Crack orientation in a complete contact fretting-fatigue problem

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ABSTRACT. *In this work, the orientation and propagation of a crack in a fretting fatigue problem is analyzed numerically and correlated experimentally. The analysis is performed using a 2D model of a complete-contact fretting problem, consisting of two square indenters pressed onto a specimen subjected to cyclic fatigue. For the simulation, we use the extended finite element method (X-FEM), allowing for crack face contact during the corresponding parts of the fatigue cycle. The problem is highly non-linear and non-proportional and a new orientation criterion is introduced to predict the crack direction in each step of the crack growth simulation. It is shown that the proposed criterion predicts crack orientation directions that are in good agreement with those found experimentally, in contrast to the directions found by application of conventional orientation criteria used in LEFM, such as the MTS criterion.*

INTRODUCTION

Fretting fatigue problems involve two or more solids in contact that experience relative displacements of small amplitude. A general feature of fretting fatigue problems is that the contact region acts as a stress raiser causing crack initiation and subsequent crack propagation until the eventual failure of the component [1]. Due to the contact stresses, fretting fatigue problems are highly non-linear. In addition, a non-proportional evolution of the stress state often exists along the loading cycle. After initiation, crack propagation occurs in regions dominated by this complex stress state, which usually induces crack face contact and closure. It is also found that there is also a crack-contact interaction at the early stages of the crack growth, by which the contact stresses have an influence on the crack and, reciprocally, the crack presence alters the contact stress distribution [2].

All these features make fretting fatigue problems difficult to analyze and numerical approaches often become necessary. In this work, we analyze a simple geometrical configuration under complete contact conditions, as sketched in Fig. 1: a specimen subjected to cyclic loading σ_{Bulk} is pressed by two square indenters on two opposite sides through the action of a normal load *P*. In complete contacts, the contact area is independent of the loading *P* due to the abrupt change of the indenter geometry, in contrast to incomplete contacts, such as hertzian contacts. The abrupt change in geometry typical of complete contacts also exhibit four edges that behave as singular lines at the end of the contact area (four corner points in the 2D model of Fig. 1 that behave as singular points). This singular stress state at the corner points leads to a rapid crack initiation stage as compared to incomplete fretting fatigue problems and a large percentage of the fatigue life is spent on the propagation stage [1,3]. Therefore, predicting the right propagation direction is essential to integrate crack growth laws in order to estimate the remaining life until failure. In this work, we assume that a small scale yielding condition prevails, both at the corner points and at the crack tips, with a linear elastic material behaviour.

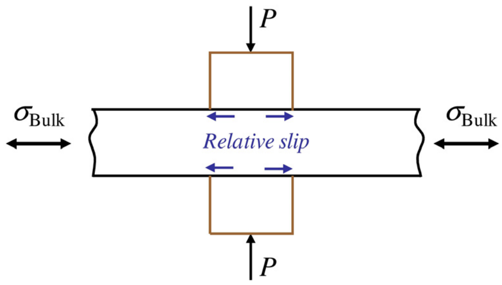

Figure 1. Sketch of the fretting fatigue problem under the complete contact conditions.

The fretting configuration is analyzed both numerically and experimentally aiming at predicting the observed crack paths using the extended finite element method (X-FEM). The analysis of a 2D model of the physical tests is carried out using the X-FEM implementation developed by the authors [4,5]. The implementation is performed as a user's subroutine in the commercial code Abaqus and can take into account crack face contacts along the loading cycle, which has been proved to be essential for the correct crack prediction. Several crack orientation criteria are reviewed in the next section. Starting from the numerical results, the crack direction in each step of the crack growth simulation is predicted using a new criterion based on the minimum shear stress range ahead of the crack tip [6]. The experimental testing was carried out in aluminum 7075-T6 and micrographies show that the experimentally observed crack paths agree well with the paths numerically predicted using the proposed approach.

CRACK ORIENTATION CRITERIA FOR FRETTING FATIGUE PROBLEMS

Review of existing criteria

As commented above, fretting fatigue problems are characterized by the existence multiaxial and high stress gradient zones subjected to mixed mode non-proportional loading [7], i.e. the maximum tensile and compressive stresses change their position and intensity along the cycle.

In the literature, several crack orientation criteria have been applied to fretting fatigue problems in order to predict the observed crack inclination with respect to the specimen surface. Following the classical description by Forsyth [8], usually, two stages are distinguished: stage I for the initiation process and stage II for the subsequent propagation. In the initiation stage, cracks can exhibit a shallow angle with respect to the surface, called type 1 crack in stage I according to [9], which are dominated by the range of shear stresses $\Delta\tau$. This is not always the case and some cracks initiate with an angle much larger with respect to the surface (type 2 crack in stage I, according to the nomenclature used in [9]). This type 2 initiation cracks are controlled by the normal stress range $\Delta\sigma$, where a high level of tensile stress exists. Type 2 initiation cracks are the case observed in our experimental tests with complete contact.

It is well known [10,11] that proportional orientation criteria, such as the maximum tangential (circumferential or hoop) stress $\sigma_{\theta\theta}$ criterion (MTS) or the minimum of the strain-energy-density factor S among others, are only valid for proportional loading. For the analysis of fretting fatigue propagation (stage II) under non-proportional loading for an incomplete contact, Baietto-Dubourg and Lamacq [9] and Ribeaucourt et al. [12] consider the following criteria based on the work of Hourlier and Pineau [13]:

1. $\max(k_I(\theta,t))$ criterion: direction θ for which k_I attains its maximum along the cycle (absolute maximum in direction and time). Note that k_I is the mode I SIF associated with a virtual, infinitesimally small kinked segment emanating from the original crack with an angle θ.
2. $\max(\Delta k_I(\theta))$ criterion: direction θ for which Δk_I attains its maximum along the cycle.
3. $\max\left(\frac{\mathrm{d}a}{\mathrm{d}N}(\theta)\right)$ criterion: direction θ for which $\mathrm{d}a/\mathrm{d}N$ is maximum (maximum crack growth rate criterion).

These criteria use the critical plane concept in the sense that the sought direction (plane) is the one in which the maximum magnitude is reached. The second of these criteria provided good results in [9] when applied to spherical (incomplete) contacts acting on prestressed specimens. Baietto-Dubourg and Lamacq [9] also proposed the following criterion:

4. $\max(\Delta\sigma_{\theta\theta,\mathrm{eff}}(\theta))$ criterion: direction θ for which the effective range of the circumferential stress $\Delta\sigma_{\theta\theta}$ is maximum along the cycle (by effective, it is meant that $\sigma_{\theta\theta} = 0$ when $\sigma_{\theta\theta} < 0$).

In [9] this criterion led to similar results to criterion 2. The results in [9] emphasize the importance of evaluating the ranges Δ of the magnitude and not simply the maximum values: criteria 2 and 4 are both based on the concept of the maximum amplitude of crack opening.

The criterion of minimum shear stress range

From the numerical analyses and for the geometric and loading configuration considered in this work, it is found that the crack remains closed during a large part of the loading cycle. The application of some of the criteria reviewed in the previous section did not lead to good predictions of the actual crack path as observed in the experimental tests performed in this work. Consequently, we decided that the stress states existing under crack face contact could have an important influence. Of course, the maximum K_{II} values are obtained when the crack is totally open, as crack face sliding is not hindered by friction and interlocking of asperities. The maximum value of K_{II} also would happen if there were no friction between crack faces (which is an unrealistic case).

In the practical case of fretting contact in which the growth must develop, the crack is closed during a large part of the loading cycle. Therefore, it is reasonable to assume that growth will occur in the direction θ in which $\Delta\tau(\theta)$ is minimum, leading to less energy loss due to friction between crack faces under the compressive contact stresses. Shear stresses develop always in two orthogonal planes and there are two orthogonal planes on which $\Delta\tau$ is minimum. From these two potential crack growth directions, we choose the plane with the maximum $\Delta\sigma_{\theta\theta,\mathrm{eff}}$, because it will be the plane where less frictional energy is lost and there is more energy available for propagating the crack. When applying this criterion to the propagation stage, $\Delta\tau(\theta)$ is evaluated ahead the current crack tip. To a certain extent, this criterion is an extension for non-proportional loading of the $K_{II} = 0$ criterion used for proportional loading (equivalent to MTS criterion), since the direction of propagation minimizes $\Delta\tau$.

DESCRIPTION OF THE EXPERIMENTAL TESTS

In this work, we have performed fretting fatigue tests with a square-ended indenter in a partial slip regime. The symmetrical relative slip produced by this complete contact configuration is sketched in Fig. 1. Tests were carried out with a uniaxial servo-hydraulic fatigue test machine with a load capacity of 100 kN as shown in Fig. 2, where the assembly rig used to apply the normal load P can also be observed. The cyclic bulk loading was performed at constant amplitude, stress ratio $R = -1$ at a frequency of 15 Hz. Fifteen load combinations were analyzed in [3]. For this study, the following tests No. 1, 3, 5, 8, 11 and 15 were selected. Some of them were ground after failure on the plane of Fig. 1 in order to take micrographies of propagated cracks emanating from the four potential corners of Fig. 1 that did not lead to failure. The applied loads for each test and the experimentally registered number of cycles to failure are listed in Table 1. The nominal contact pressure is defined as $\sigma_P = P/2ct$, where $2c$ is the contact width and t the specimen and indenter thickness. The specimen used are dog-bone shaped, with a rectangular section t x 2B = 5 x 10 mm (see Fig. 3). The material is aluminum alloy 7075-T6, with a Young's modulus of 72 GPa and a Poisson's ratio of 0.3.

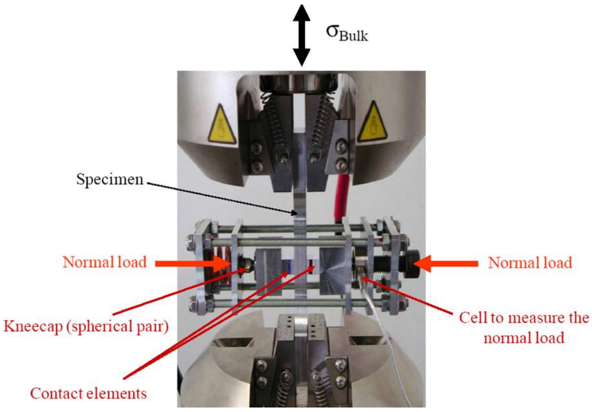

Figure 2. Complete contact testing rig, showing the contact elements

Table 1. Loads for the tests considered

Test number	P (kN)	σ_P (MPa)	σ_{Bulk} (MPa)	N_f (cycles)
1	2	40	110	105958
3	8	160	110	82549
5	4	80	130	47714
8	4	80	150	32905
11	4	80	170	27391
15	8	160	190	8760

DESCRIPTION OF THE NUMERICAL MODEL

Due to symmetry conditions, a quarter 2D finite element model has been considered to represent the fretting fatigue tests, as shown in Fig. 3. The rectangle L x B corresponds to the analyzed specimen and has a length of $L = 4B = 20$ mm, the half length of the indenter c is 5 mm, and the distance between the contact plane and the point of the indenter at which loads are applied is $h = 10$ mm. Four node, plane strain quadrilateral elements were used with a thickness t = 5 mm. The smallest element size considered is 5 μm at the right end of the contact zone.

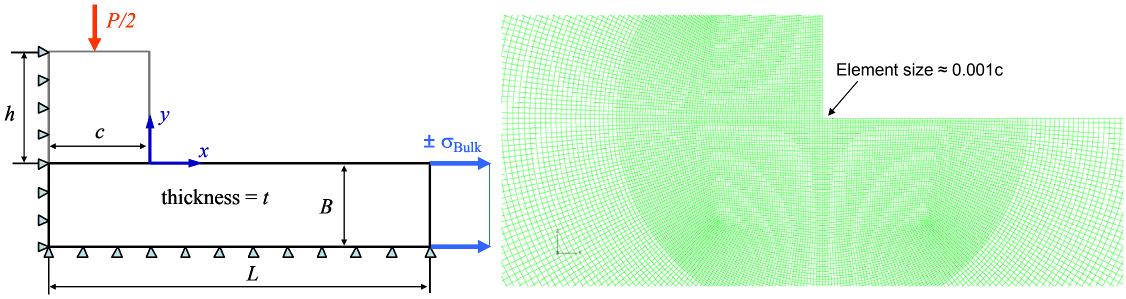

Figure 3. Model geometry and enlarged view of the FE discretization.

The friction model assumed for the contact zone is a Coulomb model and the ABAQUS contact formulation based on Lagrange multipliers is used to model the contact between the indenter and the specimen. The friction coefficient is taken as μ=0.8.

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CRACK GROWTH SIMULATION AND COMPARISON WITH EXPERIMENTAL RESULTS

The crack growth simulation is performed using the extended finite element method (X-FEM). This method presents the enormous advantage that it does not need remeshing to simulate the crack propagation, because the element sides do not need to conform to the crack faces [14]. During the last decade, it has become a well established technique and we will not review its fundamentals here (for its application to fretting fatigue we refer to our previous works [2,3]). We have used the implementation of the method described in [4] in combination with the essential feature of crack face contact given in [5].

Figure 4 shows the estimation of the initiation angle for Test 1. For the complete contact configuration of this work, the experimental evidence shows that the initiation crack is a type 2 crack. Figure 4 (left) is computed from the numerical model of Fig. 3 prior to the presence of any crack (i.e. X-FEM is not necessary). It can be observed that the criterion of $\Delta\tau_{min}$ provides two minima. Choosing the one with the highest $\Delta\sigma_{eff}$ a good prediction of the initiation angle is found ($\theta \approx 60^o$). Note that the application of the criterion 4, max($\Delta\sigma_{eff}$), yields the estimation $\theta \approx 90^o$, which is not correct, presumably because in this problem the crack is closed during a large part of the cycle.

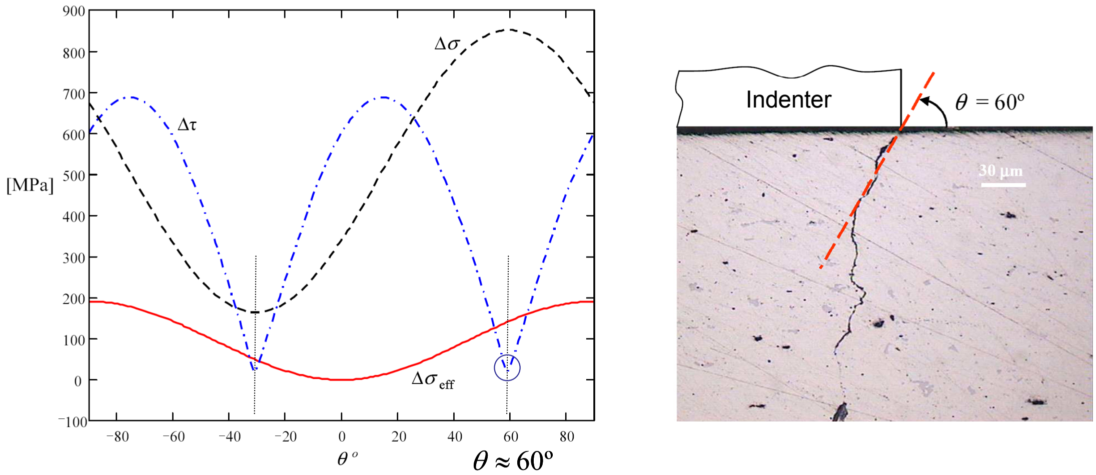

Figure 4. Test 1. Predicted initiation angle for a type II crack using the $\Delta\tau_{min}$ criterion.

Figure 5 shows the micrographs for the propagation stage (the total length shown for the longer cracks in the picture is about 1.2 mm). These are cracks that did not lead to final failure and that emanated from one of the four corners of Fig. 1. It can be observed that the crack paths are very similar for all of them: the crack grows inwards and deviates from the angle of 60º (initiation angle) to about 80º. Note that, despite the irregularities due to the local microstructure, the trend of the growth is always inwards in this region and not at 90º with respect to the surface.

Figure 6 plots the prediction for the propagation stage (stage II) for Test 1. The figure at the left represents the predicted propagation path with the proposed criterion

$\Delta\tau_{min}$ after six crack growth increments using X-FEM taking into account crack face contact. The initial crack a_0 is assumed as a straight segment of 50 μm at 60º. The length of the six crack increments is also Δa = 50 μm. The proposed criterion was applied evaluating $\Delta\tau$ at the first non-enriched finite element ahead the crack tip element. The predicted path is in good agreement with the experimental observations. Note that the simple application of the MTS criterion (which depends on K_I and K_{II}) at the instant of maximum σ_{Bulk}, i.e. when the crack is fully open (ignoring what happens at the rest of the cycle), does not yield good predictions of the crack path (see Fig. 6 right). .

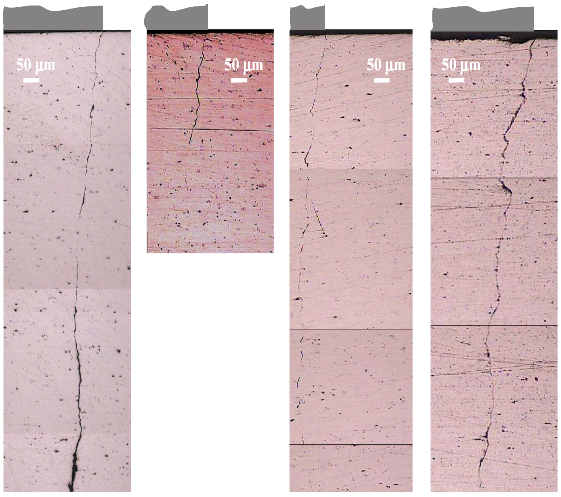

Figure 5. Micrographs for the propagation of non-failure cracks. Tests 1, 5, 8 and 15.

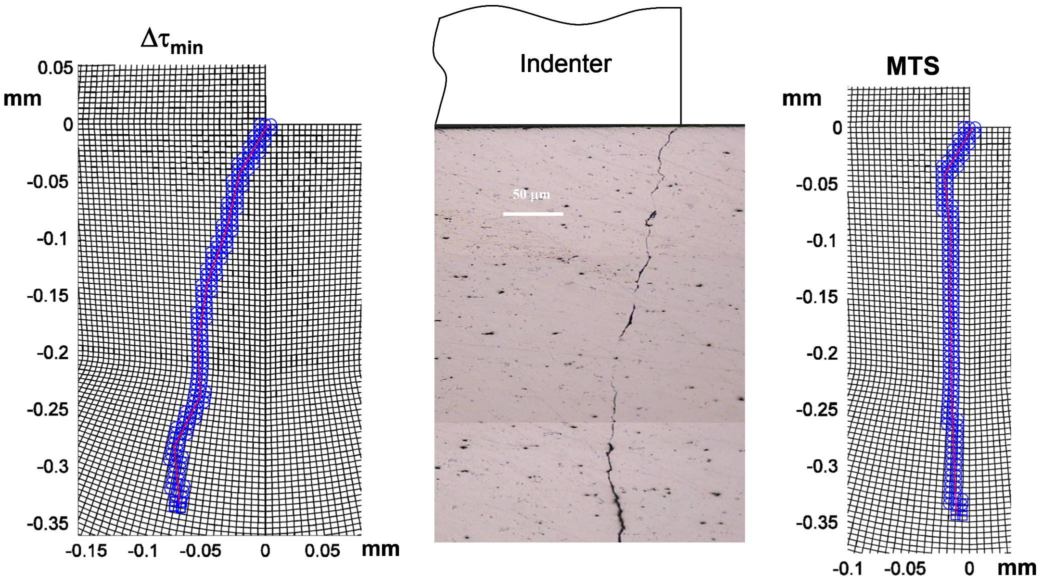

Figure 6. Test 1. Predicted propagation path using XFEM and the $\Delta\tau_{min}$ vs. MTS criteria.

CONCLUSIONS

Crack propagation paths have been predicted for fretting fatigue tests under complete contact conditions. This type of problem is subjected to non-proportional loading, which precludes the application of conventional orientation criteria used in LEFM that are only useful for proportional loading. To achieve these results, we have proposed a new criterion based on the minimum value of $\Delta\tau$ evaluated ahead the crack tip and along the entire cycle. The prediction has been performed numerically using X-FEM including a formulation that allows for crack face contact and the results show good agreement with the experimental observations.

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