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Applications of crack analogy to fretting fatigue

Sam Naboulsi *

Department of Aeronautics and Astronautics, Air Force Institute of Technology, AFIT/ENY, Wright–Patterson Air Force Base, OH 45433-7765, USA

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Abstract

In literature the most common approach to investigate fretting fatigue is based on contact mechanics. Crack initiation parameters of fretting fatigue are developed using elastic solution of two contacting bodies. Even though contact based parameters has been used extensively, they could not fully capture crack initiation mechanism due to the complexities of the fretting fatigue damage process, which depends on pad geometries, surface properties, material properties, and mechanical loading conditions. This has instigated fretting fatigue researcher to investigate other approaches. Recently, taking advantage of the similarities between contact mechanics and fracture mechanics lead to the development of crack analogy methodology (CAM), which defines the stress intensity factor as a fretting fatigue crack initiation parameter. CAM has shown a great potential investigating fretting fatigue. However, it has not been applied to wide range of fretting fatigue scenarios. The scope of this paper is not to focus on analytical development of CAM as much as validating its ability to analyze various fretting fatigue scenarios. Based on CAM, the present study introduces the crack analogy fretting parameter (CAF-parameter) to investigate crack initiation of fretting fatigue, which is equivalent to the change of mode II stress intensity factor at the contact surface, since the change in the stress intensity factor reflects the cyclic mechanism of fatigue. Further, a modification to the CAM is adopted to include various indenter-substrate geometries. Also, CAF-parameter–life curve, similar to the stress–life S–N curve, will be developed as a prediction tool to crack initiation for various geometric configurations using experimental data. This is consistent with presenting fatigue data. The results show similar pattern to plain fatigue with lower damage tolerance. It also shows scatter and dependency on the pad configuration as expected. Finally, the CAF-parameter shows potentials in effectively analyzing/predicting the complex mechanism of fretting fatigue.

Keywords: Fretting fatigue; Crack initiation parameter; Fracture mechanics; Contact mechanics

* Tel.: +1 9372556565; fax: +1 9374273369.
E-mail address: samir.naboulsi@afit.edu

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1. Introduction

Fretting fatigue plays a great role in the design of modern turbine engine jet for aircrafts. It is a primary cause of crack initiation and mitigation at the dovetail of turbine engine blades. It leads to reduction in the structure integrity tolerance. As the case for fatigue, fretting fatigue in general is a complex subject, where some of the problems modeling it may be characterized as follow [1]:

- calculations of life are generally less accurate and less dependable than strength calculations. Order of magnitude errors in life estimate are not unusual,
- fatigue characteristics of a material cannot be deduced from other mechanical properties. They must be measured directly by experiment,
- full-scale prototype testing is usually necessary to assure an acceptable model predictions,
- results of different but identical tests may differ widely, requiring therefore, a statistical interpretation by designer.

To better predict the life of turbine engine, an effective fretting fatigue crack initiation parameter is required. In the past, most developments of crack initiation parameters are based on contact mechanics, which is the most common approach. However, the lack of such parameters to effectively predict the complex nature of fretting fatigue, which is attributed to fretting dependency on pad geometries, surface properties, material properties, and mechanical loading conditions, has lead researcher to explore other approaches. Recently CAM approach was presented by Giannakopoulos et al. [2,3], and a short incomplete overview of some of the works that lead to CAM, will be presented next for clarity.

Hertz [4] is one of the earlier pioneers in driving the contact stresses for an elastic normal load of a cylindrical punch. Mindlin [5] developed a detailed solution for spherical surfaces. Later, these studies have inspired many contact mechanic investigations in which elastic semi-analytical solutions of variety of contact configurations under various operational conditions were developed and used to investigate fretting fatigue crack initiation, e.g. [6–10]. Others [10,11] modeled contact using elastic finite element to predict the crack initiation of various fretting pad configurations under various loading conditions. The advantage of FE is modeling complex geometry contrary to analytical models. However, it requires very fine mesh near the contact region, which is numerically extensive and computationally expensive, and it requires re-meshing in case of a change in the dimensions of the model.

Alternatively, CAM took advantage of the similarity in the singular solution observed between contact stress state of an indenter-substrate and fracture mechanic stress field of a cracked body. For examples, Nadai [12] analyzed the asymptotic stress solution within an elastic substrate in the vicinity of the corners of a punch geometry for both normal and tangential loading. His solution confirmed the elastic singular fields at the sharp edges of two-dimensional contact between a rigid flat punch and planar surface derived by Sadowski [13] and the contact surface stresses derived earlier by Hertz [4] for normal loading of a cylindrical punch. The singular field for sharp edge contact (e.g. [6,7] and cracked body (e.g. [14,15]) suggest similarity (e.g. [16,17]). However, a quantitative connection has not been established in sufficient detail. Recently, Giannakopoulos et al. [2,3] presented a detailed summary of the CAM to validate and interpret their experimental data. In their study, a quantitative equivalence has been explored in detail between the contact mechanics and fracture mechanics using the vast literature of both fields. This equivalence is established by identifying geometries of cracked bodies, which facilitate an analogy with contact geometries. Their experimental validations are for a spherical pad in contact with substrate. Furthermore, they used mode II stress intensity factor as life prediction parameter to predict crack initiation. They assumed fatigue crack initiate at the stick-slip boundary when the mode II stress intensity factor is greater than threshold stress intensity corresponding to load ratio of negative one and under mixed constant mode I and oscillatory mode II fatigue.