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A non-linear model for the fatigue assessment of notched components under fatigue loadings

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ABSTRACT

This paper presents a general theory for the estimations of an entire fatigue curve in ductile materials based on the implicit gradient approach. In order to modify the slope of the Woehler curves, the material was considered non-linear. The average stress of the hysteresis loop was taken into account by means of Walker's model. Subsequently, the implicit gradient method was adopted for the numerical evaluation of the effective stress and strain at low- and medium-cycle fatigue life and was then related to the fatigue strength of the material. The characteristic length, relating to the fatigue behaviour of the material, was considered constant for the fatigue lifetime. In order to confirm the proposed method, new experimental data were obtained, relating to axisymmetric notched specimens loaded with nominal stress ratio $R = -1$ and $R = 0$. In terms of the effective strain amplitude, evaluated by means of the implicit gradient approach, the different Woehler curves of notched specimens were summarised in a unique fatigue curve as a function of Walker's cycle parameter.

1. Introduction

The implicit gradient method proved to be a powerful tool regarding the study of the fatigue life of welded structures in order to predict fatigue life for high- and medium-cycle fatigue for many different types of joints. The effective stress was calculated by following the same procedure and the same characteristic length was taken into account for both thick and thin welded joints [1–4]. In these papers, for the sake of simplicity, the welded joints were considered as a sharp V-notched component made of a linear elastic material. Therefore, regardless of the shape of the welded joint and its thickness, a unique fatigue scatter band was defined mainly because, in terms of nominal stress, the slopes of the Woehler curves were very close to each other [5]. Using this method, hundreds of experimental results were gathered into a single scatter band having a slope equal to 3 and intercept at $2 \cdot 10^6$ cycles equal to 151 MPa at 50% of life probability. The stress of 151 MPa was calculated by considering the effective principal stress mainly related to fatigue damage.

In the case of notched components, the classical theory, reported in many engineering design books, such as Collins [6], Juvinall and Marshek [7], Shigley [8] and Dowling [9], is able to predict the slope of the Woehler curve. The methodology is based on the work of Peterson [10] and Neuber [11] and keeps the strength of material fixed at low-cycle fatigue, so that, by changing the strength characteristics of the material at high-cycle fatigue, the Woehler curve moves and can fit the experimental data. However, these methods cannot be generalised to all components since this requires the definition of the stress concentration factor K_t that can be correlated to the fatigue strength reduction factor K_f. In order to overcome this problem, the scientific literature provides different methodologies based on an elasto-plastic local approach [12]. The effect of the non-linear behaviour of the material on K_f factors was taken into account, for example, by Ye and Wang [13]. The approach regards an energy point of view and K_f was calculated simply by using the plastic strain range $\Delta\varepsilon_p$ and the elastic strain range $\Delta\varepsilon_e$ acting on the cyclic. The plastic $\Delta\varepsilon_p$ and elastic strain range $\Delta\varepsilon_e$ were obtained by means of the modified Neuber's relation [11,12].

One method that is widely adopted in the literature is the Smith Watson Topper (SWT) approach [14]. This method proposes a relation between the local value of maximum stress times the strain amplitude and the fatigue limits of parent materials. In this way, mean stress, the non-linear behaviour of the material and the notch effect are considered.

For threaded connections, the SWT approach was considered in Ref. [15] in conjunction with a simple model to describe the local

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Nomenclature

b	exponent for the elastic strain of the Manson–Coffin strain–life curve
b_w	exponent for a Walker strain–life curve
$\bar{c}$	characteristic material parameter
c	exponent for the elastic strain of the Manson–Coffin strain–life curve
c_w	exponent for a Walker strain–life curve
E	elastic modulus
k	strength coefficient monotonic stress–strain curve
k'	strength coefficient cyclic stress–strain curve
K_t	stress concentration factor
n	hardening exponent monotonic stress–strain curve
n'	hardening exponent cyclic stress–strain curve
N_f	fatigue life; cycles to failure
N_i	cycle number for the intersection point for a two-segment stress–life curve
N_{fw}	equivalent value of N_f from Walker's method; Walker's equivalent life
R	stress ratio, $R = \sigma_{min}/\sigma_{max}$
$\Delta\varepsilon$	strain range, $\Delta\varepsilon = 2\varepsilon_a$
$\Delta\sigma$	stress range, $\Delta\sigma = 2\sigma_a$
ε_a	strain amplitude
ε_{pa}	plastic strain amplitude
γ	exponent for Walker's method
σ_a	stress amplitude
σ_m	mean stress
σ_{max}	maximum stress
σ_{min}	minimum stress
σ_{o1}	offset yield strength, 0.1%
σ_{uts}	ultimate tensile strength
σ_1	first principal stress
ε_1	first principal strain
σ'_f, ε'_f	material properties in strain–life curve

cyclic creep as a function of stress amplitude. In order to improve the accuracy of the SWT method for Incoloy 901 superalloy and ASTM A723 steel, Ince and Glinka [16], proposed a modification of the SWT parameter. Recently, Kujawski [17] presented a new energy based interpretation of the SWT. In this case, the complementary strain energy densities were considered as the main cause of fatigue damage and then a deviatoric version of the SWT parameter was proposed. Both modifications of the SWT method appear promising, but as underlined by the authors themselves, the procedures should be re-examined using more experimental non-zero mean stress data sets in the future. Alternatively, as suggested by Dowling [18,19], the effect of the average stress of the cyclic hysteresis loop can be taken into account using Walker's model [20]. For smooth specimens, Dowling showed the efficacy of Walker's model for different materials and different levels of mean stress; material such as steel, aluminium alloy and titanium. By means of a new power exponent γ, Walker modified the classical Morrow fatigue life equations and introduced the nominal stress ratio R.

The SWT method is usually applied to stress at the notch tip but, as underlined in Ref. [21] and successively in Ref. [22], it could be extended to its average values. On the other hand, the designer can take into account not only the maximum local concentration factor but also a volume-averaged value as proposed by Neuber [11] (for a discussion on the characteristic lengths used in notch fracture mechanics, see Ref. [23] where four kinds of characteristic length parameters were compared). Starting from the theory developed by Pluvinage in Ref. [24], other models based on non-linear material behaviour proposed the strain energy as a critical component in a critical volume near the notch [25,26]. The method assumes that the mean strain energy range, in the process volume where the damage takes place, has to be high enough in order to produce failure. The size of the process zone is situated in the high stressed region where the stress gradient is not too high. In this way, the effective distance that can be approximated with the diameter of a cylinder depends on the load level. Therefore, the effective distance is not considered as a material property as indeed it is considered in many others approaches [21,29–31]. Another approach that changes the critical distance as a function of the load level was proposed in Ref. [32]. On the basis of the critical distance theory, lifetime of notched components in the medium-cycle fatigue regime was estimated by considering an L distance between two extreme values (the characteristic length at high-cycle fatigue and the length for static problems) so far the L distance will be a function of the number of cycles to failure, N_f.

The aim of this paper is to extend the validity of the implicit gradient method procedure also for three-dimensional notched components made of ductile material at low- and medium-cycle fatigue life. A new non-linear procedure based on classical low cycled fatigue concept was proposed. In this way, a unique Woehler curve depending exclusively on the non-linear material proprieties can be defined based on Walker's model and by taking into account a constant material parameter independently of the load level. First of all, new experimental data relating to axisymmetric notched specimens, loaded with nominal stress ratio $R = -1$ and $R = 0$, were presented. Then, the fatigue strength was assessed by means of the implicit gradient. Both the non-linear material (through FE) and the mean principal stress effect (through Walker) were considered. Finally, two-dimensional specimens made of FeP04 drawing steel and weakened by sharp lateral U and V-notches were investigated.

2. Experimental analysis

2.1. Specimen geometry

The tested specimens were taken from the extruded tube with an external diameter of 20 mm and a 5 mm diameter hole along the extrusion direction. Three different specimen geometries were machined through the turning process. Fig. 1 shows the dimensions of the specimens and the geometry shape: smooth specimens (Fig. 1a); V-notched specimen (Fig. 1b) and semi-circular notched specimen (Fig. 1c).

Table 1 gives the values of stress concentration K_t, evaluated in relation to the nominal net section. K_t has been evaluated by means of a three-dimensional FE analysis under the hypothesis of linear elastic material behaviour. The values of K_t reported in Table 1 were obtained after a mesh convergence analysis.

2.2. Chemical composition

This work was conducted using extruded low-carbon steel with 0.1% in weight of carbon. The material composition is shown in Table 2.

2.3. Microstructure analysis

Microstructure analysis was carried out using optical microscopy. The sample surface was polished with abrasive grinding