Tribology International 127 (2018) 245–254

Contents lists available at ScienceDirect

Tribology International

journal homepage: www.elsevier.com/locate/triboint

Prediction of fretting fatigue crack initiation location and direction using cohesive zone model

K. Pereira[a], N. Bhatti[a], M. Abdel Wahab[b,c,d,*]

[a] Department of Electrical Energy, Systems and Automation, Faculty of Engineering and Architecture, Ghent University, Belgium
[b] Division of Computational Mechanics, Ton Duc Thang University, Ho Chi Minh City, Viet Nam
[c] Faculty of Civil Engineering, Ton Duc Thang University, Ho Chi Minh City, Viet Nam
[d] Soete Laboratory, Faculty of Engineering and Architecture, Ghent University, Technologiepark Zwijnaarde 903, Zwijnaarde B, 9052, Belgium

ARTICLE INFO

Keywords:
Fretting fatigue
Finite element analysis
Crack initiation
Cohesive zone model

ABSTRACT

Contact stresses distributions may substantially reduce the fatigue life of components subject to fretting, leading to early unexpected failures. Accurately predicting the components lives is, therefore, an important topic to be addressed, in particular from a design point of view. This topic has received great attention in the past decades and several numerical tools that better estimate these components lives have been proposed. In this paper, the focus is in the crack initiation phase. At this stage, it is important to correctly predict the crack initiation location and orientation, which is often achieved by using critical plane approaches. Instead, the use of cohesive zone model (CZM) as an alternative approach to accurately estimate those parameters is investigated. Cohesive zone model as well as two of its common initiation criteria, namely quadratic traction-separation criterion and maximum nominal stress criterion, are used to study crack initiation location and orientation under fretting conditions. Our results are compared with the traditional critical plane approaches and with experimental data, suggesting that cohesive approaches can accurately be used in crack initiation prediction.

1. Introduction

Numerical tools, especially finite element methods, that can predict the life of components under fretting conditions have been receiving considerable attention of the research community [1–4]. However, most models require assumptions and simplifications that may no longer be plausible for cases where there is considerable amount of fretting. For instance, many numerical methods available in the literature simulate the propagation phase assuming linear elastic fracture mechanics [5–8]. However, as there may be high stresses at contact interface, plasticity can play a significant role and linear elastic fracture mechanics theory may no longer be valid. Moreover, the life estimates often rely heavily on the empirical models for the crack growth law, which may not be adequate for non-proportional loading conditions, a common characteristic of fretting fatigue problems. A more robust alternative that does not rely on the assumptions above is to consider the failure using cohesive zone models (CZM).

As discussed by Kuna and Roth [9], the CZM was developed to replicate the fracture process in front of a crack tip and its basic idea is to describe the entire fracture process in a thin cohesive region. The material behaviour inside this region follows a local law, based on the tractions and separations transferred across the cohesive zone. This constitutive law creates a more realistic description of the stress at crack tip, removing the stress singularity modelled in linear elastic fracture mechanics [10]. Fig. 1(a) shows a representation of the CZM, and it can be seen that damage starts once the traction reaches a strength parameter ($T_{\max}$) or separation reaches δ_0. This defines two regimes characteristic of cohesive models: a reversible state from which there is no damage accumulated and a softening region, where the local material cohesive strength is reduced. Complete failure happens when cohesive strength reduces to zero or once separation reaches a critical value δ_f. Note that, as elucidated by Roth et al. [10], to model failure using CZM, there is no necessity to have an incipient crack in the model. Therefore, CZM allows a unique way to model crack initiation, propagation and final failure.

As pointed out by Brocks et al. [11], the fact that cohesive zone model is a phenomenological model implies that the shape of the traction-separation constitutive law is independent on the material being analysed. In the literature, many different shapes have been proposed, for instance: polynomial function [12], exponential [13], bilinear function [14], among others. For simplicity, in this work, a bilinear traction-separation law is adopted and it is represented in

* Corresponding author. Division of Computational Mechanics, Ton Duc Thang University, Ho Chi Minh City, Viet Nam.
E-mail addresses: magd.abdelwahab@tdt.edu.vn, magd.abdelwahab@ugent.be (M. Abdel Wahab).

https://doi.org/10.1016/j.triboint.2018.05.038
Received 1 April 2018; Received in revised form 24 May 2018; Accepted 27 May 2018
Available online 02 June 2018

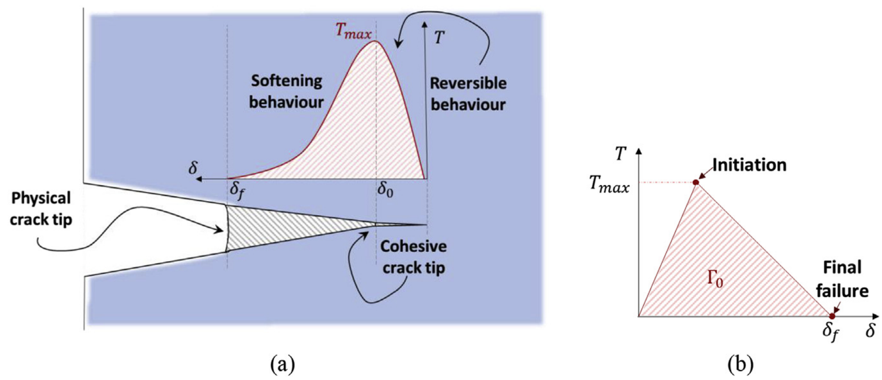

Fig. 1. Cohesive zone model: (a) representation of its use for modelling fracture; (b) bilinear model.

Fig. 1(b). The initial material response is presumed to be linear until a damage initiation criterion (initiation point) is fulfilled. After that, degradation of the material starts and damage follows a linear softening evolution law until complete failure.

The use of cohesive zones to simulate fretting phenomenon has been restricted to only few papers in the literature [15–17]. The present paper attempts to extend the literature, investigating the use of a cohesive zone model (bilinear traction-separation law) to predict crack initiation location and orientation under fretting fatigue conditions, considering two experimental configurations (flat and cylindrical pads). Here, only the initiation point of the cohesive zone is considered, ignoring the accumulation of damage during loading/unloading in a fatigue cycle. This assumption simplifies the analysis, but at the expense of inhibiting the application of CZM for life predictions, which will require a cycle-by-cycle (with or without a time acceleration procedure) analysis in conjunction with a damage evolution law.

Focusing on the use of CZM to estimate the crack initiation location and orientation, this paper is divided in the following way. Firstly, a brief description of the implementation and modelling of cohesive zone damage initiation is done in Section 2.1. In order to compare the accuracy of the results obtained using cohesive zone model, they are compared with traditional critical plane approaches. Two classical critical plane damage parameters have been used in this comparison (Findley (FP) and Fatemi-Socie (FS) parameters). Details of the implementation required to compute those parameters is presented in Section 2.2. Section 3 shows details of the finite element models used in this study. The results and discussions are presented in Section 4. Finally, some conclusions are drawn in Section 5.

2. Theoretical background

2.1. Cohesive zone models

The cohesive zone model was incorporated in our simulations of fretting phenomenon by using ABAQUS® XFEM with cohesive segments module. The behaviour of this model can be summarized as presented in Fig. 2. Initially, a stress analysis of the undamaged material (subjected to some load and boundary conditions) is performed. The stress/strain obtained at the centroid of the XFEM elements, at each loading increment, is then used to compute a damage function. Once this damage function reaches a value of one (within some tolerance), a crack is introduced in the model, crossing one entire element. The cohesive tractions and separations at the crack faces are used to model the degradation and eventual failure of the enriched element. The initial crack location and direction can be directly formulated by the user, using a user defined initiation criterion, programmed by the UDMGINI subroutine in ABAQUS®. For further details, the reader is referred to the ABAQUS® documentations [18].

The crack initiation is assumed to happen at the start of the degradation of the cohesive response of the enriched element (Initiation point in Fig. 1(b)). This process of degradation starts when the stresses and strains in the material meet a specified initiation criterion. This criterion can be written as a normalized function of the stresses or strains with respect to the critical cohesive strength of the material (T_{max}), and it is here called damage initiation criterion. As it is a normalized function that describes the degradation of the element, it is likely that crack initiates when this damage function reaches a value of 1 with some tolerance.

For mixed mode conditions, as in the fretting fatigue case, the critical cohesive strength of the material T_{max} can be expressed as two material properties: the cohesive strength of the material under pure mode I condition ($t_{n,c}$) and the tangential cohesive strength of the material under pure mode II condition ($t_{s,c}$). Their values can be estimated based on laboratory tests using fracture specimens for each failure mode (I or II) individually correlating the fracture toughness (area under the graph Γ_0 in Fig. 1(b)) and the critical separation δ_f. However, one may have a reasonable estimate of $t_{n,c}$ and $t_{s,c}$ based on the fracture mechanism. For instance, it is known that the fracture of brittle materials involves very little plasticity. Therefore, a reasonable assumption would be that $t_{n,c}$ is roughly one order of magnitude of the Young's Modulus of the material [19]. For ductile materials (such as the aluminium alloys studied in this paper), the fracture process involves large plasticity, with the nucleation, growth a coalescence of voids ahead of crack tip. For this case, $t_{n,c}$ may be approximated equal to or in the same order of magnitude of the ultimate strength of the material [17,20]. Regarding the tangential cohesive strength of the material

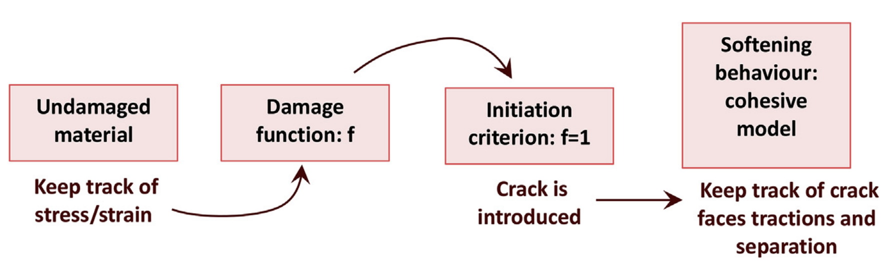

Fig. 2. Behaviour of XFEM with cohesive segments model in Abaqus®.