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Considering fatigue load sequence effects by applying the Local Strain Approach and a fracture mechanics based damage parameter

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ABSTRACT

Calculating the fatigue life of a structure under loadings with variable amplitudes is of current interest in German industry. This paper analyses the problems and the causes of sequence effects for life calculations and discusses an approach to handling sequence effects, considering mean stress sensitivity and taking size effects into account by modifying different damage parameters.

1. Introduction

Constant amplitude life curves, Fig. 1a, provide the number of cycles to failure, N, depending on the magnitude of applied loading amplitudes, S. The variable S is used as loading indicator including applied loads, forces, moments, nominal or local stresses or strains. Using either of these mechanical quantities is connected to the selection of a specific fatigue assessment approach. For geometrically simple structures formulas provided by engineering mechanics are available.

The stress–life-curve (S–N-curve) provides no information on the contribution of an individual cycle to fatigue damage. For such a purpose, fatigue damage must first be defined. Here physical damage is defined as a physically measurable quantity, i.e. the length of a fatigue crack, a; other choices might be crack densities, dislocation densities, compliance, electrical resistance, or even temperature, etc. Damage growth curves provide information of the increase of damage with the number of applied cycles, Fig. 1c. Under variable amplitude fatigue, Fig. 1b, a fatigue life prediction can be performed based on these curves. However, the physical fatigue damage must be a unique function of the loading indicator. This condition is not fulfilled for all loading indicators used in practical applications In contrast, in scientific applications unique loading indicators have been proposed. The crack closure free, effective range of a loading cycle as proposed by Elber [1] is mentioned here as an early example.

The present paper describes the actual state of an attempt to provide a practically applicable procedure for evaluating unique loading indicators for the cycles of arbitrary variable amplitude loading sequences. With the constant amplitude damage growth curves also at hand, it is expected that calculated variable amplitudes fatigue life might be in better agreement with their experimentally determined counterpart.

2. General aspects of fatigue damage accumulation

2.1. Linear damage accumulation rule

Variable amplitude fatigue life can be calculated using damage growth curves. For example, in Fig. 1c, for n_1 cycles of a first block follow the curve for S_1, continue with the next curve for the next S_{next} and follow it for n_{next} cycles. Repeat this procedure until final failure is reached. The sum of all cycles $\overline{N} = \sum_i n_i$ is the variable amplitude fatigue life.

If, after normalization with the failure life, a load independent damage growth curve can be found, Fig. 1d, the damage accumulation of the example in Fig. 1 is shown in Fig. 1d. The sum of normalized cycles, i.e. ratios of the applied number of cycles to failure number of cycles, becomes unity, indicating failure,

$$\sum n_i/N_i = 1 \quad (1)$$

The ratios (n_i/N_i) cannot be identified in the structure. The sum of these ratios is a normalized or relative life consumption or life usage. Eq. (1) is termed Palmgren–Miner's rule [2–4]. It can always

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Nomenclature

A_i	$i = 0,\ldots 3$; parameters in crack opening stress equation
A_m	mean stress parameter
a	crack length
a_0	fictitious starting crack length
a_e	end crack length
b	fatigue strength exponent
c	fatigue ductility exponent
C	coefficient in fatigue crack growth rate equation
E	Young's modulus
J	J-Integral
K'	cyclic strength coefficient
l^*	microstructural constant for short crack threshold description
m_j	exponent in P_J Wöhler curve
n	number of applied fatigue cycles
n'	cyclic hardening exponent
N	number of fatigue cycles to failure
P	damage parameter
R	ratio of minimum and maximum values in a fatigue cycle
R_m	ultimate tensile strength
$R_{p0.2}$	stress at 0.2% plastic strain offset
S	normal net section stress
Δ	indicator for ranges of a fatigue cycle
ε	normal strain
ε_f'	fatigue ductility coefficient
σ	normal stress
σ_F	yield stress average
σ_f'	fatigue strength coefficient

Indices

0	initial value
a	amplitude
cl	value at crack closure
eff	effective value
J	related to the cyclic J-Integral
max	maximum value
min	minimum value
op	value at crack opening
RAJ	modified P_J
RAM	modified P_{SWT}
SWT	according to Smith, Watson and Topper
th	threshold value

be derived from affine damage growth curves where affine indicates that the physical damage is only a function of life usage, $a = f(\sum_i n_i/N_i)$. The summation is commutative. The sequence of occurrence of cycles has no influence on the fatigue life evaluated on the basis of this rule.

If fatigue crack growth is modeled by the Paris [5] law without limitation due to a threshold or a final failure condition and if the crack length is a sound physical measure of fatigue damage, the linear elastic fracture mechanics-based fatigue crack growth calculation leads to Palmgren–Miner's rule, see Schijve [6].

2.2. Sequence effects due to plastic deformation

There are innumerable investigations showing the shortcomings of Palmgren–Miner's rule, see e.g. the review paper of Fatemi and Yang [7]. Schütz [8] proposed the relative Miner's rule where usage sums different from unity are inserted at the right hand side of Eq. (1). Some relative damage sums can be found in [9–14]. The reasons for deviations are sequence effects during the accumulation of fatigue damage. A unique loading indicator has not been used for the derivation of damage growth curves. Purely elastic

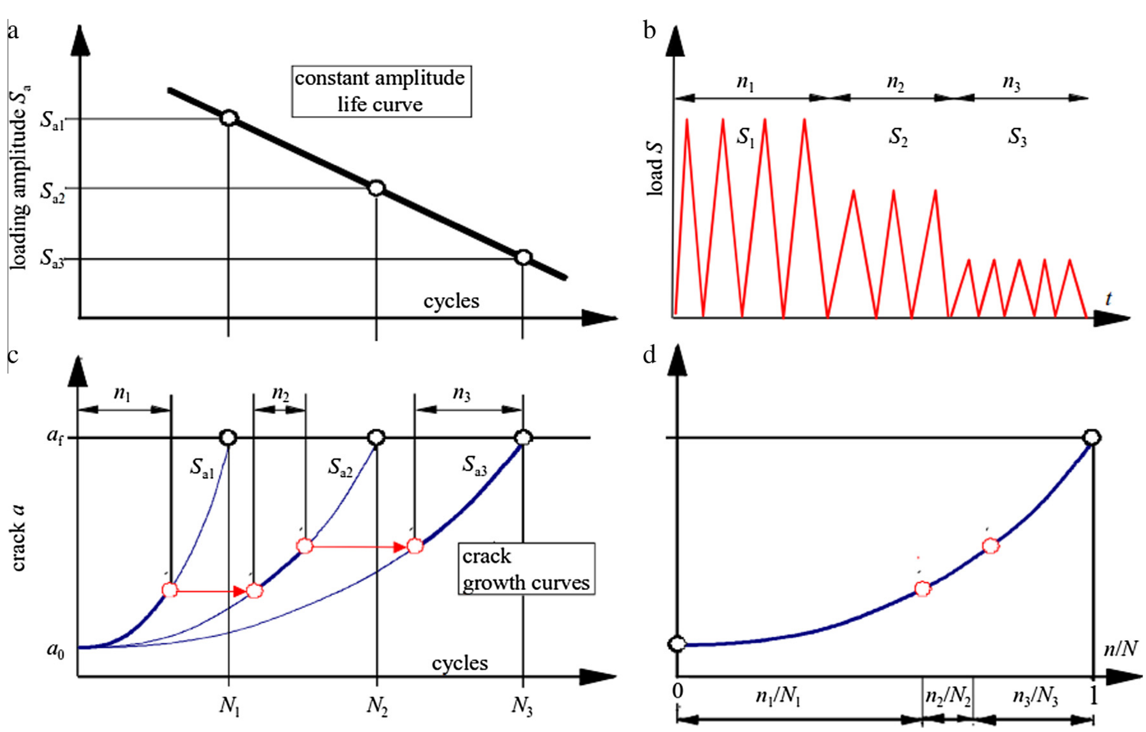

Fig. 1. (a) S–N curve; (b) load sequence; (c) crack growth curves; (d) normalized crack growth curve.