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A fatigue model for sensitive materials to non-proportional loadings

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ABSTRACT

The present study proposes a novel fatigue model based on virtual strain energy. This model separates loading paths based on their non-proportionality where directly takes into account the loading in fatigue life prediction. The proposed fatigue model is expressed in two tension-based and shear-based equations for two tensile and shear cracking failure modes. The model was validated against several experimental datasets available in the literature. In addition, obtained results were compared to predicted lives through some well-known fatigue models comprising maximum shear strain, Smith–Watson–Topper, and Fatemi–Socie. The results were strongly correlated with the experimental data indicating accuracy of the model.

1. Introduction

Fatigue is the principal cause of failures in many engineering components subjected to multiaxial loading. Multiaxial stress and strain states are partly due to the geometrical complexity of engineering components and complex loadings. Most in service components are subjected to multiaxial loading which is either proportional, with fixed principal stresses and strains directions, or non-proportional, with variable directions of principal stresses and strains during a cycle. In low cycle fatigue region, non-proportional loading is most often more damaging than proportional loading [1–3]. Changing directions of principal stresses and strains may result in additional hardening and consequently life reduction [4,5]. This fatigue life reduction under non-proportional loading is also attributed to the rotation of maximum shear stress planes which leads to initiating plastic deformation along several slip bands. Thus it is worthwhile to take into account the effect of loading path in fatigue life prediction. In order to quantify loading path non-proportionality and taking into account loading path effect on fatigue life, several works have been done and different non-proportionality factors have been developed.

Kanazawa et al. [6] studied cyclic deformation of 1% Cr–Mo–V steel under non-proportional loading. For explaining the difference between cyclic deformation under proportional loading and non-proportional loading, they proposed a rotation factor in terms of shear strain range experienced by critical plane. The rotation factor can be used for defining the non-proportionality of loading path. Another well-known approach for defining non-proportionality factor of loading is the longest chord [7]. This approach defines non-proportionality as half the length of the longest chord between two points in the shear stress path. In minimum circumscribed ellipse approach [8], non-proportionality is defined as ratio of minor to major chord ratio of the ellipse circumscribed the strain path. Chen et al. [9] proposed non-proportionality factor as ratio of a circle area with a radius equals the maximum shear strain to the swept area by maximum shear strain in different directions in polar coordinates.

Fatigue models do not predict a higher level of damage under non-proportional loadings than proportional loadings [10–12], this leads to over-estimated fatigue life for non-proportionality sensitive materials under non-proportional loadings [10,11].

This study proposes a novel fatigue model based on virtual strain energy (VSE). Liu calculated the VSE using two crack initiation modes and two Mohr's circles [13]. The proposed model separates loading paths based on their non-proportionality where directly takes into account the loading non-proportionality in fatigue life prediction. The fatigue model is proposed in two shear-based and tension-based formulations for two tensile and shear cracking failure modes. The modeling results were validated against several experimental datasets available in the literature including different loading paths and materials such as Inconel 718, 304 steel, 1045 Steel, S460N, 30CrNiMo8HH, and Titanium TC4.

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Moreover, obtained results were compared to predicted lives through some well-known fatigue models comprising maximum shear strain, SWT, and Fatemi–Socie. The amount of error in fatigue life prediction for all models and all loading paths was calculated and discussed.

2. Fatigue life predication

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

2.1. Maximum shear strain

The most common reason of fatigue crack initiation is the localized plastic deformation inside persistent slip bands. The directions of these slip bands always trend to align with maximum shear strain direction. Hence, fatigue cracks are always found to initiate on maximum shear strain planes [14,15].

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

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

where $\gamma_{a,max}$ is maximum shear strain amplitude, τ'_f is torsional fatigue strength, γ'_f is torsional fatigue ductility coefficient, G is shear

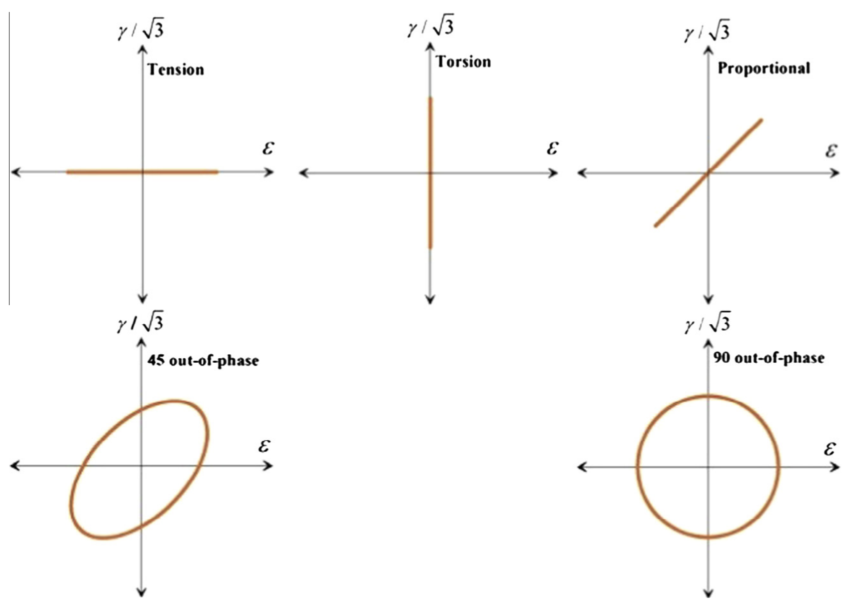

Fig. 1. Loading paths for Inconel 718 and titanium TC4.

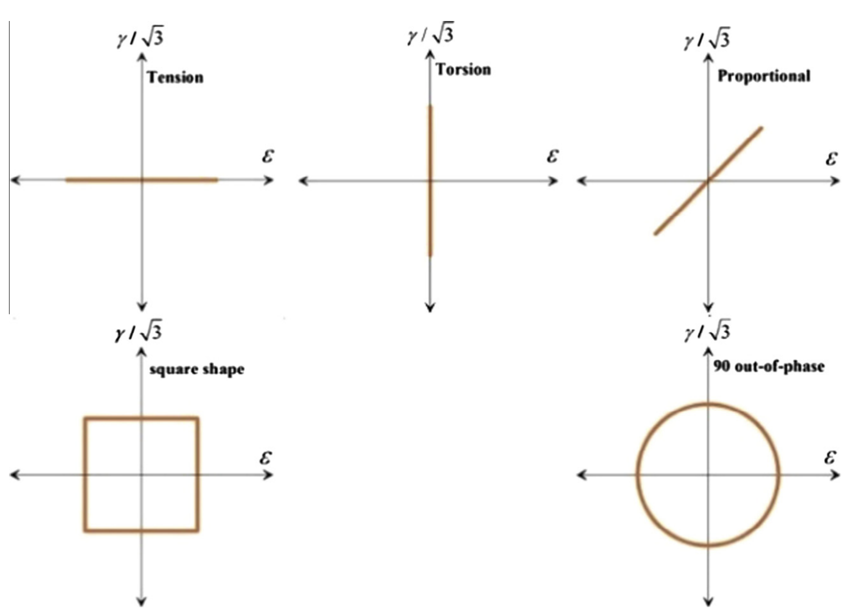

Fig. 2. Loading paths for 304 steel and 1045 steel.