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Fatigue life estimation of notched elements with use of non-local volumetric method

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ABSTRACT

The work presents non-local fatigue computations method together with volumetric approach, in which energy parameter has been used. Proposed model has been used for simulation computations, based on experimental testing of unnotched (smooth) and notched specimens subjected to two types of loads, i.e. tensile – compressive and oscillatory bending. Computations of energy parameter value have been done based on results of FEM elastic–plastic analysis for cyclic properties of a material. Averaging operation was performed for assumed constant threshold value, resulting in averaged value of energy parameter, on the grounds of which fatigue life has been read off from characteristics of unnotched specimens. The threshold value assumed depends on load type, and the volume within which averaging is performed depends on load level.

1. Introduction

Methods of fatigue life estimation for notched elements can be divided on local and non-local ones. The local methods, used mainly in case of unnotched elements, consist in considering a local value of failure parameter, which can be stress, strain or energy criterion [1,2]. Local methods works well in case of unnotched elements, where the phenomenon of stress concentration does not occur. In case of elements with geometric notch, however, estimation of fatigue life by means of local methods may lead to incorrect results, because maximum value of fatigue parameter achieves high value in result of local stress concentration [3,4]. This often leads to arising of plastic strain in vicinity of notch, which should be also taken into consideration in calculations. Therefore in order to compute effective stress value, corrections of stresses by means of available models [5–8] are used. The calculated stress values may be subsequently used for computation of fatigue life with use of multi-axial fatigue criteria [9].

Non-local methods, which assume averaging of fatigue parameter in some point [10–12] on some distance [13–17], surface [18–20] or volume [21,22,4,23–26], constitute the second approach. The pointwise method consists in assuming for computations a value present in some point, distant by some value from vertex of the notch. The linear method consists in averaging of fatigue parameter on some distance from local point featuring the highest effort; the similar rule applies to superficial methods. The volumetric method is an interesting approach. According to it there is assumed, that only in some material volume of adequate effort fatigue processes take place. The work [27] indicated that in case of stress gradients presence only the actively efforted material volume, above the fatigue limit, influences fatigue phenomena. On the grounds of experimental research it has been similarly confirmed in works [21,23,26], that fracture initiation process may occur for some stress value (threshold one), lower than fatigue limit, but such created fracture will not propagate, if the stress value has not exceeded the fatigue limit. This points out the fact that only certain, adequately high value of fatigue parameter and some volume of material should be taken into consideration in fatigue computations. The limit value of fatigue parameter and volume assumed for averaging may vary, it is assumed that this is a material property [22,28,29,30,31], or results from some threshold value, lower than fatigue limit [21,23,26]. The volumetric method, as compared to superficial method features also additional asset, which is its relatively easy implementation into FEM. The results obtained with use of FEM have been verified against experimental research in works [32–34], where its effectiveness has been proved. Currently use of FEM appears to be necessary and inevitable, and additionally entails many advantages, such as possibility of adapting computational models created to elements having arbitrary shapes. Use of FEM leads, however, to some difficulties, such as proper preparation of load, restrain and contact conditions, providing of material properties and selection of finite element grid sizes. The FEM analyses being performed within linear-elastic range, and particularly within range of low fatigue strength and

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Nomenclature

Designations

A	constant of regression model
b	exponent of fatigue strength
c	exponent of fatigue plastic strain
E	Young's modulus
K'	cyclic hardening coefficient
m	constant of regression model
n'	exponent of cyclic hardening
N_f	number of cycles
$2N_f$	number of reverses
R_e	static yield strength
R'_e	cyclic yield strength
t	time
T	fatigue lifetime
W	energy parameter
ε	strain
ε'_f	coefficient of fatigue plastic strain
ν	Poisson's ratio
σ	normal stress
σ'_f	coefficient of fatigue strength

Superscripts

a	amplitude
av	averaged
cal	calculated
e	elastic
eff	effective
eq	equivalent
exp	experimental
i	subsequent item
LM	Łagoda–Macha model
max	maximum
n	nominal
p	plastic
un	unnotched

presence of notches are becoming senseless. Computation executed with use of stress and strain values calculated within linear-elastic range is beneficial because of analysis simplification, but it has to raise doubts for fatigue computations of elements with stress concentration, where fatigue results from macroscopic plastic strains. Obviously, corrections of stress and strain results can be used in such situation, but it has to be remembered that values such obtained does not describe the complete stress and strain tensor. Obtaining of complete tensors is possible with use of plasticity models [35,36]. Models of isotropic and kinematic hardening of material are adapted in FEM programs and enable computations in elastic–plastic range. For fatigue computations in FEM programs (Patran, Comsol, Ansys), where results of statistical analyses are to be used for fatigue computations, correct parameters of fatigue characteristics, i.e. converted from nominal to effective stresses, should be entered. The effective stress is meant here as a value computed in elastic–plastic range for cyclic loads, that is described with a factor and exponent K', n', respectively, of stabilized cyclic hardening.

$$\varepsilon_a = \frac{\sigma_a}{E} + \left(\frac{\sigma_a}{K'}\right)^{\frac{1}{n'}}. \tag{1}$$

The cyclic properties do not remain unchanged in case of many materials; a material may strengthen, weaken or change cyclic properties with increasing number of cycles. Fatigue stress characteristics in double logarithmic coordinate system (Basquin)

$$\log N_f = A - m \cdot \log \sigma_a \tag{2}$$

are most frequently determined on the grounds of nominal stress, also for notched specimens, where net stress is most often computed, that is in relation to cross-section within bottom of the notch. Such approach has practical bases, which, considering simple computations, constitutes good reference to number of cycles. One should be, however, aware that comparing of effective stresses, obtained for example from FEM simulation, against such characteristics (nominal values) will be erroneous. Admittedly, difference of nominal stresses and effective stresses, considering the hardening present, should not be too high, nevertheless this is incorrect approach. Strain characteristics (Manson–Coffin–Basquin)

$$\varepsilon_a = \varepsilon_a^e + \varepsilon_a^p = \frac{\sigma'_f}{E}(2N_f)^b + \varepsilon'_f(2N_f)^c \tag{3}$$

are not subjected to these errors, because they are determined on the grounds of experimentally measured strain of a specimen. Energy characteristics are most often determined during experimental research, where a stress value is computed from torque or load force (nominal stresses) and measured strain. If energy characteristics is determined by means of computations from Basquin stress characteristics, then it should be assumed that stress and strain value during computing of energy parameter value should also be given within elastic–plastic range (effective stress and strain).

In paper [20] it was presented the extensive state of the art of local strain energy density concepts. The main aim of the work is presentation of initial, non-local fatigue computation model with volumetric approach, which will enable estimation of notched specimens fatigue life on the grounds of characteristics for unnotched specimens. Similar methods are used in works [37,38], yet they are based mainly on application of fictitious notch radius term [37–41]. The work presents results of simulation research completed with use of FEMAP and MATLAB programs.

2. Material data and fatigue characteristics

Experimental data for tension–compression and oscillatory bending have been used in the work. For the case of

Fig. 1. UFP 400 stand for fatigue testing.