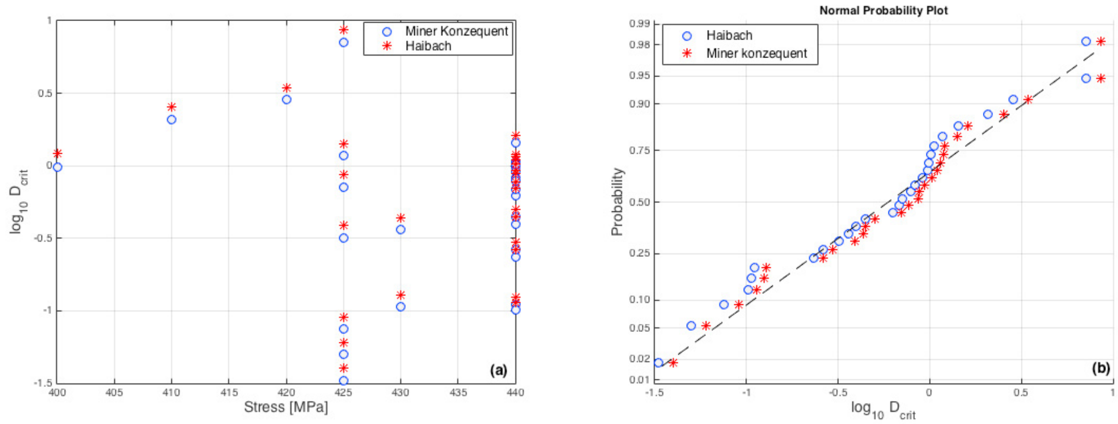

Fig. 7. Analysis of the experimental damage sum derived from the variable amplitude loading tests on small scale specimens: (a) observed values as a function of the maximum amplitude in the (test) spectrum; (b) distribution of the observed values of the damage sum.

In order to provide designers with a simple assessment rule, the choice has been to follow the *format* of the FKM guidelines, which prescribes that assessment is made considering an S-N diagram with $P_f = 2.5\,\%$ and a critical damage sum $D_{\text{min}} = 0.3$. As it can be seen from Fig. 8 such a simple assessment rule is able to provide a conservative estimate for the variable amplitude tests carried out within this research. These results have been already adopted in Beretta and Regazzi (2016) for determining the minimum safety factor to be adopted for design of railway axles under variable amplitude loading.

4. Conclusions

From the analysis of the fatigue tests under variable amplitude loading and the the comparison S-N curves derived from the fatigue experiments under constant amplitude loading with EA4T and EA1N steel grades according to the concept of *uniform scatter bands*, it can be concluded that assuming an allowable damage sum $D_{crit} = 1$, with calculations performed on the mean S-N curve, would lead to *un-conservative* results. Moreover, an allowable damage sum $D_{crit} = 0.5$ seemed to be adequate to represent the experimental results, adopting the S-N curve (with 50% probability of failure, mean curve) for the calculations. Vice versa, calculations as for the FKM guidelines have proved to provide *conservative* fatigue lifetime assessment. The suggested parameters, set as $D_{crit} = 0.3$ onto the 2.5% percentile (p2.5%) S-N curve, seems to be adequate as design criterion, with calculations performed adopting the Haibach's rule, or the more complex Miner konsequent approach resulting in nearly identical lifetime assessment.

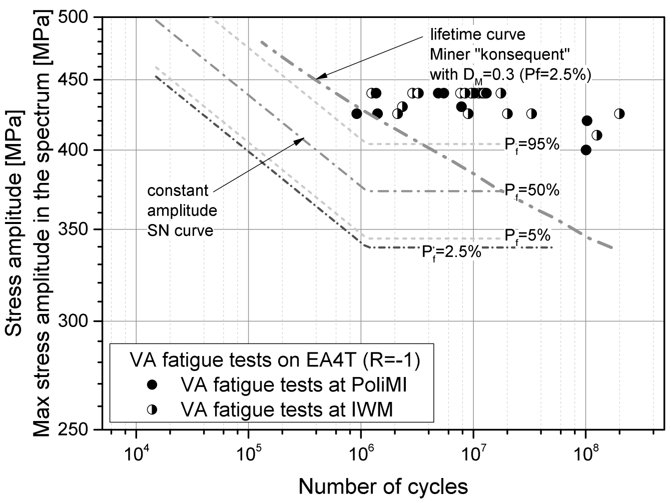

Fig. 8. Application of the Miner consistent (“konsequent”) rule to the test spectrum with a allowable damage sum $D_M = 0.3$ and comparison with the fatigue test results under variable amplitude loading.

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