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Fatigue life prediction for some metallic materials under constant amplitude multiaxial loading

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ABSTRACT

Based on the critical plane approach, the Sun-Shang-Bao (SSB) model is analyzed and verified. It is discovered that SSB model cannot take the non-proportional cyclic hardening into account and gives non-conservative fatigue life predictions under the non-proportional loading. To solve this problem, a stress-correlated factor is introduced to describe the degree of the non-proportional cyclic hardening as well as the effect of the non-zero mean stress. The accuracy of the proposed method is systematically checked against the experimental data found in literature for 16 different materials under constant amplitude multiaxial loading paths.

1. Introduction

Engineering components and structures in service, such as axles, crankshafts, and turbine disks and blades, are generally subjected to multiaxial fatigue loading, some proportional and others non-proportional [1–3]. During recent decades, fatigue life predictions for such components and structures under non-proportional loading have become a growing research interest. However, the conventional multiaxial fatigue criteria may lead to non-conservative results under non-proportional loading since they are usually based on proportional fatigue tests. Therefore, accurate fatigue life prediction for these components under non-proportional loading should be further studied.

For non-proportional loading, fatigue behavior under 90° axial–torsional loading is often investigated since it is considered to be a critical example. Nishihara et al. [4] showed that the fatigue limits of ductile materials are apparently higher for out-of-phase bending and torsion loading than that for in-phase loading. However, Guo [5] showed that for a given applied stress, the maximum shear stress amplitude under out-of-phase loading is lower than that under in-phase loading. Among all out-of-phase loading paths, Garud [6] and McDiarmid [7] reported that the special loading case (shear stress/strain amplitudes equal on all plane orientations) gives the worst fatigue performance. Kanazawa et al. [8] found that out-of-phase loading results in a shorter fatigue life as compared with in-phase loading after conducting a number of axial–torsional low cycle fatigue (LCF) tests with various phase angles in 1%Cr–Mo–V steel. Especially, the 90° out-of-phase loading gives the shortest fatigue life [8]. Jordan et al. [9] found that the relative phase angle between normal and shear strains on the maximum shear plane did not affect the fatigue life. Hence, he suggested a life correlating parameter using an integral root mean square of positive normal strain on the maximum shear plane to replace the normal strain amplitude [9]. However, Wang and Brown [10] found that the above-mentioned phase angle did have influence on fatigue life and suggested to take it into account in a life correlating parameter. Fatemi and Stephen [11] and Itoh et al. [12] also found that out-of-phase loading is detrimental for LCF life in terms of maximum shear strain amplitude. Socie [13] claimed that the shorter fatigue life observed under non-proportional loading may be ascribed to the additional hardening associated with complex loading paths. In the proposed Fatemi–Socie damage parameter [14], the normal stress was introduced to replace the normal strain amplitude. For LCF life prediction, some improved models based on the equivalent strain parameter were also proposed by considering the additional hardening and correcting the strain parameter for non-proportional loading path [12,15–19]. Jahed et al. [20–21] proposed a fatigue damage parameter by the energy-based critical plane fatigue damage analysis, which successfully correlated the

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Nomenclature

A_{max}	circle area with radius of maximum shear strain during one cycle
$A_{\alpha,max}$	swept area of γ_α–α polar coordinate space of each cycle
α_c	orientation angle of the maximum shear strain range plane
b	fatigue strength exponent
c	fatigue ductility exponent
E	modulus of elasticity
$\Delta\varepsilon_{app}$	applied axial strain range
ε_m	mean axial strain
ε_n^*	normal strain excursion
$\Delta\varepsilon_{eq}$	von-Mises equivalent strain range
$\Delta\varepsilon_n$	normal strain range
ε_f'	fatigue ductility coefficient
$\varepsilon_{n,a}^{pro}$	in-phase normal strain amplitude
$\Delta\varepsilon_{eq}^{cr}$	equivalent strain range
$\Delta\gamma_{app}$	applied shear strain range
γ_m	mean shear strain
$\Delta\gamma_{max}$	maximum shear strain range
H	hardening factor
k	empirical constant contained in FS model
K'	cyclic strength coefficient
L	non-proportional hardening coefficient
n'	cyclic strain hardening exponent
ν_{eff}	effective Poisson's ratio
ν_e	elastic Poisson's ratio
φ	phase shift
λ	strain ratio, $\Delta\gamma_{app}/\Delta\varepsilon_{app}$
Φ	factor of non-proportionality
$\Delta\sigma_{eq}$	von-Mises equivalent stress range
$\sigma_{eq,a}^{npro}$	non-proportional equivalent stress amplitude
$\sigma_{eq,a}^{pro}$	proportional equivalent stress amplitude
$\sigma_{n,m}$	normal mean stress
$\sigma_{n,max}$	maximum normal stress
$\sigma_{n,a}^{pro}$	in-phase normal stress amplitude
σ_f'	fatigue strength coefficient
σ_y	yield strength
ξ, η	phase angle
$\Delta\gamma$, $\Delta\varepsilon$, σ_n	shear strain range, normal strain range and normal stress on the maximum damage plane, respectively

fatigue lives of metallic materials under various non-proportional loading paths. The cyclic energy, for a given component knowing material, geometry and cyclic loading, was calculated by performing elastic–plastic analysis using cyclic behavior of material [20–21]. Shahrooi et al. [22] verified the Jahed's model for a series of non-proportional loading conditions on 1%Cr–Mo–V steel based on the nonlinear kinematic hardening model of Chaboche [23] and the multi-surface model of Garud [6]. It is found that a weighting factor on shear plastic work should be introduced. So, a factor of 0.5 was used by Shahrooi et al. [22] to reduce the life scatter band. In fact, from the point of microscopic view the additional cyclic hardening can be attributed to different dislocation structures between in-phase loading and out-of-phase loading. Doong et al. [24] found that in planar slip materials, single slip occurs under proportional loading, while multi-slip occurs under non-proportional loading. As a result, ladder and planar structures are found for proportional cycling, while structures such as cell and labyrinths structures are observed for non-proportional cycling [24]. Different materials show different amounts of non-proportional cyclic hardening [24]. Materials such as the 300 series stainless steels show a large amount of non-proportional cyclic hardening, whereas aluminum alloys usually do not exhibit any additional cyclic hardening. The different additional hardening behaviors in different materials may also be related to the different dislocation structures, which are the results of different slip characters in different materials [5,24]. Therefore, fatigue life prediction should be connected with both loading history and material.

A significant amount of researches have been devoted over the past few decades to gain a better understanding of the mechanisms by which fatigue damage accumulates under multiaxial loading and to develop damage parameters to model the observed behavior [25–31]. The majority of these models can be broadly classified into equivalent stress-based models, energy-based models, and critical plane approaches [32]. The early development of the equivalent-stress models are usually based on extensions of static yield theories to fatigue under combined stresses. Constant amplitude multiaxial stresses are transformed into equivalent uniaxial stress amplitude by the von-Mises or Tresca yield criteria. This equivalent quantity of stress is assumed to produce the same fatigue damage or life as the multiaxial cyclic stresses. However, the equivalent stress criteria are usually limited to high cycle fatigue (HCF) regime where stresses can be easily estimated by the elastic stress–strain relations. The advantage of these models lies in their relative simplicity of implementation. It is necessary to point out here that the critical plane-based maximum shear stress and/or maximum normal stress criteria should not be classified as the equivalent stress criterion, which can be used as the critical plane parameters. The energy-based models, in general, utilize the scalar parameter as a measure of fatigue damage. The plastic strain energy parameters have been preferred because of their inherent capability to reflect the stress–strain path dependence of the fatigue process. A shortcoming of the energy-based models is in their inability to portray the physics of the damage process. Experimental evidence has shown that cracks nucleate and grow along shear planes or other crystallographic orientations in many polycrystalline metals [14]. However, a scalar parameter cannot distinguish among planes on which cracks may form. Critical plane approaches are based on the physical observations that cracks initiate and grow on specific planes and that the crack growth is assisted by the stress and/or strain normal to those planes [14,30–35]. According to this approach, the fatigue evaluation is performed on one plane across a critical location in the component. This plane is called the critical plane, which is usually different for different fatigue models. In using these parameters, damage is calculated in terms of cyclic stresses or strains on each plane within the material to identify the plane containing the greatest amount of damage or alternatively on planes experiencing the maximum level of a predetermined damage parameter, such as cyclic shear strain. In recent years, criteria based on the critical plane approach for multiaxial fatigue evaluation are becoming more popular because they generally give more accurate predictions of the fatigue damage, especially under non-proportional loading [26].

In the present study, the shortcoming of the Sun–Shang–Bao (SSB) model is firstly analyzed, and then a modified multiaxial fatigue life prediction model for some metallic materials is proposed by taking into account the degree of the non-proportional cyclic hardening as well as the effect of the non-zero mean stress. In order to verify the fatigue life prediction capability of the SSB and the modified model, a comparison using the test results of