

CYCLIC COHESIVE ZONE MODELS AND ITS APPLICABILITY TO FRETTING FATIGUE CRACK PROPAGATION

K. Pereira¹, S. Bordas², S. Tomar², R. Trobec³, M. Depolli³, G. Kosec³, M. Abdel Wahab¹

¹Department of Electrical energy, systems and automation, Ghent University, Belgium

²Faculté des Sciences, de la Technologie et de la Communication, Université du Luxembourg, Luxembourg

³Department of Communication Systems, Jozef Stefan Institute, Slovenia

Abstract: This paper presents a brief discussion of cohesive zone models (CZM) and their application for predicting fretting fatigue crack propagation. Firstly, an introduction on fretting phenomenon is given, followed by an overview of the recent finite element (FE) modelling techniques used to investigate fretting fatigue. In the literature, the majority of models, used to predict crack propagation under fretting conditions, are based on Linear Elastic Fracture Mechanics (LEFM), relying on the assumption of small-scale yielding and also requiring the definition of an initial crack. Nevertheless, due to the high stresses at contact, fretting is a highly non-linear phenomenon and plastic deformations are to be expected. As a result, it is likely that models based on LEFM predict incorrect crack propagation paths and fatigue lives. Cyclic cohesive zone models might be an interesting option to deal with this problem. This methodology is able to capture non-linear effects and also can be used coupled with a plasticity model, being a powerful tool for fracture studies of situations where LEFM assumptions are not fulfilled.

Keywords: fretting fatigue crack propagation; cyclic cohesive zone models

1 INTRODUCTION

Fretting happens when contacting surfaces are subjected to high normal loading and small amplitude cyclic relative movement. This combination of contact and oscillatory sliding motion may cause unexpected premature failure due to fretting fatigue, a common process that affects many mechanical assemblies (such as bolted joints, shrink-fitted shafts and dovetail joints). As contacting parts are subjected to vibrations during their service life, fretting fatigue becomes an inevitable damage process that must be considered. Due to its importance, this phenomenon has been vastly studied in the literature over the last few decades.

It is known that many different variables (surface finishing, coefficient of friction, normal load, relative slip amplitude, among others) impact on the characteristics of fretting and, therefore, on the component's lifetime. In order to evaluate the effects of those variables, different laboratory tests are normally used. One of the most common is a cylinder-on-pad set-up, as illustrated in Fig. 1. In this configuration, two cylindrical fretting pads are placed in contact with a flat specimen, through the application of a constant clamping or normal force F . The specimen is fixed at one side and the other side is exposed to an oscillatory bulk stress σ_{axial} , causing small amplitude oscillatory relative movement between the contacting surfaces. Upon application of the bulk stress, the compliance springs transmit an oscillatory tangential force Q at the pads. Under fretting fatigue conditions, the absolute value of the tangential load $|Q|$ is smaller than the product of the coefficient of friction μ by the normal load F and the contact is divided into two regions: a stick zone and a slip region.

As presented by Jeung et al. [1], under fretting conditions, the fatigue limit of a material may be shortened up to 50%. It is known that the influence of contact stresses distributions on the crack and vice-versa makes the crack growth under fretting conditions significantly different than under plain fatigue [2]. This contact-crack interaction is particularly important for cracks' length smaller than the magnitude of the contact zone dimension [3] and impact directly on the lifetime of the component. It is known that the stress field near the contact region is variable, multiaxial and non-proportional [4], which increases the complexity of the phenomenon. In the regard of modelling crack propagation under fretting fatigue, numerical methods have been used in the literature.

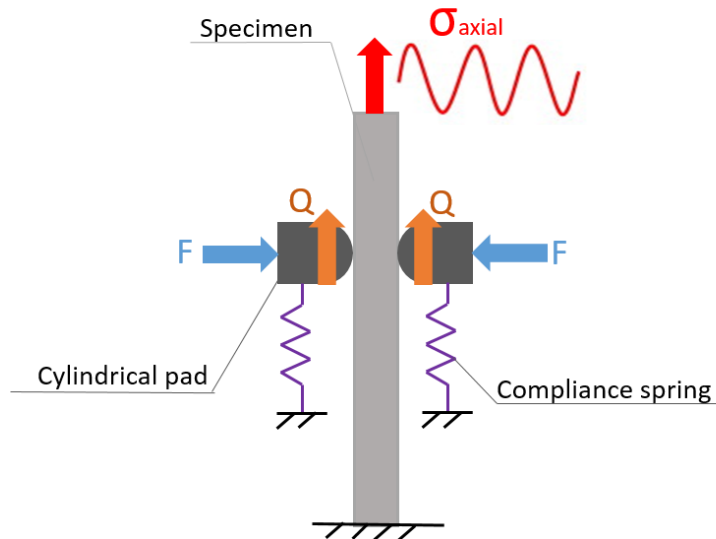


Fig. 1 Cylinder-on-plane configuration of a fretting fatigue experiment.

In the 90's, finite element (FE) was already an important tool used to help researchers to better understand and predict fretting. For instance, McVeigh and Farris [5] used finite element analysis to study the influence of the bulk loading σ_{axial} on the contact stresses distributions. Their results showed very good agreement between analytical prediction of principal stresses and the finite element analysis, validating their analytical solution. Petiot et al. [6], combined the contact stress calculated from an elastoplastic FE analysis with a multiaxial fatigue criterion being able to predict crack initiation location for a steel/steel cylinder-on-flat in good agreement with experiments. Tur et al. [7] also performed an elastoplastic FE analysis and showed that the plastic zone started at the edge of the contact area and that the effects of contact stresses decayed rapidly as the distance from the contact increased. Many other studies [8]–[11] were later published using FE analysis to predict fretting fatigue crack initiation. Regarding crack propagation analysis, recently, many works [2], [12]–[15], have been using extended finite element method (XFEM) instead of classical FE method due to its computational advantages. It has been applied to prediction of crack propagation path and as well as propagation lifetime [16]. In the case of complete contact, Giner et al. [17] predicted successfully the crack propagation path using a propagation criteria based on the minimum shear stress range along the entire loading cycle.

Most numerical models are based on Linear Elastic Fracture Mechanics (LEFM) [13], [18]–[20] and do not account for the significant plastic deformations to be expected due to the high stresses at contact. Gandiolle and Fouvry [21] showed that plasticity impacts significantly the numerical prediction of crack nucleation and crack arrest boundaries and therefore its effects should be accounted for. An interesting option to incorporate this plasticity effect on the numerical analysis is to treat the fracture using cyclic cohesive zone models (CCZM). In this regard, the main goal of this paper is to present possibilities of using cyclic cohesive zone approach to model fretting fatigue crack propagation. In section 2, the basic principles of cohesive zone models are presented and, in section 3, their application in fretting is discussed.

2 COHESIVE ZONE MODELS

Cohesive zone model is an alternative methodology to assess damage and failure of materials with or without cracks. In comparison with LEFM, cohesive zone models eliminate the stress singularity at crack tip and they account for nonlinear material behaviour. When compared with continuum damage mechanics, CZM may be understood as a damage model that considers failure only by the material separation and not by its deformation [22]. Cohesive zone models have their initial development dated back in the 60's with the introduction of Dugdale's and Barenblatt's strip models. Over the last 40 years, many models have been proposed for different materials and analysis. Brocks and Cornec [23] presented a detailed literature review on the topic, discussing the most common models and presenting different applications for CZMs. Park and Paulino [24] published another literature review on the topic, focusing on a critical discussion of the different models and their applicability.

As illustrated in Figure Fig. 2, CZM is centred on the existence of a fracture process zone ahead of the real crack tip. The material separation, and thus failure, depends upon the tractions (in normal and tangential to the crack face directions) inside this cohesive region. Consequently, the cohesive properties can be expressed on traction-separation laws (cohesive laws) that will be briefly discussed in the next section.

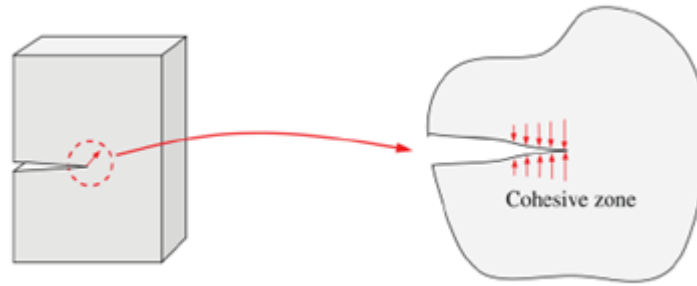


Fig. 2 Schema of a cohesive zone model [24].

2.1 Common traction-separation laws

The most common cohesive laws in the literature contain at least three parameters: the cohesive strength T_0 , the fracture energy dissipated by the cohesive elements Γ_0 (area below of the traction-separation curve) and one or more critical values of separation ($\bar{\delta}_0$, $\bar{\delta}_1$ and/or $\bar{\delta}_2$).

As discussed by Brocks and Cornec [23], for most traction-separation curves, the traction becomes zero if the separation reaches the critical value $\bar{\delta}_0$ and the material loses its load carrying capacity. An exception is the exponential law (Fig Fig. 3b), the traction at this point still 10.5% of T_0 . Also, for most curves, the dissipated energy Γ_0 can be reduced to the J-integral for Mode I, under assumptions of the elastic-plastic fracture mechanics, and $\bar{\delta}_0$ can be seen as the fracture parameter CTOD. For ductile materials, T_0 can be estimate as $3\sigma_y$.

Depending on the material, different traction-separation curves can provide more accurate results than others. Fig Fig. 3 illustrates the most common laws in the literature. Both polynomial and exponential functions have been used to model ductile materials failure. For brittle materials, the linear softening function is an option, but a more versatile approach will be adopting a trapezoidal function. A brief discussion on those curves is also available in the work from Scheider [25].

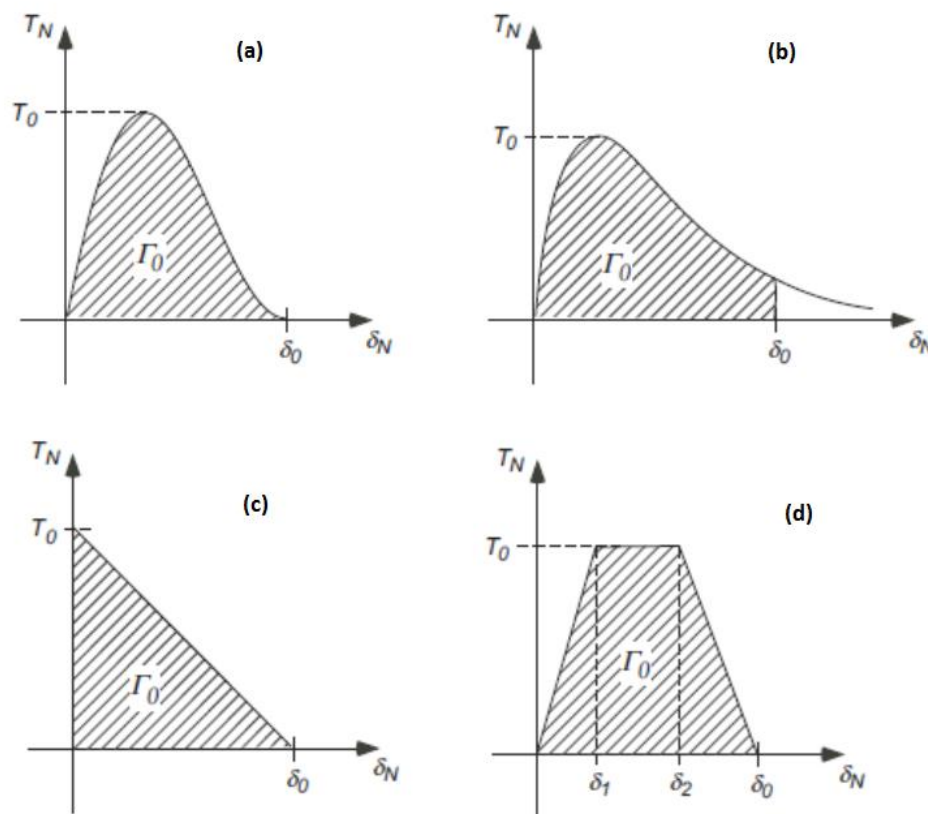


Fig. 3 Common traction-separation laws: (a) polynomial function; (b) exponential function; (c) linear softening and (d) trapezoidal function [23]

2.2 Cohesive zone approaches

Regarding its numerical implementation, classically, the cohesive response is described using interface elements. In this technique, the model is divided into two parts: damage free continuum elements with an arbitrary material law (elastic, elastoplastic, among others) and the boundaries of those elements are connected by zero-thickness interface cohesive elements incorporating the damage of the material. In this case, when damage occurs at the interface elements, they fail and the continuum elements are disconnected from each other. It is important to notice that using this approach, the crack can only grow at the boundaries of the continuum elements and, therefore, the directions of propagation are dependent on the initial mesh. Su et al. [26] implemented this methodology embedding cohesive interface elements already available in ABAQUS in a mesh of continuum elements, using an in-house script that modified the INP file from ABAQUS. They used their model to study crack propagation of quasi-brittle materials with inclusions. Later, Su et al. [27] extended their methodology to 3D case and their results showed good agreement with experiments and previous literature data.

In general, the mechanical response of an arbitrary structure is a combination of the cohesive model and the bulk material behaviour. Another technique to define cohesive would be thus unifying both responses (cohesive model and bulk material properties) in the same element definition. This methodology is called strong discontinuity approach and have been used in the literature to ...

2.3 Cyclic cohesive zone models

The first CZMs developed were used to simulate crack propagation under monotonically load and the process zone could be formulated based on reversible traction-separation laws. In the 90's, the first irreversible models to account for unloading-reloading hysteresis were proposed. For instance, Tvergaard [28] account for it by introducing a linear unloading path that pointed towards by the origin of the traction-separation diagram. The loading and unloading paths did not coincide any more, introducing irreversibility to the system.

Another possibility to account for irreversibility is to create a damage variable that affects the value of the cohesive strength T_0 and its stiffness (slope of the traction-separation curve). In this way, a damage evolution equation could be used to incorporate the effect of cyclic loading in the cohesive zones parameters. This types of models are called cyclic cohesive zones (CCZM) and they enable the use of cohesive zone models to predict crack propagation under fatigue scenarios. Kuna and Roth [22] presented a good selection of works that have been done CCZM to predict fracture crack growth rate.

3 COHESIVE ZONE MODELS AND FRETTING FATIGUE

Little in fretting fatigue has been done using the cohesive zone methodology. Zhang et al. [29] have coupled CCZM to XFEM in order to study the effect of residual stress in fretting fatigue lives. In a later work, they used the same methodology to investigate the effects of tangential force on fretting fatigue [30]. Although the goal of their papers was not to accurate predict crack paths, their prediction is already an improvement from previous literature [16]. Even though no experimental validation of their model was done, results looks promising indicating that this might be a good approach to treat the problem.

4 CONCLUSIONS

This review presented an overview of the CZM methodology and its applicability to take into account the plasticity in fracture simulations. CCZM approach has already been recently used in computational simulations of fretting fatigue and it is providing better understanding of the fretting phenomenon and providing reasonable crack propagation predictions.

As future work, we intend to apply the discussed methodology in fretting simulations and validate the results with experimental data. Firstly, we intend to develop crack propagation model using cohesive interface elements already implement in ABAQUS. Then, a strong discontinuity approach is going to be used in conjunction with XFEM, avoiding the disadvantages of interface element approach regarding the mesh dependency of the results and also the large computational cost.

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