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A continuum damage mechanics approach for fretting fatigue under out of phase loading

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ABSTRACT

The phenomenon of fretting fatigue involves multiaxial stress states near the contact interface and is mainly characterized by nucleation and propagation phases. Based on the mechanism of each phase, various approaches have been developed to predict damage initiation location and life. This paper aims to investigate the effectiveness of continuum damage mechanics (CDM) approach under in phase and 90° out of phase loading. Two cases with different material and loading conditions are considered for this analysis. The first case includes constant normal load and phase difference is generated between axial cyclic stress and tangential load. Whereas in the second case, cyclic normal load is applied and phase difference is generated between normal load and other two loads i.e. cyclic axial stress and tangential load. The results obtained using CDM approach are compared to those obtained using critical plane (CP) approach. The numerical results are also compared with experimental results from literature. It is observed that, both approaches provide good estimate of initiation location and life for in phase loading. With phase difference of 90°, the initiation locations also match well with the experimental results, however, for life estimation CDM approach has shown better prediction than CP approach, especially at lower loads. In addition, both approaches have shown that with phase difference of 90°, the fretting fatigue life increases as compared to in phase loading.

1. Introduction

Fretting introduces degradation of the material at and near the contact interface due to interaction of the contacting bodies. It can lead to wear [1–4] and development of micro cracks at the surface especially under fatigue load [5–8]. The presence of non-proportional loads can accelerate the failure process which involves nucleation and propagation phases. Researchers have used various approaches to model this failure process under fretting fatigue conditions. Some approaches include computation of both phases, whereas some approaches considers damage as a continuous process without distinction between both phases. The present work focuses on application of continuum damage mechanics (CDM) approach, which uses thermodynamics laws for damage accumulation and critical plane (CP) approach, where the damage parameters are computed on specific planes known as critical plane.

The CDM approach employs a damage variable, which constitutes an effective stress based on effective surface area as the damage nucleates. The damage is assumed to nucleate at certain threshold level and leads to initiation of crack on certain critical value of damage parameter. This approach was first introduced by Kachanov [9], and is based on thermodynamic principle, which allows to analyze the damage by coupling it with elasticity. Based on this concept, several theories have been developed and applied to different fields. Lemaitre introduced damage models based on CDM approach for low cycle fatigue [10] and for fatigue creep [11]. Chaboche [12] introduced a damage model for the case of high cycle fatigue. Later, Lemaitre introduced a model for ductile fracture [13]. Bhattacharya and Ellingwood [14] also presented a model based on CDM, which can predict damage initiation with the assumption that fatigue damage occurs before localization. Their model also accounts for mean stress effects, stress controlled and strain controlled loading cycle effects. Quraishi et al. [15] adopted Bhattacharya and Ellingwood model for fretting fatigue problems. They used tensile and compressive components of alternating shear stress to predict fretting fatigue life. Zhang

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et al. [16] developed non-linear continuum damage model and validated for uniaxial and multiaxial plain fatigue, notched and un-notched conditions. They also validated the model for fretting fatigue conditions using cylindrical pad and flat specimen. Based on Lemaitre work [17–19], a promising work is contributed by Hojjati-Talemi and Wahab, by formulating an uncoupled damage model for elastic [20] and elasto-plastic [21] conditions and applied to fretting fatigue problems. They developed a predictor tool to calculate fretting fatigue damage initiation location and life by combining CDM approach with finite element method.

The other popular approach that has been widely used to describe damage initiation in plain and fretting fatigue is CP approach. To incorporate the multiaxial nature of stresses, different multiaxial parameters compute damage on certain preferred planes. Mostly these planes are either maximum shear or maximum tensile stress planes. The multiaxial damage model for critical plane approach can broadly be divided into three categories. The first category comprises of shear stress based parameters, which are suitable to model high cycle fatigue. The most widely used shear stress based parameters are Findley parameter [22], McDiarmid parameter [23], Matake parameter [24] and Modified shear stress parameter [25]. The second category includes shear strain based parameters that are suitable to model low cycle fatigue region. The popular parameters of this category are Fatemi-Socie (FS) parameters [26], Brown and Miller parameter [27] and Lohr and Ellison parameter [28]. The last category uses both stress and strain terms to form virtual strain energy. The parameters include Smith-Watson-Topper (SWT) parameter [29], Liu I and II parameters [30] and Chen, Xu and Huang parameter [31]. The strain energy based parameters are applicable to both high cycle fatigue (HCF) and low cycle fatigue (LCF) regimes. In general, it is believed that damage nucleates on maximum shear stress or strain planes and grow either on maximum shear plane or perpendicular to maximum principal stress direction [25,26]. Critical plane approach also allows to study the initiation angles along with nucleation site and fretting fatigue life. Araújo and Nowell [32] established an averaging technique and combined with critical plane method for fretting fatigue problems, as higher stress gradients are present at the contact interface. Almajali [33] studied the effect of out of phase loading on fretting fatigue life using MSSR parameter for titanium alloy. Madge et al. [34,35] used critical plane approach to model combined effect of wear and fretting fatigue nucleation. Sabsabi et al. [36] used critical plane approach to model initiation phase and extended finite element method to model propagation phase. Halloran et al. [37] employed successfully critical plane approach to predict damage in 3D applications.

Although a lot of work has been done regarding formulation of CDM and CP approaches, but most of the work comprises in-phase loading and constant contact load under fretting conditions. The current work provides a comparison between CDM approach and CP approach with variable normal load and out of phase loading condition. For CDM approach, the HCF CDM model is used, while for CP approach, SWT and FS parameters are used. The SWT and FS parameters have been selected based on their capability to model failure predominantly under tensile and shear mode, respectively.

The objective of this study is to evaluate the effectiveness of CDM approach under out of phase loading and its comparison with CP models. The case of variable normal load is also considered in this study and its effect of phase difference (with axial stress and tangential load) on initiation life. The study of variable normal load is important in fretting fatigue because stick zone width changes with respect to time, which changes slip amplitude and consequently affects initiation life. The present study presents two cases with different loading conditions and materials. In case I, normal load is constant and phase difference is applied between axial cyclic stress and tangential load. The material used for this case is Al 2024-T351 and experimental data is taken from Ref. [38]. For case II, variable normal load is applied and phase difference is generated between this normal load and other two loads i.e. axial cyclic stress and tangential load. Ti-6Al-4V is used for this case and experimental data is taken from Ref. [33]. In the proceeding sections brief theoretical background is provided for both approaches. Then, details of experimental data and numerical implementation of both approaches is described. At the end, comparison of above mentioned approaches is given for both cases.

2. Continuum damage mechanics approach

This section introduces the background of CDM approach. After basic terms and variables, the damage equivalent stress criterion is described, which is used to determine initiation location at the contact interface. Further, the elastic damage model to obtain initiation life is also explained.

The CDM approach uses the concept of damage variable D that can be defined in a representative volume element. If A is the total surface area of the element and A_D is the area of the damage then the effective stress $\tilde{\sigma}$ resisting the applied load F can be calculated as [13]:

$$\tilde{\sigma} = \frac{F}{A - A_D} \tag{1}$$

The primary variable, which governs the damage phenomena is the strain energy density release rate Y [19], which is a function of total elastic strain energy density w_e and damage D.

$$Y = \frac{w_e}{1 - D} \tag{2}$$

$$w_e = \int \sigma_{ij}^D d\varepsilon_{ij}^D + \delta_{ij}\delta_{ij} \int \sigma^H d\varepsilon^{eH} \tag{3}$$

The linear elastic and isotropic law in conjunction with damage can be expresses as:

$$\varepsilon_{ij}^{eD} = \frac{1+\nu}{E}\left(\frac{\sigma_{ij}^D}{1-D}\right) \tag{4}$$

$$\varepsilon^{eH} = \frac{1-2\nu}{E}\left(\frac{\sigma^H}{1-D}\right) \tag{5}$$

$$w_e = \frac{1}{3}\left[\frac{1+\nu}{E}\left(\frac{\sigma_{ij}^D\sigma_{ij}^D}{1-D}\right) + 3\frac{1-2\nu}{E}\left(\frac{\sigma^H\sigma^H}{1-D}\right)\right] \tag{6}$$

$$Y = \frac{\sigma_{eq}^2}{2E(1-D)^2}\left[\frac{2}{3}(1+\nu) + 3(1-2\nu)\left(\frac{\sigma^H}{\sigma_{eq}}\right)^2\right] \tag{7}$$

The damage equivalent stress σ^* is defined as the uniaxial stress, which gives the same amount of elastic strain energy as a multiaxial state of stress [13]. By assuming $\sigma_{eq} = \sigma^*$, $\sigma^H = \sigma_{eq}/3$ and $R_\nu = 1$, the damage equivalent stress can be written as:

$$\sigma^* = \sigma_{eq}(R_\nu)^{1/2} \tag{8}$$

The above expression allows to interpret that nucleation is mainly caused due to the shear in slip bands and fracture is driven due to the influence of hydrostatic stress. The equivalent damage stress is based on total elastic strain energy but it does not take into account the effect of mean stress [18].

Hojjati-Talemi and Wahab [20] proposed an uncoupled damage evolution model. Based on Lemaitre work they derived a damage law for the case of HCF regime. For complete derivation readers are referred to [20]. Since in HCF the plasticity is negligible, therefore elastic damage model is selected to simulate the fretting fatigue behavior in the present work. According to this model the damage variable D can be expressed as a function of number of cycles as: