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A level set model for simulating fatigue-driven delamination in composites

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ABSTRACT

This paper proposes a level set model for simulating delamination propagation in composites under high-cycle fatigue loading. For quasi-static loading conditions, interface elements with a cohesive law are widely used for the simulation of delamination. However, basic concepts from fatigue analysis such as the notion that the crack growth rate is a function of energy release rate cannot be embedded in existing cohesive laws. Therefore, we propose a model in which the cohesive zone is eliminated from the computation while maintaining the flexibility that the crack shape is not bound to element edges. The model is able to predict the delamination growth rate and its front shape accurately. To demonstrate the validity of the model, several tests under different fracture modes are conducted and the results are compared with experimental data, analytical solutions and results from cohesive zone analysis.

1. Introduction

Composite materials are increasingly used in engineering structures such as wind turbines and aircrafts where fatigue is a common cause of failure. Delamination is one of the most important modes of failure because of the relative weakness of the interface between the layers of composite laminates. Therefore, computational tools are needed to predict fatigue-driven delamination in composites. Experimental observations from fatigue tests can generally be described well with the phenomenological Paris law (see Fig. 1) which formulates the crack growth rate as a function of the energy release rate. The Paris law relates the load and material-dependent notion of crack growth under cyclic loading to the strain energy release rate with a power law:

$$\frac{da}{dN} = C\left(\frac{\Delta G}{G_c}\right)^m \tag{1}$$

where da/dN is the crack growth rate, G_c is the fracture energy, and ΔG is the cyclic variation of energy release rate. The material parameters C and m must be determined experimentally. The main subject in implementing the Paris law in a model is computing the energy release rate due to crack growth. Two main approaches to crack growth modeling, namely damage mechanics and fracture mechanics, provide different solutions for this issue.

The first approach is damage mechanics. In this context interface elements with a cohesive law have been commonly used to simulate delamination under quasi-static loading conditions. Due to the successful application of these models, researchers have tried to extend cohesive laws to high-cycle fatigue analysis. However, cohesive laws do not define the energy release rate and crack growth rate explicitly. Therefore, a straightforward implementation of the Paris law in a cohesive law is not possible.

In [1–5], the cohesive law has been modified to incorporate the effect of cyclic loading. These models add a new damage variable to the quasi-static damage variable to account for fatigue degradation. The rate of this fatigue parameter is related to the crack growth rate computed from the Paris law. The strain energy release rate in the Paris law formulation is extracted from cohesive interface elements by integrating the traction–displacement response of these elements. However, this integration must be performed before the actual response is known. Therefore, idealization of the cohesive fatigue response is needed. This idealization of the cohesive law and the lack of an accurate analytical formula for estimating the fatigue cohesive zone make them imprecise in fatigue analysis. Recently, Kawashita et al. [6] proposed an updated method which is independent of estimating the cohesive zone length. This method provides a more accurate extraction of the energy release rate; however, this improvement comes at the cost of implementing crack tip tracking algorithms for interface elements.

In the second approach, fracture mechanics, the virtual crack closure technique (VCCT) has been widely used to compute energy

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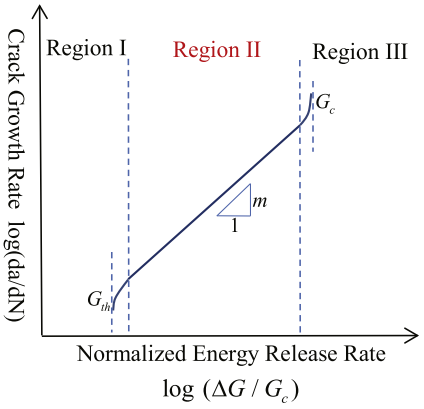

Fig. 1. Typical pattern of crack growth rate: Paris law is valid in region II.

release rates for delamination modeling. With this technique, the energy released during a virtual crack extension Δa, is computed as the energy required to close the crack over the same distance. This method is not valid in bimaterial interfaces [7]; therefore, a thin homogeneous interphase layer should be considered at the interface [8], and a very fine mesh is needed around the crack front. Zou et al. [9] have solved the problem of VCCT in bimaterials without assuming an interphase layer. This method applies the kinematic formulation of shell theory; which has a consequence, that the stress singularity around the crack tip is transformed into a discontinuity in stress resultants over the plane through the thickness of the laminate. The total energy release rate can be computed from these discontinuities. Later, Van der Meer et al. [10] improved the accuracy of this method for coarse meshes by including concentrated bending moments in the expression for mode I dissipation.

The VCCT requires the crack front to be positioned along element boundaries which leads to a poor estimate of energy release rates when the crack growth is not self-similar. This problem does not apply to the level set model presented in [11], because this model computes the energy release rate from local quantities instead of nodal values. In this method, which also belongs to the category of fracture mechanics, the crack front location is implicitly described with the level set method [12]; therefore, this method allows for representing arbitrary shape of the crack front and continuous growth of the crack. The method was extended for full crack growth analysis with out-of-plane deformations by modeling a laminate as a stack of shell elements for small deformations in [13].

In this paper, the level set model for delamination is applied to high-cycle fatigue analysis. Because the model is based on fracture mechanics, it is very suitable for the implementation of the Paris law. To define the crack front location and compute the energy release rate, the level set approach developed in [11] and the modified formulation of Zou's method [10] are used, respectively.

This paper is structured as follows. Section 2 describes the formulation of the level set model for fatigue analysis, and in Section 3, to validate the level set model, numerical predictions are compared with experimental data.

2. Methods

In high-cycle fatigue applications which may involve more than 10^6 cycles, tracking loading/unloading and stiffness degradation on a cycle-by-cycle basis is computationally impractical; therefore, instead of the real cyclic load which is oscillating between minimum and maximum of applied load, a load envelope is considered (see Fig. 2). In this loading envelope strategy, a constant numerical load or displacement is applied which is equal to the maximum value of the cyclic boundary conditions. In every time step, a certain number of cycles ΔN is passed. The crack growth per time step is therefore computed by multiplying the crack growth rate da/dN from Eq. (1) with the time step size ΔN.

The model is comprised of two submodels, the cracked laminate model and the crack growth model, which are solved with a staggered solution scheme. The cracked laminate model computes the displacement field of a partially delaminated plate, where the elements containing the crack front have a special kinematic formulation, which is explained in Section 2.1. The second submodel takes the displacement field from the cracked laminate model and computes the energy release rate for delamination growth. The computed energy release rate is used to compute a velocity field at the crack front. Based on this velocity, the level set field is updated and a new front location is obtained. The second submodel, from computation of energy release rate to the level set update, is explained in Section 2.2.

2.1. Cracked laminate model

The central idea in the level set model for delamination is that the location of the crack front is described with the level set method. This means that there is a sharp front that does not have to be aligned with the finite element boundaries. In other words, the front can be located inside the finite elements. In the current implementation a laminate is represented with shell elements for small displacements. In this model (see also Van der Meer et al. [13]), there are two layers of elements in the cracked and uncracked subdomains which are connected in the uncracked part. Each layer is composed of five parameter shell elements (two rotational and three displacement on each node). In order to achieve the connection between the layers of elements in the uncracked subdomain, a displacement-only version of five parameter shell is used. The resulting mesh is similar to a mesh with solid-like shell elements, except that all connected nodes with the same (x, y) coordinate share a single z-displacement degree of freedom [13].

The potential energy of the laminate (Π) based on First-order Shear Deformation Theory (FSDT) is given by [14]:

$$\begin{aligned}\Pi_{FSDT}(\hat{\mathbf{u}}, u_3, \boldsymbol{\phi}) = &\frac{1}{2}\int_\Omega \mathbf{A}\nabla_s\hat{\mathbf{u}}\cdot\nabla_s\hat{\mathbf{u}}d\Omega + \int_\Omega \mathbf{B}\nabla_s\hat{\mathbf{u}}\cdot\nabla_s\boldsymbol{\phi}d\Omega \\ &+\frac{1}{2}\int_\Omega \mathbf{D}\nabla_s\boldsymbol{\phi}\cdot\nabla_s\boldsymbol{\phi}d\Omega + \frac{1}{2}\int_\Omega \mathbf{H}(\nabla u_3+\boldsymbol{\phi}) \\ &\cdot(\nabla u_3+\boldsymbol{\phi})d\Omega - \Pi_{ext}(\hat{\mathbf{u}}, u_3, \boldsymbol{\phi})\end{aligned} \quad (2)$$

where $\hat{\mathbf{u}}$ is the in-plane displacement vector of the mid-surface, $\boldsymbol{\phi}$ collects the rotation components, and u_3 is the out-of-plane displacement. $\mathbf{A}$, $\mathbf{B}$ and $\mathbf{D}$ reflect the effects of membrane, and bending deformations and their coupling respectively, while $\mathbf{H}$ is the corrected shear stiffness. The symbol ∇_s indicates the symmetric part

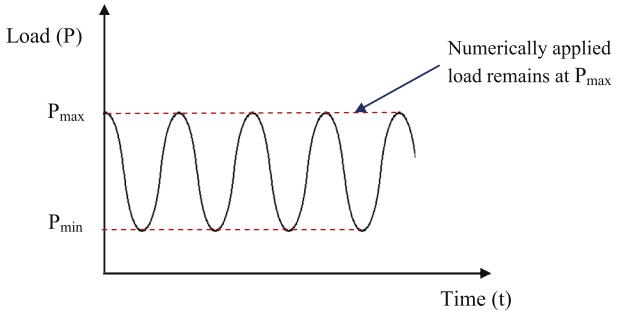

Fig. 2. Actual cyclic load and numerically applied load based on loading envelope strategy.