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Fatigue life prediction method for the practical engineering use taking in account the effect of the overload blocks

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ABSTRACT

It is generally known that during the service life high load cycles occur in addition to the operational loads. Development of an accurate fatigue life prediction rule taking in account overloads around the yield strength and slightly above, with a minimal level of effort for the practical engineering use at design stress level is still highly significant. In the present paper a fatigue life prediction method based on an *S*/*N* curve for constant amplitude loading will be presented. Similarities and differences between the proposed method and the linear cumulative damage rule of Pålmgren–Miner are briefly discussed. Using the presented method an interpretation of the Pålmgren–Miner rule from the physical point of view is given and clarified with the aid of a practical two-block loading example problem. Experimental data cited by other authors will finally be used for the validation.

1. Introduction

The fatigue life prediction of structural components plays a significant role in many fields of the mechanical engineering in the design stage as well as in the construction stage. The most common and probably the simplest fatigue life prediction known as the linear cumulative damage rule was first applied by Pålmgren [1] in 1924 and later in 1945 postulated by Miner [2], who proposed the now generally known mathematical form of the rule. According to this rule, failure occurs when under fatigue loading the whole fatigue resistance of the material is consumed. The mathematical form of the rule can generally be written as:

$$D = \sum_i \frac{n_i}{N_i} \tag{1}$$

where n_i is the number of applied cycles, N_i is the limit number of cycles to failure at the same stress level and D is the damage.

Experiments under variable amplitude loading carried out by Miner led to fatigue damage values from $D = 0.61$ to $D = 1.45$ [2].

Several experiments were carried out [14–21] to verify the linear cumulative damage rule and the results have shown that it often leads to inaccurate fatigue life predictions.

The influence of the load sequences or history effects as a result of the load cycle interaction effects due to the plasticity, residual strength and local hardening effects in the crack tip region, as well as the load cycles below the knee of the *S*/*N* curve are not taken in account.

Many investigations at microscopic level have shown that fatigue mechanism contains different phases starting with micro cracks at the slip band level, following by their nucleation and growth, transition of the micro- to macro-crack and finally the growth of the macro crack until failure occurs. The mechanism of the fatigue and its particular phases are detailed discussed in the literature [8,11,12].

The fatigue crack growth of metallic materials can generally be divided in three distinct regions as schematic shown in the following picture (see Fig. 1):

The first region also known as threshold region is characterized by a slow fatigue crack growth if the value of $\Delta K > \Delta K_{th}$. The second linear region of the fatigue crack growth curve plotted in a double logarithmic scale can be described by the power law equation of Paris–Erdogan [13].

$$\frac{da}{dN} = C \cdot \Delta K^n \tag{2}$$

where da/dN is the crack growth rate, C and n are material constants obtained from experimental tests and ΔK is the cyclic stress intensity range between K_{max} and K_{min}.

The third and simultaneously the last region of the curve describes a rapid asymptotic unstable crack growth until failure occurs. To expand the Paris–Erdogan equation several sigmoid equations which take in account the mean stress impact on the crack growth rate as well as the asymptotic behavior of the curve

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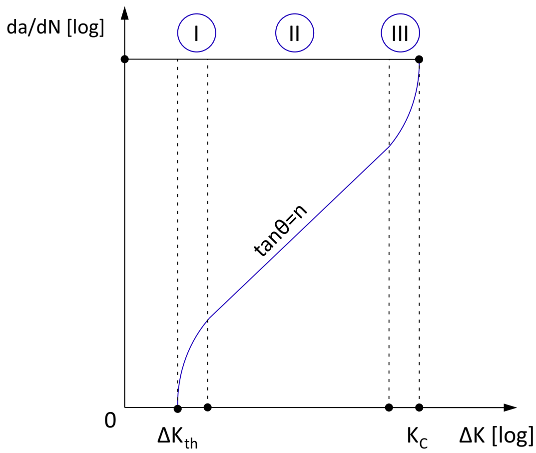

Fig. 1. Characteristic sigmoid shape of the crack growth curve in double logarithmic plot.

in the (I) and (III) regions were proposed. Despite the above mentioned limitations of the Paris–Erdogan equation, it can be useful for estimation of the effects of the design stress level on the crack growth life [8].

Substitution of the stress intensity factor ΔK in the Paris–Erdogan equation gives:

$$\frac{da}{dN} = C \cdot \Delta K^n = C \cdot (\beta \cdot \Delta\sigma \cdot \sqrt{\pi \cdot a})^n \tag{3}$$

where β is a dimensionless geometry factor, a is the crack length and $\Delta\sigma$ is the cyclic stress.

The crack growth life results by integrating the Eq. (3).

$$N = \frac{1}{C \cdot \Delta\sigma^n} \cdot \int_{a_0}^{a_f} \frac{da}{(\beta \cdot \sqrt{\pi \cdot a})^n} \tag{4}$$

Over the last decades a large number of phenomenological, semi-analytical and analytical damage models have been proposed to improve the accuracy of the fatigue life prediction of structures. This paper doesn't intend to review these models. For an exhausting and comprehensive review of the fatigue damage and life prediction theories, both for the metallic and composite materials the reader can refer to [3,4].

Due to the complexity of the most of these theories their validity is still questionable for the practical engineering applications [8].

Generally we can say that a fatigue life prediction rule is reasonable for the practical engineering use if it fulfils the following two essential aspects:

1. Accurate estimation of the fatigue life with a tolerable discrepancy from the real fatigue life.
2. Universality and easy applicability of the rule in any stage of the development process.

In the recent years, efforts to improve the fatigue life prediction of fiber-reinforced composite materials under variable amplitude loading have been done [5]. One of them is the so called "cycle jump approach" based on a local fatigue damage model which covers stiffness degradation and stress redistribution was proposed by [6]. Next the model was implemented in a commercial finite element code which combines progressive damage models with hysteresis operators and allows finite element simulation at structural level [7].

The present paper proposes a simple fatigue life prediction method, which takes in account the overload block effects and consequently is a useful engineering tool for an easy estimation of the fatigue lives of metallic structures at the design stress level. As overload blocks are meant in the present paper loads around the 0.2% offset yield strength level and slightly (~10%) above. The validation of the method has been performed using uniaxial experimental test results carried out by [14–21].

Special care was taken to ensure that the specimens used for validation are both notched und un-notched respectively the load types and the stress ratios are different. The materials of the specimens were fine grain low alloy structural steel, aluminum alloys and bolt joints made from austenitic steel. The metallic materials were isotropic with elongations at break $A_5 > 5\%$. The specimens made from fine grain structural steel are slightly orthotropic due to the thermo-mechanical rolling process of the wrought material. The fatigue life estimation in accordance to the presented method has shown good correlations with the verified experimental results which were carried out in a range between E4 and 2E6 cycles.

2. Fatigue life prediction method

The fatigue life prediction proposed in the present paper is based on the S/N fatigue curve for constant amplitude loading. S/N fatigue curves can be obtained from a set of fatigue tests, carried out on specimens at different stress levels with the same stress ratio ($R = \sigma_{min}/\sigma_{max}$) at each level. The S/N curve can be mathematically approximate using different relationships as Wöhler, Basquin, Stromeyer, Pålmgren, Weibull, Stüssie, etc.

Load cycles below the knee of the S/N curve can be taken in account using the Basquin [9] relationship, which is a linear approximation of the S/N curve on a double logarithmic plot.

The relationship between the stress amplitude and the number of cycles is written as:

$$\lg N = \lg k - m \cdot \lg \sigma \rightarrow \sigma = \left(\frac{k}{N}\right)^{\frac{1}{m}} \tag{5}$$

where k and m are constants of the S/N curve, N is the fatigue life and σ is the associated stress level. The extension of the S/N curve below its knee can alternatively be realized using the Basquin equation and replacing the slope factor m with 2m−1. This modification of the S/N fatigue curve proposed by Haibach [10] leads to less conservative fatigue life predictions than the one proposed by Basquin.

To illustrate the fatigue life prediction method proposed in the present paper, a four-block loading example will be presented and briefly described.

We consider a four-block loading event as shown in Fig. 2, where n_1, n_2, n_3 and n_4 denote the applied load cycles at each load level and σ_1, σ_2, σ_3 and σ_4 the associated stress (or load) amplitudes. The stress levels in the first and the last load blocks are equal $\sigma_1 = \sigma_4$. The equality of the stress levels in the first and the last load blocks has been chosen arbitrary and it doesn't have any impact on the flow of the method.

The number of the applied load cycles in the first three blocks n_1, n_2, n_3 and the stress amplitudes σ_1, σ_2, σ_3, σ_4 in each load block is defined at the outset. The number of the load cycles in the last block n_4 denotes the remaining cycles to an eventually fatigue failure. The task is to estimate the fatigue life at the end of the four-block loading.

The S/N fatigue curve of an un-notched specimen (or structural component) from a metallic material is given in double linear scale as can be seen in Fig. 3.

$N_1 = N_4$, N_2, N_3 depict the fatigue lives for each load level and $W_1 = W_4$, W_2, W_3 depict the damage points on the S/N curve. The calculation procedure will be done only for the first and the last load blocks. The calculation for each other load block can be performed similarly.