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A fracture mechanics life prediction methodology applied to dovetail fretting

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Abstract

This work evaluates a fracture mechanics based crack growth life prediction methodology for dovetail fretting fatigue laboratory experiments. The Ti–6Al–4V specimens were configured with angles of 35°, 45° and 55°. Experiments were conducted with constant amplitude loading at R of 0.1 and 0.5 with lives ranging from 100,000 to 10 million cycles. The approach included the contact loads and bulk stress calculated from the finite element method as inputs to the stress and life analysis. Contact stresses were calculated using the contact stress analysis software CAPRI. These stresses were input into a stress intensity factor calculation at the edge of contact. Crack propagation life was calculated from an assumed initial crack size. Analysis showed that propagation consumes a majority of the total life and is insensitive to a large range of initial crack sizes.

Keywords: Fracture mechanics; Fatigue crack growth; Fretting fatigue; Dovetail; Ti–6Al–4V

1. Introduction

This research is being conducted as part of the National Turbine Engine High Cycle Fatigue program. The objective of the materials damage tolerance portion of this program is to reduce the uncertainty of high cycle fatigue (HCF) behavior in components with damage such as foreign object damage, low cycle fatigue and fretting. This paper is focused on the issue of fretting in the blade to disk attachments of turbine engines. Fretting in these regions is recognized as one of the most costly sources of in-service damage related to HCF in the US Air Force [1].

One method for managing these damage mechanisms in the presence of HCF is to apply damage tolerant design principles. The usual damage tolerance technique of inspection intervals defined by crack growth from an inspectable flaw size is impractical for HCF, because damage that is severe enough to extend under HCF could quickly grow to a critical size due to high cyclic frequencies. An alternative method is to limit the allowable HCF vibratory loading such that the largest damage that is likely to occur between inspections by fretting is below the fracture mechanics fatigue crack growth threshold [1]. This type of philosophy has been incorporated into the US Air Force Engine Structural Integrity Program (ENSIP) handbook which currently states "it should be assumed that a crack of depth $2a_0$" can develop during service due to contact loading [2]. Here, a_0 is the short crack parameter defined by El Haddad et al. [3]. The ENSIP handbook also states "the threshold stress intensity [factor] should be used to insure HCF propagation will not occur … unless it can be shown that crack arrest will occur after further crack growth." This necessitates a good understanding of crack growth and crack arrest in the high stress gradients near the edge of contact.

The objective of this work was to evaluate the capability of a fracture mechanics life prediction methodology to predict the performance of dovetail fretting fatigue laboratory experiments. Many fracture mechanics models have been applied to the high edge of contact stress gradients that characterize fretting problems. Rooke and Jones [4] calculated solutions to the modes I and II stress intensity factors, K_{I} and K_{II}, respectively, for a crack in a semi-infinite body due to the surface tractions. If significant geometry effects are present, however, the K solutions may

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need geometry corrections that consider the subsurface stress state solution. Hills and Nowell [5] applied the method of distributed displacement discontinuities or dislocations along the line of the crack such that the crack face is traction free. Without describing the mathematical details, this solution leads to the modes I and II stress intensity factors for an edge crack in an arbitrary stress field. A third method of calculating the stress intensity factor for a crack in the steep edge of contact stress gradient is with a weight function. The method proposed by Bueckner [6] and later discussed by Rice [7] requires the K solution and the crack face displacement solution for the geometry considered. Although K solutions have been reported for numerous geometries, solutions for the crack face displacements are less common. To that end, Glinka and Shen [8] discussed the use of generalized weight function solutions that are based on multiple reference K solutions. The approach of this paper is to apply a generalized weight function solution derived for a surface crack in a plate.

In this paper, the K solution is employed into a fatigue crack growth analysis. This methodology is necessary to show that the fretting induced cracks will either not grow or that arrest will occur after a period of crack growth as the ENSIP guidelines state. Other researchers have applied similar fracture mechanics methodologies to the high stresses located at the edges of contact. Hattori et al. [9] is an example of fracture mechanics analysis of fretting fatigue using the Rooke and Jones K solutions. Chan et al. [10] included the effects of modes I and II K solutions as well as small crack effects to determine an equivalent stress intensity factor K_{eq}. This value was then compared to a mixed mode threshold equivalent stress intensity factor $K_{eq,th}$ to predict crack growth or arrest of small fretting induced cracks. This work showed that the mode I driving force required to grow a fretting crack, the threshold stress, decreased with increased shear stress on the bulk stress. Nicholas et al. [11] and Golden and Grandt [12] have shown, however, that at least for some test conditions the mode II component of crack driving force is not significant.

2. Experimental procedures

The dovetail fretting fatigue experiments considered in this study were conducted with Ti–6Al–4V specimens and pads. Detailed descriptions of these experiments and results can be found in Golden and Nicholas [13]. The Ti–6Al–4V material was forged into plates then solution treated at 932 °C for 1 h, followed by fan cool. Finally, the material was mill-annealed at 704 °C for 2 h. The resulting microstructure was a duplex structure with approximately 60% alpha and the remainder is transformed beta. Tensile properties of the material are $\sigma_y = 930$ MPa and $\sigma_{UTS} = 980$ MPa. This is the same Ti–6Al–4V material used throughout the National HCF program [14].

The current experimental setup is very similar to that used by Conner in previous work [15,16]. Fig. 1 is a photograph of the 45° test setup. One of the unique traits of this particular dovetail fretting fatigue fixture is the replaceable fretting pads, which allows reuse of the fretting fixture resulting in relatively inexpensive testing. Typically dovetail or fir tree attachment fatigue tests use a single piece to represent the disk. These must be replaced for each test at considerable expense. Another difference between this dovetail setup and others such as reported by Ruiz et al. [17], is that the applied loading is uniaxial rather than biaxial.

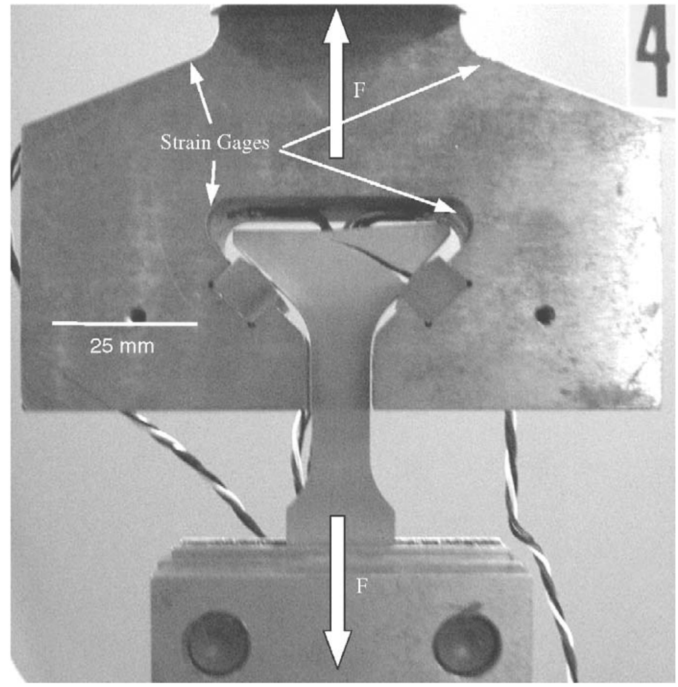

Fig. 1. Dovetail fretting fatigue experimental setup.

The experimental data used in this study [13] were generated with specimens and fixtures configured in three different geometries. The three specimens were identical except for the dovetail portion, which had angles of 35°, 45° and 55° as measured from the horizontal. Three different loading fixtures were used to accommodate the different specimens. All experiments used the same rounded flat pad profile with a 1 mm flat center and 3 mm radii at the edges. Experiments were conducted with remotely applied constant amplitude loading at load ratios of 0.1 and 0.5 until specimen failure, which was defined as a change in specimen compliance due to a crack. Lives ranged from 100,000 cycle failures to 10 million cycles run-outs.

One of the challenges of a dovetail type experiment is characterization of the test conditions such as the local contact forces. Unlike typical fretting fatigue fixtures the dovetail fixture has no direct measurement of the local contact forces, only the remotely applied force. This problem was addressed by instrumenting the fixtures with strain gages. The strain readings are then used to calculate the local normal and shear contact forces. This