A review of FE on crack initiation in fretting fatigue

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Abstract: Fretting is a considerable failure mode in many mechanical components, in which two contact surfaces undergo a small relative fluctuating motion due to cyclic loading. This phenomenon has been observed in riveted joints, blade- disc attachment in turbine, wire ropes, shrink-fitted shafts, etc. Failure process of fretting fatigue is generally divided in two main phases: crack initiation and crack propagation. Although the study of crack initiation is at its early stages, it is a really hard research domain since initiation occurs at microscopic level. However, the study of crack initiation should be considered as a major task because the initiation can trigger a significant propagation during the fatigue life of mechanical components under some special circumstances. This task would be far more important when it comes to the case of fretting fatigue as cracks and damage areas are always concealed among the contact surfaces. Furthermore, the presence of the contact imposes a drastic stress concentration at the surface of the component, which leads to the initiation of micro cracks. Hence, applying numerical modeling techniques for analysing the crack initiation in fretting fatigue, in order to predict the fatigue life of the component, is a vital task. This paper presents a broad review of the available literature discussing numerical modeling of crack initiation in fretting fatigue. Outcomes will include a sound understanding of the use of finite element method, together with demonstrating an important assessment of the quality of the numerical results in comparison with experimental data.

Keywords: Fretting fatigue; Crack initiation; FE; CDM

1 INTRODUCTION

In fretting fatigue, the combination of small oscillatory motion, normal pressure and cyclic axial loading develops a noticeable stress concentration at the contact zone leading to accumulation of damage in fretted region, which produces micro cracks, and consequently forms a leading crack and can lead to failure. Many industrial mechanical components operate under fretting fatigue condition such as, blade-disc attachment in turbine, bolted joints, wire ropes, shrink-fitted shafts, etc. Hence; applying a conservative design in order to compensate for the negative effects of fretting fatigue in such components would be inevitable. Studies show that in most of the failures occurring under high-cycle fatigue (HCF), a large portion of fatigue life is spent in crack initiation [1] (up to 90% in some cases) and the rest is devoted to crack propagation. This matter clearly shows the importance of achieving a more precise understanding of crack initiation process in fatigue-related components. This task would be far more important when it comes to the case of fretting fatigue as cracks and damage areas are always concealed among the contact surfaces.

Many studies have been done to investigate the bahaviour of multiaxial fatigue over the last hundred years. One of the very first studies in the field of multiaxial fatigue belongs to Lanza [2], who carried out experimental tests under combined bending and torsion loading. Later attempts [3-6], provided empirical criteria in order to determine fatigue life of metals under muliaxial cyclic loading. Although there are many criteria currently existing for multiaxial fatigue problems, there is no global model suitable to predict fatigue life of any material under various loading conditions. Among different criteria proposed for multiaxial fatigue, some models show a good agreement with fretting fatigue problems as well. Majority of these models are capable of predicting number of cycle to crack initiation, location and orientation of crack initiation.

Majority of multiaxial fatigue criteria are based on critical plane approach which can be generally classified into three main categories: Stress criteria, strain criteria and energy criteria. Based on which approach is used, critical plane is located by using FE analysis based on the experimental data. In recent years, new approaches (such as continuum damage mechanics) have been applied to predict fatigue initiation life. This paper provides an overview of the most important FE-based mutiaxial criteria covering fretting fatigue crack initiation life.

2 STRESS BASED CRITERIA

2.1 Effective stress criterion (Walker criterion)

A method proposed by Walker [7] (Eq. (1)) can be considered as the simplest criteria to investigate fatigue life which has been used in fretting-fatigue in some literatures. The concept, as Eq.(1) states, is based on the applied stress range ($\Delta\sigma$) or a variation thereof to consider the effect of mean stress or stress ratio on fatigue life.

$$\sigma_{\mathrm{effective}=\sigma_{\max}\,(1-R)^{m}} \tag{1}$$

In Eq. (1), $\sigma_{\mathrm{effective}}$ is the effective stress to take into account the stress ratio effect, $\sigma_{\max}$ is the maximum stress applied on the sample, R is stress ratio and m is fitting parameter that can be optimized to collapse the fretting fatigue life data from different stress ratios on to a single curve.

2.2 Shear stress range criterion (SSR)

It has been shown that there is a relation between crack location caused by fretting fatigue failures and the maximum shear stress [8]. According to shear stress range parameter (SSR) proposed by Lykins et al. [9], critical plane in which crack initiates is where the value of shear stress range , $\tau_{\mathrm{crit}} = \tau_{\max} - \tau_{\min}$, Eq. (2), reaches its maximum amount. For the specimen under fatigue loading condition, maximum shear stress is computed on all planes at different angles ranging from $-90^0 \leq \theta \leq 90^0$ on the contact zone by using FE analysis. Lykin et al. then used a similar method suggested by Walker [7] in order to take shear stress ratio into account. Hence, the Shear stress range critical plane parameter is as follows:

$$\mathrm{SSR} = \Delta\tau_{\mathrm{crit}} = \tau_{\max}(1 - R_{\tau})^{m} \tag{2}$$

In which, $\tau_{\max}$ is the maximum shear stress on the critical plane (the plane in which τ is maximum) obtained by FE or any analytical solution, R_{τ} is the shear stress ratio on the critical plane ($R_{\tau} = \tau_{\max}/\tau_{\min}$), and m is a fitting parameter which is equal to 0.45 based on data obtained from plain fatigue.

Figure 1 shows initial crack path for one of the experiments carried out by [9]. As it can be clearly seen from Figure 1, crack orientation angle based on experimental observation is $\theta = -45^{\circ}$ or $\theta = 43^{\circ}$ whereas the angle predicted by SSR criterion was $\theta_{\Delta\tau} = 38^{\circ}$ or $\theta_{\Delta\tau} = -52^{\circ}$.

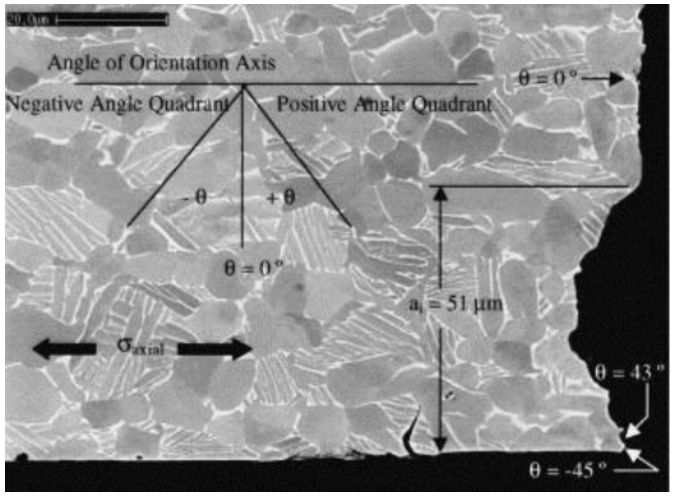

Figure 1. Experimental obserevation of initial crack path in a specimen under fretting fatigue loading

Using SSR parameter, they also suggested a relation for the number of cycles to the crack initiation (N_i). Based on $\tau_{crit} - N_i$ curve, driven either from plain fatigue or fretting fatigue initiation data, a curve which falls over $\tau_{crit} - N_i$ with a reasonable scatter band was formed as follows:

$$\Delta\tau_{crit} = C_1\,(N_i)^{C_2} + C_3(N_i)^{C_4} \tag{3}$$

In Eq. (3), $C_{1,2,3,4}$, are fitting parameters.

There are two perpendicular planes which include maximum shear stress range, and θ corresponding to them is considered as predicted orientation angles, $\theta_{\Delta\tau}$, for crack initiation.

In other fretting – fatigue related studies which SSR parameter was applied, there was a good agreement between experimental test and FE prediction in case of the number of cycles to crack initiation, angle of crack initiation and also crack location (which is always near the trailing edge) [1,10].

2.3 McDiarmid criterion

McDiarmid found out that in high cycle fatigue, maximum shear stress range has a noticeable impact on fatigue life. According to this criterion, the critical plane is the plane of maximum shear stress range and he proposed some fatigue criteria based on critical plane occurring on the maximum shear stress range. One of these criterions which is being used in the study of multiaxial fatigue is proposed as follows [11]:

$$\sigma_{eq} = \frac{\Delta\tau_{max}}{2} + \frac{\tau_f}{2\sigma_u}\sigma_{n,max} \tag{4}$$

In which, $\Delta\tau_{max}$ is the maximum shear stress range, $\sigma_{n,max}$ is the maximum normal stress on the plane of $\Delta\tau_{max}$, τ_f is shear fatigue limit and σ_u is the tensile strength. Navarro et al. [12] combined Basquin equation [13] $\left(\frac{\Delta\sigma}{2} = \sigma_f'(2N_i)^b\right)$ and considering a symmetrical cycle$\pm\sigma$, Eq. (5) is converted to the following relation to provide the number of cycles to crack initiation.

$$\sigma_{eq} = \frac{1}{2}(1 + \frac{\tau_f}{2\sigma_u}) \times \sigma_f'(2N_i)^b \tag{5}$$

In case of fretting fatigue problems, McDiarmid has been used in few studies [12, 14, 15], though, it is able to provide crack initiation orientation and location as well as the number of cycles to initiate.

2.4 Ruiz criterion

Ruiz et al. [16], based on an investigation of fretting fatigue in a dovetail joint, proposed two parameters to show the probability of crack initiation only during fretting fatigue loading condition. First parameter, $R_1 = \tau\delta$, which is a multiplication of the maximum surface shear stress and slip amplitude at any point in the contact zone, is considered as a criteria for fretting fatigue damage. In other word, the likelihood of fretting fatigue damage could be reduced by reducing shear stress or slip amplitude. Since this parameter only deals with crack nucleation, they therefore proposed another parameter(R_2), in order to take into account crack initiation as well by applying surface tangential stress(σ) to the first parameter. Hence, Ruiz' second parameter was proposed as follows:

$$R_2 = \sigma\tau\delta \tag{6}$$

Though these parameters have shown a good agreement with the location of crack initiation in some literatures [16-18]; however, some contradictory cases have been reported as well. For example, in the study done by Lykins et al. [9] which was an investigation on the fretting fatigue crack initiation of titanium alloy, Ti-6A1-4V,there was no agreement between the number of crack initiation with R_2 parameter, though it predicted the location of crack initiation near the trailing edge.

2.5 Findley criterion

Findley criterion is a linear combination of shear stress (τ_a) amplitude and maximum normal stress (on the plane of (τ_a) multiplied by a material constant (k) [19], Eq. (7).

$$F = \tau_a + k\sigma_{max} \tag{7}$$

This parameter was composed for proportional combination of bending and torsion loading. However, it has been applied for fretting fatigue conditions in several studies. Based on this parameter, the plane which has the greatest value of F is considered as the critical plane. As it can be seen clearly from Eq. (7), Findley parameter is always influenced by shear stress amplitude. This is in contradiction with those problems, which are expected critical plane occurs in the plane of the maximum normal stress (for instance: brittle materials under tension-compression tests). In case of fretting fatigue problems, there are some studies in which Findley parameter was applied in order to investigate the initiation life [1,20].

Namjoshi et al. [1] investigated fretting fatigue crack initiation in titanium alloy, Ti-6Al-4V, both experimentally and analytically by using FE analysis. For test of accuracy of Findley parameter by using FE analysis, they managed to find the plane with the highest value of F at all points on all planes ranging from $-90^0 \leq \theta \leq 90^0$ with 0.1° increment. They concluded that this parameter has not a strong reliance on pad geometry (whereas SSR parameter shows a dependence on pad geometry). Since data obtained from fretting fatigue life was not in agreement with plain fatigue ones, they came to this conclusion that predicting fretting fatigue life from plain fatigue data is not realistic. Crack orientations predicted by Findley parameter were not in agreement with experimental observations, though it predicted the location of crack near trailing edge.

3 STRAIN BASED CRITERIA

3.1 Fatemi and Socie criterion (F-S)

Based on a previous relation proposed by Brown and Miller [21], which is a linear combination of maximum shear strain (γ_{max}) amplitude and maximum normal strain (on the plane of (γ_{max}) multiplied by a material constant (S), Fatemi and Socie [22] suggested a new relation. According to experimental observations, they found that fatigue life for the specimens under torsion is longer than that of under tension and attributed this effect to the frictional force induced during shear loading. Therefore, in order consider the above mentioned effects, Fatemi and Socie proposed their relation as follows:

$$\gamma_{max}\left(1+k\frac{\sigma_n^{max}}{\sigma_y}\right)=\frac{\tau_f^{'}}{G}(2N_i)^{b^{'}}+\gamma_f^{'}(2N_i)^{c^{'}} \quad (8)$$

In Eq. (8), the right hand side term is considered as F-S parameter and critical plane is the plane with the highest amount of F-S. This parameter is considered as one of the most important criteria in the study of multiaxial fatigue. It has been applied in a few studies of fretting fatigue as well to investigate initiation life (by using FE analysis). As it can be seen from Eq. (8), FE parameter is able to determine the number of cycles to crack initiation (N_i). Meanwhile, by using FE methods, critical plane (which has the highest value of FS parameter) is specified among all points on all planes ranging from $-90^0 \leq \theta \leq 90^0$ with 0.1° increment and consequently the crack initiation location is found. Lykins et al. [9] in a study carried out on the fretting fatigue initiation life in titanium alloy, Ti-6A1-4V, applied FS parameter to evaluate its accuracy. Their results show, though, there is a relative difference between plain fatigue and fretting fatigue data, FS parameter is able to predict crack initiation location.

4 ENERGY BASED CRITERIA

4.1 SWT criterion

Smith, Watson and Topper, proposed a simple relation (Eq. (9)) to predict fatigue life for problems in which crack is inclined to grow in mode I (problems under uniaxial tension-compression).

$$SWT=\sigma_{n,max}\frac{\Delta\varepsilon_1}{2} \quad (9)$$

And the relation for the number of cycles (N_i) based on SWT parameter can be expressed as follows:

$$SWT=\frac{\sigma_f^{'2}}{E}(2N_i)^{2b} \quad (10)$$

According to SWT parameter, critical plane is a plane in which principal strain range ($\Delta\varepsilon_1$) reaches to its maximum value. In Eq. (9), $\sigma_{n,max}$ is the maximum normal stress in the plane of $\Delta\varepsilon_1$. Due to rotation of principal directions in non-proportional loading, using this parameter for such conditions seems to be difficult. Socie [23] tried to apply SWT parameter for crack nucleation in tension and torsion tests of AISI type 304 stainless steel tube-shaped samples. In correlating SWT parameter with such loading conditions and also having more simplification, he therefore assumed that in such problems; nucleation occured in a plane in which the combination of principal strain range multiply the maximum normal stress reached its maximum amount (Eq. (11)).

$$SWT=(\sigma_{max}\frac{\Delta\varepsilon}{2})_{max} \quad (11)$$

This parameter is being used very often for analyzing fatigue life under multiaxial loadings. It is also being applied in fretting fatigue problems [9,10,14]. In a research done by Szolwinski et al. [24], a numerical modeled was written by using FORTRAN in order to evaluate the assumption proposed in [23] for evaluating fretting fatigue crack nucleation. To achieve that aim, the numerical model was verified by experimental results obtained in a previous study [18]. The numerical model was able to predict crack location and its orientation.

5 CONTINUUM DAMAGE MECHANICS CONCEPT (CDM)

Apart from existing analytical models, which are mainly based on critical plane approach, for multiaxial fatigue problems, there are some other techniques have been used to deal with fretting fatigue related problems in recent years and Continuum Damage Mechanic (CDM), is one of these methods. Since existing analytical relations normally need some constants (e.g. materials contestants) to be experimentally determined, using CDM approach sounds to be a promising step in dealing with fretting fatigue initiation life issue. In addition to previous approaches in modeling damage in CDM [25, 26], Bhattacharya et al. [27] by considering a state of thermodynamic equilibrium for fatigue damage before nucleation, proposed a new framework for damage accumulation. Based on this model (which is not dependent on the arbitrary parameters used in previous approaches), fatigue damage could be obtained recursively as function of the number of cycles.

Quraishi et al. [28] used the model developed by Bhattacharya et al. [27] for predicting fretting fatigue life. Considering that the maximum shear stress cause cracks, they developed a programme to compute subsurface shear-stress distribution induced by fretting loading and locating corresponding principal plane position. Their developed programme is able to predict the number of cycles to failure (crack nucleation) for a given load, bulk material properties and coefficient of friction (Eq. (12)).

$$D = 1 - F^{2N} \tag{12}$$

In Eq. (12), D is damage parameter, F is obtained from an equation based on the loading conditions and material properties and N is the number of cycles to failure. Although their proposed model shows a good agreement with some published empirical data; however, assumptions considered in the model might reduce its accuracy in predicting the fatigue life under different loading conditions. For example, the damage parameter (D_c) was considered to be constant, whereas in changes with temperature and increase in fluctuation frequency in fretting condition leads to increase in temperature in the contact zone.

Zhang et al. [29] developed a FE based model coupled with multiaxial incremental non-linear continuum damage (NLCD) in order to validate for plain fatigue life estimation on tensile specimens with and without notches. This model was applied for fretting fatigue conditions (for small relative slip regime where the wear existence is not considerable) as well. Since their model provides a sound understanding of distribution of the high stress gradient, the estimated life is longer than that of predicted by integrated formula. Moreover, location of crack initiation was in agreement with experimental observations.

More recently, Hojjati-Talemi and Wahab [30] , based on thermodynamics potential function introduced by Lemaitre [31] and using maximum principal strain criterion coupled with CDM, developed a model to predict fretting fatigue initial life. Their proposed relation for the number of cycles to crack initiation (Eq. (13)) shows a good agreement between computed numerical results and previous experimental studies.

$$N_i = \frac{1}{A(\beta+3)} (\sigma_{eq-max}^{\beta+2} - \sigma_{eq-min}^{\beta+2})^{-1} R_v^{-(\beta/2)-1} \tag{13}$$

In Eq. (13), N_i is the number of cycles to crack initiation, A and β are material constants, σ_{eq-max} and σ_{eq-min} , are the maximum and minimum von Mises stress respectively and R_v is the triaxiality function.

5 CONCLUSIONS

This paper provides an overview of the most important FE-based mutiaxial criteria covering fretting fatigue crack initiation life. The most important key points from this paper are as follows:

1- Among different criteria proposed for multiaxial fatigue, some models show a good agreement with fretting fatigue problems as well.

2-Majority of these models are based on critical plane at a critical point.

3- Majority of these models are capable of predicting number of cycle to crack initiation, location of crack initiation and orientation of crack initiation.

4-In critical plane approach, critical plane is based on either maximum shear stress (strain), maximum normal stress (strain) or a combination of both.

5-Crack initiation could be generally divided to: crack nucleation and crack propagation from a nucleated size to a detectable size. Therefore, using a parameter based on the combination of mximum normal stress and shear stress seems to be more reasonable.

6-Apart from critical plane criteria, some new techniques have been proposed to analyse fretting fatigue initiation life. Coupling Continuum Damage Mechanics with critical plane criterion leads to interesting results which is in a good agreement with previous experimental studies. Normally, the advantage of this model is that the model is not dependent on the arbitrary parameters used in previous approaches and fatigue damage could be obtained recursively as function of the number of cycles.

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