Numerical modelling of fretting fatigue

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Abstract. Fretting fatigue is a consequence of small oscillatory movement between two contacting parts. This type of damage may give rise to significant reduction in fatigue life of the components. Many parameters such as contact geometry, contact load, friction, material strength and hardness can influence the resistance of materials against fretting damage. Experimental study of fretting fatigue parameters such as crack length measurement at the initial stages of crack growth is either very difficult or not very accurate. Numerical simulations provide a suitable tool for parametric study of fretting fatigue behavior of materials and in particular crack growth measurement. In this work, the effect of pad geometry on crack propagation is investigated by numerical simulation. The simulations are carried out using the finite element codes ANSYS and FRANC2D/L and are validated by the results of some fretting fatigue tests. It is shown that the simulations can predict the crack growth and the number of cycles from the principals of fracture mechanics.

1. Introduction

Fretting fatigue damage occurs in contacting components when they are subjected to oscillating loads and sliding movements at the same time. This phenomenon is schematically shown in Figure 1. The fretting fatigue resistance of materials may be affected by many parameters such as contact pressure, p, axial stress, \( \sigma \), friction between the pads and the specimen, pad geometry and sliding amplitude.

![Figure 1. Schematic illustration of fretting fatigue.](image)

This phenomenon may occur in many applications such as bearings shafts, bolted and riveted connections, steel cables, steam and gas turbines [1] and [2]. Fretting fatigue in turbine dovetails is illustrated in Figure 2.[2]. Fretting fatigue may reduce the endurance limit of a component by half or more, in comparison to the normal fatigue conditions. Wear and fretting cracks are two direct consequences of fretting fatigue. Figure 3 shows deep pitting in the contact zone of two specimens under fretting fatigue conditions.
fatigue phenomenon can be characterized. Fretting fatigue has extensively been studied by time consuming. Numerical sim

The study of the influence of various parameters on fretting fatigue behavior of materials is costly and expensive. Fretting fatigue is a complex phenomenon that involves the interaction of several factors, including contact geometry, contact stress, and friction. It is generally thought that crack initiation is governed primarily by the local contact stresses and propagation is more related to the far-field or bulk stresses. A micrograph of fretting crack propagation in a stainless steel alloy is depicted in Figure 5. The crack trajectory can be explained by stress intensity factors $K_I$ and $K_{II}$. Cracks initially grow oblique to the direction of normal force [4] (see figure 5). At this stage, which corresponds to a gross slip conditions between contacting surfaces, the effect of friction force prevails and $K_{II}$ is the dominant mode of fracture. After the initial oblique propagation, the angle of crack gradually reduces and finally crack coincides with normal force direction. This stage corresponds to a state of partial slip in which a combination of the effects of modes $K_I$ and $K_{II}$ takes place. In the third stage, crack grows perpendicular to the normal load direction, by shear due to tensile stress, only by mode $K_I$.

Figure 4 shows a fracture surface of a specimen after failure by fretting fatigue [3]. The figure clearly indicates that the fracture surface consists of three quite distinct regions; a fretting fatigue zone created by crack propagation, a crack growth zone and a tensile region which gives rise to fracture of specimen when it is sufficiently weakened by the crack zone development. It is generally thought that crack initiation is governed primarily by the local contact stresses and propagation is more related to the far-field or bulk stresses. A micrograph of fretting crack propagation in a stainless steel alloy is depicted in Figure 5. The crack trajectory can be explained by stress intensity factors $K_I$ and $K_{II}$. Cracks initially grow oblique to the direction of normal force [4] (see figure 5). At this stage, which corresponds to a gross slip conditions between contacting surfaces, the effect of friction force prevails and $K_{II}$ is the dominant mode of fracture. After the initial oblique propagation, the angle of crack gradually reduces and finally crack coincides with normal force direction. This stage corresponds to a state of partial slip in which a combination of the effects of modes $K_I$ and $K_{II}$ takes place. In the third stage, crack grows perpendicular to the normal load direction, by shear due to tensile stress, only by mode $K_I$.

The study of the influence of various parameters on fretting fatigue behavior of materials is costly and time consuming. Numerical simulation is a cheap and easy to use tool by means of which fretting fatigue phenomenon can be characterized. Fretting fatigue has extensively been studied by experiments. However, the number of numerical work in the context of fretting fatigue such those reported by Fadag et al. [6] and Naboulsi and Mall [7] is few. In the present work, the effect of contact geometry is studied using numerical codes such as ANSYS [8] and FRANC2D/L [9]. The

Figure 2. Fretting fatigue in turbine dovetails [2].

Figure 3. Deep pitting in the contact zone of two specimens under fretting fatigue conditions [3].

Figure 4. Fracture surface of a specimen after failure by fretting fatigue [3].

Figure 5. A micrograph of a fretting crack propagation in a stainless steel alloy [5].
numerical results are validated by a number of fretting fatigue tests. The experiments are carried out on Al7075-T6 using a crank variable device [10].

2. Test rig and specimens
The fretting fatigue testing device used in this work has been developed by Majzoobi and Hojjati et al. [10]. A general view of the device and its diagrammatic representation are illustrated in Figure 6. The axial fluctuating load is applied to the specimen by a variable crank mechanism. The mechanism consists mainly of a stepped eccentric shaft and two suspension plates [10]. The contact loading system, shown in Figure 7, is completely embedded in the lower cross head which is supported by the two main columns of the device and can be moved vertically. The contact loading system consists of two pads, two adjusting screws and two load cells. The contact load is induced by two adjusting screws and is measured using two load cells. The load cell readings can ensure that the contact loads produced by tightening screws in two opposite directions are equal. The contact is of the type of flat on flat. Each pad (see figure 8) has two bases (contacting surfaces) through which the load is exerted on the specimen. The bases have a thickness of 3.1 mm and a length of 12 mm. The pads are constrained to move vertically as this may affect the sliding oscillations between specimen and pads.

Two load cells of the type CDES mounted between the adjusting screws and the pads (see figure 7) monitor the contact load on separate digital displays. The frequency of the device can vary using an inverter up to a maximum of 25 Hz. For further details the readers are referred to reference [9].

Aluminum alloy 7075-T6 was used in this investigation. From a number of tensile tests, the yield stress and ultimate strength of Al7075-T6 were obtained as: $\sigma_y = 503$ MPa and $\sigma_{ult} = 590$ MPa, respectively. The flat specimens used in this work were prepared in accordance with ASTM standard. The specimen shown in Figure 9 had a width of 14.5 mm, a thickness of 4.5 mm and a gauge length of 70 mm. The pads are made of stainless steel 410 with yield and ultimate strength of 420 and 700 MPa, respectively. The material’s composition obtained is Al 91%, Cu 1.9%, Mg 2%, Cr 0.25, Zn 4.8% and Mn 0.7%. The specimen geometry is shown in Figure 9.
3. Numerical simulations

In this paper two numerical simulations are presented, namely a) FE model for stress distribution and estimating initial crack location and b) new approach to FEA modelling of crack propagation.

4.1. Estimation of crack initiation location

Ansys Parametric Language Design (APDL) code was used to analyze the specimen without crack. The finite element model of the test assembly is illustrated in Figure 10. The model which is constructed on the basis of the schematic illustration of fretting fatigue shown in figure 1, consists of the specimen and the pads. The model consists of one set of four-node plane strain elements (PLAN82) for the specimen and another set for the contact pad. In addition, CONTA172 and TARGE169 elements were used at interface (the interface surface between pad span and specimen). These contact elements allow pressure to be transferred between the contact pad and the specimen and avoid the pad penetrates into the specimen. The Augmented Lagrange method of friction was used with 0.5 as coefficient of friction. Note that only a quarter of the test configuration is considered due to double symmetry with respect to the X and Y axes. In addition to the boundary condition along the lines of symmetry, the specimen was constrained in Y direction at the bottom line nodes and right side of line of symmetry for specimen and both sides for contact pad constrained in X direction. As the Figure 10 shows, a normal \( P/2 \) then an axial stress, \( \sigma \) is applied to the test assembly. The normal and tangential contact stress distributions are determined from the simulations. In order to have more accurate results, the finite element mesh was refined in the contact region. An acceptable element size was determined to be at least 9 µm x 9 µm in the refined contact zone from the convergence study. However, mesh size was much finer than this, which varied from case to case with one basic requirement that at least ten elements were present behind the contact edges.
4.2. Finite element analysis of crack propagation

The fretting fatigue crack propagation part was thereafter conducted using the finite element code, FRANC2D/L [9]. For this purpose, a finite element model, the same geometry and boundary conditions as used in APDL code as shown in Figure 10 including the contact interface was modeled. Then an edge crack was inserted in the model considering the contact to perform the crack growth analysis by FRANC2D/L code, which has capability for incremental crack growth using fracture mechanics principles as elaborated later. The model was considered a quarter of the test configuration the same as model that was used in APDL code. The mesh size in the FRANC2D/L model was validated by comparing its stress values with the original ANSYS results. A deviation of less than 1% was observed between the two finite element solutions.

The contact was defined with a gap element using a new material at interface of pad and specimen, with coefficient of friction equal to 0.5. This means that in each step for crack propagation the effect of contact pad was considered and the stress intensity factors were updated after each crack increment. This proposed technique would solve most problems in previous studies where sub-modeling was used for crack propagation [11, 12].

The crack propagation analysis requires the length and orientation of the initial crack. The crack propagation path was represented by a curvilinear path consisting of, S, straight segments, as shown in Figure 11. In the first step, an initial crack of length, \( l_0 = 0.01 \text{mm} \), with an orientation, \( \theta_1 = 45^\circ \) from the y-axis was introduced on the contact surface at end of sharp edge. This position is obtained from the ANSYS FE model and the initial length and orientation is observed from experimental results. Also previous experimental studies have shown that the crack in fretting fatigue tests always initiate at or very near to the sharp edge at this angle [13, 14]. The analysis was then performed with a crack length increment of \( \Delta l \). The incremented crack kinked at the tip of the initial crack at \((x_2, y_2)\) to produce a new crack at a slope of \( \theta_2 \) in the second step of the analysis, and this process was continued.

In FRANC2D/L, the mesh is modified in each incremental step using the Suhara-Fukuda algorithm [15]; the algorithm generates a mesh of triangular elements as shown in Figure 12, and the new crack geometry is represented at each incremental step to reflect the current crack configuration. Along with other theories, the code uses the maximum tangential stress theory, proposed by Erdogan and Sih [16], to determine the crack growth direction. The crack angle, \( \theta_i \), at the \( i \)th step was computed by

\[
\theta_i = \theta_{i-1} + 2 \tan^{-1} \left[ \frac{K_{I_{\text{maxi}}} - K_{I_{\text{Imaxi}}} \sqrt{1 + 8K_{I_{\text{Imaxi}}}^2}}{4K_{I_{\text{Imaxi}}}} \right] \quad (1)
\]

Where \( K_{I_{\text{maxi}}} \) and \( K_{I_{\text{Imaxi}}} \) are the maximum stress intensity factors at the \( i \)th step corresponding to the two crack propagation modes, Mode I and Mode II, at the maximum load. In this way crack trajectory was developed incrementally for a given loading condition using maximum tensile stress criterion. Further, the crack growth rate was assumed to be governed by the Mode I stress intensity factors, \( K_{I_{\text{max}}} \), and \( K_{I_{\text{min}}} \) [4]. The modified crack closure integral technique of Rybicki and Kanninen [17] was used to calculate these stress intensity factors. These values were then used with the sigmoidal crack growth model to determine the crack propagation life, which was measured from experiments in previous studies [4, 18, 19]. Fretting fatigue crack grows with an angle of about 45° as compared with the surface. Therefore in this step a crack with length of \( l_0 = 0.01 \text{ mm} \) and angle of 45° were created. \( \Delta l \) was considered 0.1 mm for crack propagation. Final failure occurs when the value of stress intensity factor, \( K_I \), tends to its critical value, \( K_{IC} \).
FRANC2D/L CRACK GROWTH code was used in order to predict the crack growth life curve. This program, realized by Domenico Quaranta [20], calculates crack growth life in generic 2D layered structures. The core of the program is Franc2D/L (based on Franc2D, Copyright (C) Paul ‘Wash’ Wawrzynek and Tony Ingraffea) [9], which is used to extract stress intensity factors (SIF) history files for generic geometries and sets of loads. N40_F2DL_CG imports SIF history files and integrates the material da/dN equation (NASGRO model) for calculating crack growth for variable amplitude spectrum of loads. FRANC2D/L CRACK GROWTH code is able to show the amount of $K_I$, $K_{II}$ and $\Delta K$ in every increment of crack propagation and it is designed to deal with Forman NASGRO material models (equation 2). The elements of the NASGRO crack growth rate equation were developed by Forman and Newman at NASA, and it has been implemented in FRANC2D/L CRACK GROWTH as follows [21]:

$$\frac{da}{dN} = C \left[ \left( \frac{1-f}{1-R} \right) \Delta K \right]^n \left( \frac{1-\frac{\Delta K_{th}}{\Delta K}}{1-\frac{K_{max}}{K_{crit}}} \right)^q$$

(2)

Where $C$, $n$, $p$ and $q$ are empirical constants, which are obtained by curve fitting the test data and $f$ is the ratio of crack opening SIF to maximum SIF. The value of $f$ is related to stress (load) ratio, flow stress and the plane stress/strain constraint factor. These values are provided by the FRANC2D/L CRACK GROWTH material database for each material. It is worth mentioning that $\Delta K_{th}$ is not a simple threshold stress intensity range for long crack, but it includes the effect of short crack by involving ‘intrinsic crack length’, and the parameter $f$. Also $C=6x10^{-10}$ and $n=2.51$ was used as fatigue ductility exponent [22], hence number of the cycles (dN) for a crack grow (da) in each increment, can be computed. Finally, the specimen fracture life was obtained.

4. Experimental results
The experiments were conducted for stress ratio of $R=0.1$, frequency of 20 Hz at a constant normal force of $P=1200$ N at the contacts, and maximum working stress of 130, 180, 200, and 280 MPa. The stresses are the average tensile stress which are obtained from $P/A$ in which $P$ is the maximum tensile load monitored continuously by the axial load cell and $A$ is the cross sectional area of the specimen. A comparison between the S-N curves obtained for pure fatigue and fretting fatigue tests is shown in Figure. 13. It can be clearly observed that fretting fatigue can reduce the normal fatigue life considerably. The reduction is more significant for lower stresses which correspond to high cycle
fatigue (HCF) tests. For high stresses corresponding to a low cycle fatigue (LCF) conditions, the reduction is not so important.

**Figure 13.** A comparison between the pure fatigue and fretting fatigue lives of some specimens.

5. Numerical results

5.1 Validation of simulations

The simulations were validated by making a comparison between the variations of crack propagation (length) versus the number of cycles as predicted by numerical simulations in this work and the experimental measurements using replica. The results are given in Table 1 and graphically shown in Figure 14. As the results suggest a maximum of 24% difference is observed that in quite normal in fatigue context. Also there are a lot of factors that have effect on fretting fatigue crack propagation lifetime directly or indirectly that are not considered in this investigation, some parameters such as wear (i.e. removing material during the fretting fatigue cycles), environmental conditions, changing coefficient of friction due to presence of debris at contact interface, and a lot of factors that most of them decrease the fretting fatigue lifetime. So, due to authors believe this difference comes from a lot of variables that were not modeled, because the current software that is used for crack propagation does not have this capability.

| Applied stress (MPa) | Experimental cycles | Numerical cycles | Error   |
|----------------------|---------------------|-----------------|---------|
| 130                  | 33960               | 44720           | 24%     |
| 140                  | -                   | 42850           | -       |
| 150                  | 31810               | 38370           | 17.09%  |
| 160                  | -                   | 35140           | -       |
| 170                  | -                   | 33480           | -       |
| 180                  | 23720               | 31484           | 24.7%   |
5.2 The effect of pad geometry on crack propagation

Numerical simulations were performed for some different geometries including flat on flat and round on flat contact. Some typical models for different contact geometries are shown in Figure 15. The geometries of real pads have already been illustrated in figure 8. The models shown in the figure 15 also reveal the stress contours for Von-Mises stress. It is interesting to note that the maximum Von-Mises stress occurs at the contact point between the cylindrical pad and the specimen while for flat on flat specimen, the maximum stress takes place near the sharp edge contact between the flat pad and the specimen.

The effect of pad dimension on crack propagation length is shown in Figure 16. As the figure suggests, fretting fatigue life increases with the increase of pad width for both types of the pads considered in this investigation. However, for flat on flat type contact the fretting fatigue life is significantly higher than that for round on flat contacts.
6. Conclusions

Numerical simulation of fretting fatigue was performed using Ansys Parametric Design Language (APDL) and FRANC2D/L software. The former predicts the normal and tangential contact stress distributions and the latter calculates the number of cycles required for a known crack length. The calculation of cycles is based on Forman NASGRO equation when $\Delta K$ is computed by FRANC2D/L can predict the cycles for a specific value of crack growth. The results indicate that the numerical simulations are capable of prediction the crack growth cycles and orientation accurately to some extent. The computed crack propagation lives were compared to the results of experimental study where total fatigue life was measured. The effects of contact geometries were determined on crack propagation behavior. The following conclusions can be drawn based on this study:

1- Maximum stress is created in contact region and stress values are higher near the sharp edge of contact which was the region of interest at which failure is expected.

2- Von-Mises equivalent stress increases with the increase of pad width for both types of the pads considered in this investigation. However, for cylindrical on flat type contact the Von-Mises equivalent stress is significantly higher than that for flat on flat contacts.

3- A comparison between the experimental and numerical results demonstrates a difference of about 24% in crack growth. It is observed that with increase of pad width for both flat and cylindrical cases, crack propagation life increased and these two parameters (pad width and crack propagation life) have a direct relation with each other.

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