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Damage-based modification for fatigue life prediction under non-proportional loadings

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ABSTRACT

This paper proposes a new fatigue model based on virtual strain energy to predict fatigue life under both proportional and non-proportional loadings for different materials including, 1045 Steel, 30CrNiMo8HH, Titanium TC4, and AZ31B magnesium. The results were strongly correlated with experimental results available in the literature. In addition, two damage-based modifications for fatigue life prediction under non-proportional loadings are studied. These modifications are then applied to the fatigue parameters including Smith–Watson–Topper, Fatemi–Socie, maximum shear strain, and the proposed parameter for fatigue life predictions of the studied materials. The results show considering these modifications significantly improves the accuracy of the models.

1. Introduction

Fatigue is the main cause of most mechanical failures. Many engineering components are subjected to complex fatigue loadings that generate multiaxial stresses. Because of geometrical complicities multiaxial stresses exist even under uniaxial loadings at notches and discontinuities such as inclusions and voids.

Several multiaxial fatigue life prediction theories have been proposed; however no universally accepted approach yet exists. One of these approaches is based on determining energy as a correlating parameter for the multiaxial data. The fatigue process is generally involved cyclic plastic deformations which are dependent on the stress–strain path. Therefore, the stress- or strain-based criteria cannot sufficiently reflect the path dependence of the fatigue process.

Implementation of the majority of the energy based models which consider multiaxial stress–strain response and calculate energy from cyclic hysteresis loop are difficult [1]. Liu calculated the virtual strain energy (VSE) using two crack initiation modes and two Mohr's circles [2]. Our proposed fatigue model is based on virtual strain energy. The principal stresses and strains are considered as two main components of the proposed damage parameter.

Multiaxial loading history is either proportional or non-proportional. The former results in a fixed orientation of the principal axes associated with alternating stresses or strains and the non-proportional loading history is associated with rotational principal axes where the principal stresses or strains ratios vary simultaneously. Non-proportional loading is more damaging than the proportional loading in low cycle fatigue region [3,4]. In some materials, rotation of principal stress and strain axes leads to additional hardening that can reduce the life [5,6]. In addition, rotation of principal axes leads to rotation of maximum shear stress planes which in turn initiates plastic deformation along different slip bands. This process results in more damage and fatigue life reduction. However, some materials exhibit, if any, only a small degree of additional hardening. Although all materials are sensitive to the influence of non-proportionality, the amount of sensitivity varies for different materials.

Non-proportionality effect of loading path imposes uncertainties in fatigue life prediction models. Several models with different non-proportionality factors have been developed to take into account these uncertainties.

Kanazawa et al. [7] studied the cyclic deformation of 1% Cr–Mo–V steel under in-phase and out-of-phase loading. For obtaining stress–strain curve under non-proportional loading, they defined a rotation factor in terms of the amount of slip experienced by critical plane. The rotation factor which can be used as loading non-proportionality factor is defined as the ratio of the shear strain range at 45° from the maximum shear plane to the maximum shear strain range.

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Another well-known approach for determining non-proportionality of loading is minimum circumscribed ellipse (MCE) approach [8]. If strain path is circumscribed by an ellipse, non-proportionality is defined as minor chord to major chord ratio.

Chen et al. [3] investigated fatigue behavior and loading path effect on additional hardening for 42CrMo Steel. They proposed a non-proportionality factor of strain path based on physical basis and macro mechanical. They sketched maximum shear strain at different directions in polar coordinate system and defined a parameter as ratio of swept area by maximum shear strain in different directions in polar coordinates to circle area with radius of maximum shear strain during one cycle. Using this approach they separated strain amplitude and loading path effect on non-proportionality of loading.

Reis et al. [9] tested different loading paths on 42CrMo4 to study fatigue behaviors. They showed that ASME code for equivalent strain range under-estimated the equivalent strain range for non-proportional than proportional loading, which leads to over-estimated fatigue life for non-proportional loadings. They modified damage for non-proportional loading by a linear equation that used additional hardening and loading non-proportionality as variables. Minimum circumscribed ellipse (MCE) approach was used to qualify loading non-proportionality.

Noban et al. [10] conducted a set of proportional and non-proportional loading tests with different phase angles on 30CrNiMo8HH steel to study fatigue behavior and phase angle effect on the material. They reported no additional hardening because of non-proportional loading, whereas fatigue life was significantly reduced. They proposed a material dependent non-proportional modification similar to the Reis [9] model. However, since the material did not show additional hardening, they used a "material non-proportionality sensitivity factor" coefficient instead of additional hardening coefficient. They used MCE approach for non-proportional loading.

When predicted life by a fatigue parameter shows disagreement with experimental results, fatigue parameter over- or under-estimates the damage parameter. The extend of over-estimation or under-estimation depends on fatigue parameter and loading path [11,12].

For non-proportionality sensitive materials, fatigue life prediction for proportional loadings is usually associated with lower error compared with non-proportional loadings [10,13,14,21]. Furthermore, fatigue life is derived from damage quantity. Therefore, correlating damage quantities of non-proportional loadings to proportional loading reduces the error of fatigue damage prediction. In this regard, the present study investigated a method for damage modification.

The study present proposes a novel fatigue parameter based on virtual strain energy (VSE) to predict fatigue life of different materials including 1045 Steel, 30CrNiMo8HH, Titanium TC4 and AZ31B under proportional and non-proportional loadings. The results are compared to the predicted fatigue lives through some prominent fatigue models including maximum shear strain, Fatemi–Socie, Smith–Watson–Topper (SWT), and experimental lives.

Moreover, two damage-based modifications for fatigue life prediction in non-proportional loadings are studied. These modifications were used for the studied materials, and applied to fatigue damage parameters including maximum shear strain, SWT, Fatemi–Socie, and the proposed damage parameter. The results are compared to the no modification findings. Variation of the error is calculated for the proposed modifications.

2. Fatigue life prediction

Fatigue life prediction theories can be classified into three categories: equivalent stress–strain criteria, critical plane criteria, and energy-based criteria. This study predicts fatigue life using maximum shear strain as an equivalent strain-based criterion, two critical plane criteria of SWT and Fatemi–Socie, as well as the proposed model which is based on virtual energy.

2.1. Maximum shear strain

Localized plastic deformation inside persistent slip band is the most common reason of fatigue crack initiation. These slip bands always trend to align with maximum shear strain direction. Therefore, fatigue cracks always initiate on maximum shear strain planes [15,16].

The proposed life equation for maximum shear strain model is expressed as follows:

$$\gamma_{a,max} = \frac{\tau'_f}{G}(2N_f)^{b_s} + \gamma'_f(2N_f)^{c_s} \tag{1}$$

where $\gamma_{a,max}$ is maximum shear strain amplitude, τ'_f torsional fatigue strength, γ'_f torsional fatigue ductility coefficient, G shear modulus, N_f fatigue life, and b_s and c_s are torsional fatigue strength exponent and torsional fatigue ductility exponent, respectively.

2.2. Fatemi–Socie

Fatemi–Socie parameter [17] is a modification to Brown and Miller's critical plane approach. They proposed that the normal strain term should be replaced by the normal stress. The components of this modified parameter include the maximum shear strain amplitude and maximum normal stress on the maximum shear strain plane. The Fatemi–Socie parameter is expressed as follows

$$P_{FS} = \frac{\Delta\gamma_{max}}{2}\left(1 + \frac{k\sigma_{n,max}}{\sigma_y}\right) = \frac{\tau'_f}{G}(2N_f)^{b_s} + \gamma'_f(2N_f)^{c_s} \tag{2}$$

where $\Delta\gamma_{max}$ is maximum shear strain range, $\sigma_{n,max}$ is maximum normal stress on maximum shear strain range plane, σ_y is yield strength, and k is an experimental coefficient obtained by fitting the uniaxial data against pure torsion data.

2.3. SWT

Cracks usually nucleate in shear but initial life is determined by crack growth on perpendicular planes to the maximum principal stress and strain. In this regard, Smith, Watson and Topper (SWT) [18] proposed a fatigue damage parameter. This parameter is based on the principal strain range and the maximum stress on the plane of the principal strain range. The SWT parameter can be written in the form

$$P_{SWT} = \sigma_{n,max}\frac{\Delta\varepsilon_1}{2} = \frac{\sigma'^2_f}{E}(2N_f)^{2b} + \sigma'_f\varepsilon'_f(2N_f)^{b+c} \tag{3}$$

where $\Delta\varepsilon_1$ is principal strain range, $\sigma_{n,max}$ is maximum normal stress on plane of maximum principal strain range, σ'_f is axial fatigue strength coefficient, ε'_f is axial fatigue ductility coefficient, E is modulus of elasticity, and b and c are axial fatigue strength and axial fatigue ductility exponents, respectively.

2.4. Total virtual strain energy

Another approach to fatigue life prediction is the use of energy as a correlating parameter for the fatigue data. Most of the energy-based parameters calculate energy from cyclic hysteresis loop and these approaches appear to be difficult to implement [1]. Liu calculated the VSE by use of the crack initiation modes (cases A and B) and two of strain and stress Mohr's circles [2].