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# A numerical investigation on critical plane orientation and initiation lifetimes in fretting fatigue under out of phase loading conditions

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ABSTRACT

This study focuses on application of critical plane approach to in-phase and out-of-phase loading conditions in fretting fatigue problems. The efficacy of various multiaxial damage criteria is analysed to determine critical plane orientation and initiation life, and is investigated for the first time in case of out-of-phase loading condition. Furthermore, our study focuses on the estimation of initiation angle and initiation lives using multiaxial damage criteria. For analysis purpose, the damage criteria are categorized as stress-based (Findley parameter and McDiarmid criterion), strain-based (Brown-Miller criterion and Fatemi-Socie criterion) and virtual strain energy-based (Smith-Watson-Topper criterion and Liu 1 and 2 criteria). It is observed that shear stress and shear strain-based criteria are able to predict both critical plane orientation and fretting fatigue lifetimes, whereas energy-based criteria, which employ normal stress and strain, are only suitable to predict initiation life. The deviation in estimation of initiation life for stress-based criteria is observed to be higher than others if the internal stresses are higher than yield stress. It is shown that initiation can occur on either of the preferred shearing plane depending upon material and loading conditions. The phase difference of 90° and 180° increases and decreases the initiation life respectively as compared to in-phase loading. In addition, 90° phase difference introduces more shearing planes for damage nucleation.

## 1. Introduction

The presence of fretting decreases the fatigue performance of materials and is a major source of premature failure in contacting bodies. Failure process is widely accepted as a combination of initiation and propagation phase. The initiation of damage requires reversal of shear stress to form a slip band, the more severe the reversing state of stress, the higher are the chances to form a slip band [1]. This implies that tangential load together with contact load, coefficient of friction and relative slip play a key role in damage nucleation process. The propagation phase on the other hand is assisted dominantly by tensile load [2]. The number of cycles to failure for any particular phase is also dependent on the definition of initiation phase [3]. Fretting fatigue takes place in partial slip regime, however in gross sliding regime, fretting wear is most likely to occur [4–6].

Researchers have adopted different approaches to model fretting fatigue phenomena, e.g. equivalent stress-strain approach, continuum damage-mechanics approach and critical plane approach. The latter however has an advantage over others to predict initiation angle also and therefore it is employed in this study. Szolwinski and Farris [7] studied the fretting fatigue crack formation for Al 2024-T351. They combined stress field with multiaxial fatigue theory to predict initiation site and life for fretting fatigue cracks. They showed that Smitth Watson Topper (SWT) parameter predicted initiation location successfully and combining SWT parameter with strain-life equation provided good estimation of initiation life under fretting fatigue conditions. Lykins et al. [8] studied several fretting fatigue parameters including strain-life parameter, maximum strain corrected for strain ratio effects, maximum principal strain corrected for principal strain ratio effects, critical plane SWT, Fatemi-Socie (FS) and fretting specific Ruiz parameter, for Ti-6Al-4V to determine initiation location and life. They demonstrated that except strain-life and FS parameter all other parameters were equally effective in predicting initiation life under different stress ratios, however all parameter were able to capture initiation location. Later, Lykins et al. [9] used two critical plane approaches SWT and maximum shear stress range (MSSR) parameters to determine initiation life, location and angles.

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**Nomenclature**

| | |
|---|---|
| $P$ | Normal contact load |
| $\sigma_A$ | Applied axial stress |
| $Q$ | Tangential load |
| $\nu$ | Poisson's ratio |
| $E$ | Modulus of elasticity |
| $R$ | Radius of pad |
| $R_\sigma$ | Stress ratio |
| $R_Q$ | Tangential load ratio |
| $\varphi$ | Phase difference |
| $\sigma_{u,}$ | Ultimate tensile strength |
| $\sigma_y$, $\tau_y$ | Tensile and shear yield strength |
| $\sigma_{f-1}$, $\tau_{f-1}$ | Tensile and shear fatigue limit |
| $\sigma'_f$ | Tensile fatigue strength coefficient |
| $\tau'_f$ | Shear fatigue strength coefficient |
| $\varepsilon'_f$ | Tensile fatigue ductility coefficient |
| $\gamma'_f$ | Shear fatigue ductility coefficient |
| $b$ | Fatigue strength exponent in tension |
| $b'$ | Fatigue strength exponent in torsion |
| $c$ | Fatigue ductility exponent in tension |
| $c'$ | Fatigue ductility exponent in torsion |
| $G$ | Modulus of rigidity |
| $a$ | Semi contact width |
| $\Delta\tau_{max}/2$ | Maximum shear stress amplitude |
| $\sigma_n^{max}$ | Maximum normal stress on plane |
| $k_1$ | Material constant for Findley parameter |
| $\Delta\gamma_{max}/2$ | /2 Maximum shear strain amplitude |
| $k_2$ | Material constant for BM and FS criteria |
| $\Delta\sigma_n$, $\Delta\varepsilon_n$ | Normal stress and normal strain range |
| $\Delta\varepsilon_1/2$ | Principal strain amplitude |
| $\Delta\varepsilon_n/2$ | Normal strain amplitude |
| $\sigma_{xx}$ | Normal stress in x-direction |
| $\tau_{xy}$ | Shear stress |
| $\Delta\tau$, $\Delta\gamma$ | Shear stress and shear strain range |
| $\theta_p$, $\theta_c$ | Principal and critical plane |
| $\bar{x}$ | Normalized mean of initiation life |
| $SD_x$ | Normalized standard deviation |
| $N_p^i$ | Predicted initiation life in cycles |
| $N_{exp}^i, N_i$ | Experimental life in cycles |
| $\sigma_{dc}$, $\varepsilon_{dc}$ | Stress and strain based damage criteria |
| $\Delta W_{dc}$ | Virtual strain energy based criteria |
| $\overline{X_i/a}$ | Mean normalized initiation location |
| $SD_N$ | Standard deviation |
| $R_{SD}$ | Standard deviation range |

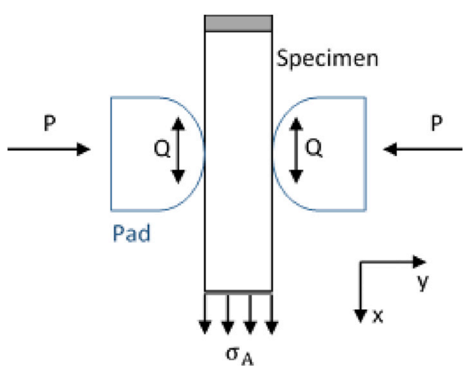


**Fig. 1.** Schematic of experimental setup, cylindrical pad with flat specimen.

Through combined experimental and numerical work, they showed that crack initiation was governed by maximum shear stress range plane. Namjoshi et al. [10] also noticed that initiation mechanism was governed by shear stresses, however, both normal and shear stresses on critical plane seemed to play a role in fretting fatigue life independent of pad geometry.

Araújo and Nowell [11] studied the critical stressed volume and developed the averaging method along with critical plane approach for the cases of rapidly varying contact stress fields. Their study showed that critical averaging dimension of the order of grain size provided more realistic estimate of fretting fatigue life. Sum et al. [12] applied critical plane approach to 3D aero-engine spline couplings to determine spline life and initiation site under fretting conditions. Their study showed that 3D results were identical to 2D results with small variation across the thickness directions. Proudhon et al. [13] investigated the effect of unidirectional surface roughness on nucleation and found that, with higher roughness, lower tangential force was required for initiation. For prediction of initiation site, process volume approach was used along with critical plane SWT parameter.

Most of the work in fretting fatigue is done with in-phase loading conditions [14,15], some researchers however have used out-of-phase loading as well. Lee and Mall [16] investigated the effect of phase difference between axial stress and tangential load. They found that relative slip and tangential force changed, for a given pad displacement and axial load, due to change in-phase difference. The fretting fatigue test with fully reversed axial stress showed longer life than with positive stress ratio. In addition, they noticed that critical plane based parameter (MSSR) was effective to take into account, the stress ratio effect. Almajali [17] studied the effect of phase difference between normal contact load and cyclic axial stress. They observed an increase in fatigue life for both in-phase and out-of-phase loading with decrease in axial stress range.

Navarro et al. [18] studied fretting fatigue life assessment for aluminium and titanium alloy with different geometries, sizes and contact forces using different damage criteria. They reported that total predicted life was sensitive to the depth at which stresses were evaluated. Further, they mentioned that the initiation phase was dependent on various factors like, failure criteria, material properties, geometry of the contact and applied forces. Sabsabi et al. [19] used experimental and numerical technique for estimating influence of stress intensity factor on total life estimation. They used critical plane approach to determine initiation phase and X-FEM to estimate propagation phase and observed that Fatemi-Socie and McDiarmid parameters correlated well with the experimental results. Li et al. [20] proposed a fretting related damage parameter based on experimental results and damage mechanism and showed that tangential force could be used to quantify the fretting effect. Further, they mentioned that modified strain-based criterion was more suitable to predict fretting fatigue life. Halloran et al. [21] analysed fretting variables in a 3D assembly using a critical plane approach. They showed that coefficient of friction had significant effect on predicted tensile stresses and hence on initiation life.

This paper is the continuation of the authors' previous work [22], which was related to damage initiation location. The current research however, focusses more on critical plane orientation and initiation lifetimes under out-of-phase loading condition. After providing brief introduction of various multiaxial damage criteria, detailed implementation of critical plane approach is discussed for in-phase and out-of-phase loading. Then, different criteria are compared to determine the critical plane orientation and initiation life. The numerical results are also