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A damage mechanics approach to fretting fatigue life prediction with consideration of elastic–plastic damage model and wear

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ABSTRACT

In this investigation an approach to fretting fatigue life prediction is developed with consideration of damage-coupled elastic–plastic constitutive model and wear. Nonlinear kinematic hardening is employed in the analysis of elastic–plastic damage, and the total damage is divided into two parts, elastic damage and plastic damage, which are related to the cyclic stress and accumulated plastic strain, respectively. Wear is modeled by the energy wear law to simulate the evolution of contact geometry. A two dimensional plane strain finite element implementation is presented for fretting, including the case of partial slip and gross sliding. The progressive fatigue damage and wear is simulated and the results are compared with experimental data from the literature.

1. Introduction

Fretting is a contact damage process arising from surface micro-slip associated with small scale oscillatory motion of clamped structural members. The contact and relative slip between the components affect the nucleation of fatigue cracks significantly when compared to fatigue situations without fretting. Many components in real service are subjected to fretting, such as bolted and riveted connections, blade–disk attachment in gas and steam turbines [1], hip joint implants [2] and so on. Due to the complexity and the lack of understanding, around 50 variables have been identified as relevant to fretting [3], the effects of which on the fretting fatigue were analyzed in numerous studies. Jin and Mall investigated the influence of contact configuration [4] and slip amplitude [5,6] on fretting fatigue. The effect of contact pressure was studied in the works of Nakazawa et al. [7] and Ramakrishna et al. [8]. It is generally accepted that coefficient of friction, contact pressure and slip amplitude are the primary factor in fretting fatigue.

One approach adopted to predict fretting fatigue life is the critical plane approach, which is based on the multiaxial fatigue model. The method searches for the maximum fatigue parameter, such as Smith–Watson–Topper (SWT), over a number of planes and predicts fatigue life based on the maximum value. Szolwinski and Farris [9] extended a multiaxial fatigue theory that combines strain versus fatigue life ideas with a maximum normal stress to predict both the location of fatigue cracks and fretting fatigue life. Lykins and Mall [10] evaluated many parameters for predicting fretting fatigue crack initiation, such as strain based fatigue parameters, critical plane based fatigue parameters and Ruiz parameters. However, the critical plane approach employs fatigue parameter to predict fretting fatigue life, which reveals little characteristic of fatigue damage.

The damage mechanics approach also has been introduced to fretting fatigue problem and predicts the evolution of internal damage before macro-cracks become visible. The approach deals with the mechanical behavior of a deteriorated medium on macroscopic scale and evaluates progressive damage accumulated in material until damage reaches a critical value. Damage evolution law derived from thermodynamic is combined with damage-coupled constitution model of material to simulate the evolution of material damage. Zhang et al. [11] developed a coupled damage mechanics approach in conjunction with finite element analysis to predict fretting fatigue life and the results were compared with that predicted by the critical plane method. Hojjati-Talemi et al. [12] used an uncoupled damage evolution law to predict fretting fatigue crack initiation lifetime. Sadeghi et al. [13] proposed a damage mechanics approach, in which the material microstructure was modeled using Voronoi tessellation, to investigate the fretting fatigue, and the variability of fatigue life due to the randomness in material microstructure was also studied. The crack nucleation behavior of rough surfaces in line contact was investigated via damage mechanics method by Aghdam et al. [14]. The stress on the contact surface and sub-surface are used to estimate fretting fatigue life for the unworn and elastic loading case. However, the effect of wear caused by relative slip between the contacting components is not considered in the damage

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mechanics approaches mentioned above. Besides, plastic deformation can occur in the contact zone due to the evolution of contact geometry induced by wear [3]. The effect of cyclic plasticity needs to be considered when plastic deformation occurs.

The effect of wear on the contact surface and sub-surface contact variables, such as contact pressure, slip, stresses and critical plane parameters is widely studied. McColl et al. [15] developed a finite element simulation for fretting wear based on a modified Archard wear model. Madge et al. [16,17] combined modified Archard wear model with critical plane method to successfully evaluate the effect of fretting wear on fretting fatigue life. A combined finite–discrete element method was employed to model the fretting wear of coated and uncoated surfaces by Leonard et al. [18]. Zhang et al. [19] predicted fretting performance of two different contact geometries with the adoption of energy wear model proposed by Fouvry et al. [20]. The energy wear model has been shown to be superior to the Archard-based approach in that a single wear coefficient can be used across a range of fretting load–stroke combinations, specifically including both partial slip and gross sliding regimes [19]. Recently, Sadeghi et al. [21] proposed a damage mechanics approach to simulate wear at the level of material microstructure and the results of the simulation are compared with the Archard wear law. The damage mechanics approach was employed to simulate crack nucleation, propagation and element deletion, leading to the progression of the wear scar. When considering the effect of wear, the predicted fretting fatigue life is more reasonable, especially for the case of gross sliding. However, the fretting fatigue life was predicted by combining the critical plane fatigue model and wear model in the literatures [16,17,19] and the Miner–Palmgren rule was adopted to accumulate the fatigue damage, which is a linear accumulation law and ignores the effect of loading sequence. The damage accumulation is carried out after the numerical simulation of wear.

The present work is concerned with fretting fatigue crack initiation behavior. Fretting fatigue damage and wear is considered simultaneously in the damage mechanics approach. The effects of the fatigue damage and wear are coupled with each other. Damage evolution law and energy wear law are used to model the fatigue damage and wear based on the calculated stress and strain by damage-coupled elastic–plastic constitutive model, respectively. A numerical implementation of these models is developed with the commercially available ABAQUS finite element software to simulate the evolution of fatigue damage and wear scar. The predicted results are compared with experimental data from the literature.

2. Theoretic background

2.1. Damage-coupled elastic–plastic constitutive model

Lemaitre and Chaboche [22] have presented some fundamental concepts in damage mechanics. A number of continuum models and micromechanical models for material damage were presented in the literature [23]. Damage in its mechanics sense in solid materials is the creation and growth of micro-voids or micro-cracks which are discontinuities in a medium considered as continuous at a larger scale. A damage variable is introduced to estimate the progressive deterioration of material due to fatigue loading. In this study isotropic damage is assumed and the damage variable D is a scalar.

In the framework of small deformation, total strain ε_{ij} can be divided as

$$\varepsilon_{ij} = \varepsilon_{ij}^{e} + \varepsilon_{ij}^{p} \tag{1}$$

where ε_{ij}^{e} and ε_{ij}^{p} are elastic strain and plastic strain, respectively. In the damage-couple constitutive model, damage is coupled with elasticity and plasticity by using the effect stress instead of the stress in the elasticity law and Mises yield criterion based on the strain equivalent principle [24]. The elastic strain takes the form

$$\varepsilon_{ij}^{e} = \frac{1+\nu}{E}\left(\frac{\sigma_{ij}}{1-D}\right) - \frac{\nu}{E}\left(\frac{\sigma_{kk}\delta_{ij}}{1-D}\right) \tag{2}$$

where E, ν and σ_{ij} are elastic modulus, Poisson's ratio and Cauchy stress, respectively. The evolution of plastic strain is defined as

$$\dot{\varepsilon}_{ij}^{p} = \dot{\lambda}\frac{\partial F}{\partial \sigma_{ij}} \tag{3}$$

where $\dot{\lambda}$ is the plastic multiplier and F is the Mises yield function with damage defined as

$$F = \sqrt{\frac{3}{2}\left(\frac{s_{ij}}{1-D} - \alpha_{ij}\right)\left(\frac{s_{ij}}{1-D} - \alpha_{ij}\right)} - Q \tag{4}$$

where s_{ij} is the deviatoric part of stress and α_{ij} is the deviatoric part of back stress. Q is the radius of yield surface and its evolution is defined as

$$\dot{Q} = \dot{\lambda} b (Q_{\infty} - Q) \tag{5}$$

where parameters b and Q_{∞} are material constants determined experimentally. The rate equation of plastic strain is deduced as

$$\dot{\varepsilon}_{ij}^{p} = \frac{3}{2}\frac{\dot{\lambda}}{1-D}\frac{(s_{ij}/(1-D)) - \alpha_{ij}}{((s_{ij}/(1-D)) - \alpha_{ij})_{eq}} \tag{6}$$

Then the plastic multiplier $\dot{\lambda}$ is determined by applying the consistency condition

$$\dot{p} = \sqrt{\frac{2}{3}\dot{\varepsilon}_{ij}^{p}\dot{\varepsilon}_{ij}^{p}} = \frac{\dot{\lambda}}{1-D} \tag{7}$$

where $\dot{p}$ is the accumulated plastic strain rate.

For accurate estimation of the yield surface movement, the deviatoric part of back stress is divided into finite components. Each component is modeled based on the Armstrong and Frederick [25] nonlinear kinematic hardening (NLKH) model, which has the advantage of reducing the computational time due to the simplicity. It is to be noted that this model may overestimate the accumulation of plastic strain [26–28]. The evolution law of nonlinear kinematic hardening rule is

$$\alpha_{ij} = \sum_{k=1}^{M} \alpha_{ij}^{(k)} \tag{8}$$

$$\dot{\alpha}_{ij}^{(k)} = (1-D)\left(\frac{2}{3}C_k\dot{\varepsilon}_{ij}^{p} - \gamma_k \alpha_{ij}^{(k)}\dot{p}\right) \tag{9}$$

where C_k and γ_k are material constants also determined experimentally.

2.2. Damage evolution models

The contact conditions, including contact geometry and material properties, vary from cycle to cycle, leading to the occurrence of plastic strain. The elastic damage law [11,12] cannot simulate the evolution of damage for material point with plastic strain well. A plastic damage law is needed to model the plastic damage induced by the plastic strain. In general, the evolution of damage for a material point can be calculated by either the elastic damage evolution law or the plastic damage evolution law depending on the current stress status in a cycle [29]. However, the plastic strain in the fretting fatigue is small and only the plastic damage increment is not adequate to represent the evolution of damage when plastic deformation occurs. Therefore, the total damage is divided into two parts, elastic damage and plastic damage, in the present study. The elastic damage is merely dependent on the state of cyclic stress and the plastic damage is governed by the