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Fretting fatigue damage nucleation under out of phase loading using a continuum damage model for non-proportional loading

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ABSTRACT

Damage nucleation involves creation of micro cracks, which are discontinuities in a material considered as continuous at a larger scale. Continuum Damage Mechanics (CDM) approach provides a tool to study damage nucleation under plane and fretting fatigue conditions. Under fretting fatigue conditions, the loading sequence may produce non-proportional stresses. This paper aims to investigate the effect of non-proportional loading on damage nucleation. For this purpose, a CDM based damage model for non-proportional loading is developed and applied to cylindrical pad and flat specimen configuration. The numerical results are also compared with experimental results from literature. It is found that, taking into account the triaxiality function variation in damage law, improves crack initiation lifetime estimation. In addition, a sensitivity analysis is performed by varying stress range and triaxiality function. It is found that for in phase loading only the stress range affects the initiation life, whereas, for out of phase loading both stress range and triaxiality function affect initiation life, especially at higher ranges.

1. Introduction

The damage in a material is a continuous physical process, which leads to the failure of material. Damage mechanics refers to the study of mechanisms involved in this deterioration process, using mechanical variables. At microscale, this process implicates the accumulation of micro stresses in the vicinity of defects and rupturing of bonds. At mesoscale, it characterizes the coalescence of the micro cracks or voids, which collectively can initiate a single crack [1]. Usually for analysis purpose, the representative volume element (RVE) of mesoscale is used to characterize nucleation process. Considering nucleation as a process [2], the start of the nucleation phase may be termed as damage initiation and end as crack initiation. Generally, crack initiation refers to the length of a flaw, which comprises few grains of the material.

The concept of continuous damage variable D was introduced by Kachanov [3], which was subsequently used as internal state variable in thermodynamics framework. This concept provided the basis for Continuum Damage Mechanics (CDM) approach. The CDM approach links the damage variable with an effective stress, based on effective surface area, as the damage accumulates. The damage is considered to initiate at a certain threshold level, which subsequently leads to initiation of crack at a critical value [4]. Rabotonov introduced the concept of effective stress [5]. According to the failure mechanism, several theories were introduced based on this concept. Lemaitre and his co-workers developed various damage models [6,7] and applied them to low cycle fatigue [8], fatigue creep [9], and ductile fracture [10]. Using thermodynamics laws, they proposed basic formulation to model coupling between strain and damage behaviour. The damage was considered as a scalar internal variable, which can characterize the strength loss of material in processes such as fatigue, creep or ductile strains. They presented a generalized scheme of structural calculations for crack initiation using coupled and non-coupled strain damage equations. Chaboche developed a non-linear continuous damage (NLCD) model for fatigue applications [11]. The NLCD model can be applied to analyze, one level and two level stress controlled fatigue tests, influence of mean stress, remaining life, block program loading conditions and LCF tests [12]. They included the effect of micro crack initiation and early propagation in the model. Later, by combining multiaxial fatigue criteria with von Mises, this model was extended to 3D case by Chaudonneret [13]. Zhang et al. [14] extended the work of Chaboche, Lesne and Chaudonneret. They developed an

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incremental NLCD model and applied to plain and fretting fatigue cases. They found that the implemented damage model, predicted longer life compared to integrated formula. However, the results showed a similar trend for predicted life and relative slip as shown by SWT parameter and experimental results. Bhattacharya and Ellinglwood [15] also introduced a model based on CDM approach. They conducted experiments on different steel and aluminium alloys and proposed a cumulative damage model, which incorporated the effect of mean stress, loading sequence, stress and strain controlled loading cycles. This model was extended for multiaxial loading and applied to fretting fatigue by Qureshi et al. [16]. A method of decomposition was based on resolving shear stresses into tensile and compressive components and assumed that only cyclic shear stresses contributed to damage nucleation. It was observed that alternating shear forces produced same effect as alternating tensile forces acting at 45° from the shear stress direction. Based on Lemaitre's model, Hojjati-Talemi and Abdel Wahab derived a damage model for high cycle fatigue (considering elastic state) and successfully applied it to the fretting fatigue problems [17]. The damage model was applied to determine initiation location and crack initiation life and showed good results in comparison to experimental results. In addition, they also derived a damage model for elasto-plastic condition [18] and applied to fretting fatigue case by combining extended finite element method and fracture mechanics. There are several other numerical crack analysis techniques, which considers damage in discrete sense, e.g. cracking particles [19,20], dual-horizon peridynamics [21,22] and screened Poisson method [23,24], however these methods have not been applied to fretting fatigue problems.

In fretting fatigue, the nucleation life is dependent on various factors like loading amplitude and sequence, material and surface properties. The combined effect gives rise to internal stresses, which determines the service life of the component. Due to contact condition, severe stress gradients are also present at the interface due to presence of tangential load [25]. As fretting fatigue involves multiple loads in different directions, therefore multiaxial and non-proportional stresses may be produced [26]. In addition, if a phase difference exists between the applied loads, the degree of non-proportionality between the stresses may be increased. Some researchers have shown that out of phase loading affected contact stress profiles, slip range, crack initiation location and life [27–29]. For multiaxial stress state, there is no definitively admitted scalar function of stress components, in the form of fatigue norm, which can be used to compare fatigue limit in tension such as von Mises yield criterion [4]. The fatigue damage model proposed by Lemaitre was based on triaxiality function and von Mises stress range, which was extended by Hojjati Talemi and Abdel Wahab as mentioned above. The previous work however was based on the assumption that triaxiality function does not vary with time. Since under non-proportional or out of phase loading conditions, it may vary with respect to time, in the present work the damage evolution law is extended, considering the variation of triaxiality function.

In this paper, a modified damage model based on CDM approach for non-proportional loading, is derived and implemented using Finite Element Method (FEM). The numerical results are compared with experimental results from literature. Sequence of paper includes the following sections. Section 2 presents brief introduction of CDM and two damage evolution models. Firstly, Continuum Damage Model for Proportional Loading (CDM-PL) is presented, followed by a Continuum Damage Model for Non-Proportional Loading (CDM-NPL). In section 3, material data and experimental details are presented. Section 4 describes the numerical model and the implementation of CDM-NPL. In the last part of the study, a comparison of crack initiation life using the two above mentioned damage models, with experimental results is presented. In addition, sensitivity analysis is preformed showing the effect of related parameters on crack initiation life using CDM-NPL model.

1.1. *Continuum damage mechanics (CDM)*

According to thermodynamics principles, the fundamental variable, which initiates damage, is the strain energy density release rate $-Y$, which can be expressed as [10]:

$$-Y = \frac{\sigma^{*2}}{2E(1-D)^2} = \frac{S^2 R_\nu}{2E(1-D)^2} \tag{1}$$

$$R_\nu = \frac{2}{3}(1+\nu) + 3(1-2\nu)\left(\frac{H}{S}\right)^2 \tag{2}$$

The strain energy density depends on von Mises equivalent stress S and triaxiality function R_ν, which includes the effect of Poisson's ratio and triaxiality ratio ($T{=}H/S$). Here, H represents the hydrostatic stress. The damage process is influenced by triaxiality ratio as damage is the debonding from atomic level to mesoscale level. For non-proportional or out of phase loading, the triaxiality ratio varies with time and hence the triaxiality function. By defining the damage equivalent stress $\boldsymbol{\sigma}^*$ as the uniaxial stress, which gives the same amount of elastic strain energy as a multiaxial state of stress, the equality for total strain energy leads to [10]:

$$\sigma^* = S(R_\nu)^{1/2} \tag{3}$$

The above equation, shows that the damage equivalent stress $\boldsymbol{\sigma}^*$ includes the triaxiality function in addition to von Mises stress, which makes it suitable for application to multiaxial cases. The von Mises stress can be used to determine plastic stress state, which occurs mainly due to slips at molecules level and does not depend on hydrostatic stress.

1.2. *CDM for proportional loading (CDM-PL)*

In this section the CDM model introduced by Lemaitre [1] and extended by Hojjati-Talemi and Abdel Wahab [17] is presented. They applied the damage model (CDM-PL) successfully to fretting fatigue damage initiation cases. However, this model assumes that the triaxiality function does not vary with time. The dissipation potential function, which combines strain energy release rate and damage variable can be written as [1,17]:

$$\varphi = \frac{C}{(s_o/2)+1}\left(\frac{-Y}{C}\right)^{(s_o/2)+1}(-\dot{Y}) \tag{4}$$

Where, C is the damage strength of the material, s_o is the damage exponent and Y is the strain energy density release rate. By differentiating Eq. (4) and assuming linear accumulation of strain energy with respect to time ($\dot{Y}$=constant), the damage evolution can be written as:

$$\dot{D} = -\frac{\partial\varphi}{\partial Y} = \left(\frac{-Y}{C}\right)^{\frac{s_o}{2}}(-\dot{Y}) \tag{5}$$

Differentiating Eq. (1) with respect to time:

$$-\dot{Y} = \frac{2S\dot{S}R_\nu}{2E(1-D)^2} \tag{6}$$

Inserting Eqs. (1) and (6) in Eq. (5) and simplifying, Eq. (5) becomes:

$$\dot{D} = \alpha\left(\frac{S^{s_o+1}R_\nu^{(s_o/2)+1}}{(1-D)^{s_o+2}}\right)\dot{S} \tag{7}$$

where

$$\alpha = \frac{2}{C^{s_o/2}(2E)^{(s_o/2)+1}} \tag{8}$$