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A novel method for fatigue delamination simulation in composite laminates

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ABSTRACT

This paper presents a FEM model for the simulation of delamination in composite materials under fatigue loads using extended cohesive interface elements. A virtual fatigue damage variable is proposed to continually locate the crack tip elements with local element information only. The proposed method allows for a fully automatic identification of crack tip elements without any global information. Once crack tip elements are identified, the fatigue damage accumulation is determined by a modified Paris-law with a strain energy release rate correction method to reduce mesh sensitivity. The predicted delamination growth rates of different mesh sizes were compared with experimental results from open literature using a mode-I Double Cantilever Beam specimen and a mode-II 4-point End Notch Flexure specimen respectively. In all cases good agreement was obtained with weak mesh dependency.

1. Introduction

Nowadays cohesive elements are wildly used to simulate damage propagation in composite materials under static loads. Particularly for interfacial failure of laminated fiber reinforced composite materials, in which delamination is considered to be one of the most critical failure modes since it can significantly reduce the structure's ability to carry loads and often occur at relatively low loads. Therefore, prediction of delamination is of great interests for the purpose of composite structure design.

Cohesive interface elements are based on the cohesive zone model (CZM) which was originally proposed by Dugdale and Barenblatt [1,2]. CZM assumes the existence of a softening zone at the tip of the crack where stresses are not zero and relative displacements can occur. The model allows for not only a new crack to initiate and also for existing cracks to grow. In a cohesive element, damage onset is determined by predefined interfacial strength and crack propagation is realized by using one or more damage variables. The damage variables are introduced to describe the loss of the capability of an element to carry loads. Traditional cohesive elements offer a good prediction ability of interfacial delamination, matrix crack and even fiber break under static loads [3–8]. Fig. 1 shows the quasi-static response of a typical cohesive element formulation. It is a traction-displacement curve, which in most cases is a bilinear curve and is comprised of two segments: the first is the elastic segment where the element shows a linear elastic response; the second one is the softening segment where a damage variable is applied to reduce the stiffness of elements as a simulation of damage propagation. Although a traction-displacement curve can come in different shapes, a global load-displacement response is relatively insensitive to the exact shape of the traction-displacement curve [9]. However, the area enclosed by the curve must equal the fracture toughness of the material to ensure an accurate simulation of the damage propagation.

More recently, the CZM approach has been further extended to model the delamination propagation under cyclic loads in composite materials. Paris-law is incorporated so that the prediction of damage growth under cyclic loads is possible. One major problem concerning this type of models is how to convert the global delamination growth rate obtained from Paris-law into the damage variable accumulation rate of a local element. One solution recently proposed by Harper et al. [10] is to use a fatigue damage length ahead of the numerical crack tip. They assumed the fatigue damage length was related to the integrated strain energy release rate of interface elements and can be estimated accordingly. They obtained fairly good results by assuming the fatigue damage length was half of the quasi-static damage length. Luiz F. Kawashita et al. [11] then proposed a nonlocal crack tip tracking algorithm that can identify the crack tip elements by exchanging information between adjacent elements whenever a cohesive element fails. Thus a crack

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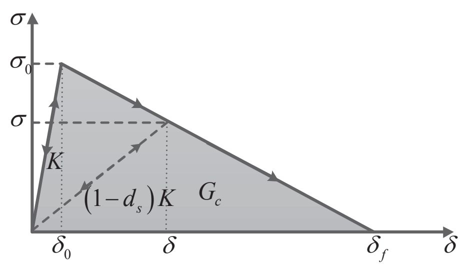

Fig. 1. Bilinear constitutive law for cohesive elements.

front can be tracked and only the crack tip elements undergo fatigue degradation. By employing this algorithm, the global estimation of a fatigue damage length is no longer required. Instead only the length of crack tip elements in the damage propagation direction is needed. This provides a more reasonable conversion between the global delamination growth rate and the local fatigue damage variable accumulation rate. However, the implementation does add a certain degree of complexity by using a separate algorithm to do the nonlocal computation. In this paper, a local crack tip tracking method is proposed to identify crack tip elements without any global information or any additional algorithm so that local element lengths can be applied to convert the global delamination growth rate to a local damage accumulation rate. Another issues related to the extended cohesive interface elements is the mesh dependency problem. This is a result of both the underestimate of strain energy release rate when extracted directly from interface elements and the large fatigue exponent parameter of composite materials. Very fine meshes were therefore adopted in early works [10,12] to avoid this problem. However, this is not applicable when the structure is complex and large due to the limitation of computational resources. Therefore, a model with reduced mesh sensitivity is needed for real applications, for this to be achieved, a strain energy release rate correction method is proposed to mitigate the mesh dependency problem to reduce computation time.

The paper is organized as follows. Section 2 gives a recap of the important features regarding the constitutive law of interface elements under static loads. The traditional cohesive element is then extended to incorporate fatigue damage. In Section 3, a virtual damage variable is proposed to continually track crack tip elements so that no global estimation of fatigue damage length is needed, instead, a local element length is used to convert delamination growth rate to damage variable accumulation rate. In Section 4, a strain energy release rate correction method is proposed to help avoid the mesh dependency problem. Section 5 gives details of the FEM model for model validation. The fatigue damage model is then validated with experimental data from open literature in Section 6. Finally, main conclusions of the presented work are drawn in Section 7.

2. Cohesive element constitutive law

2.1. Static damage

The commonly used bilinear cohesive constitutive law has been implemented in commercial software ABAQUS and takes the form of 8-node three dimensional elements with reduced integration point. The full details regarding the constitutive law of cohesive elements can be easily accessed in open literature [1–8], thus only a brief recap of the important features are given below.

In a bilinear cohesive formulation, the initial response is linear elastic before damage initiation as shown in Fig. 1 [4,7,8]. The linear elastic part is defined using a penalty stiffness parameter, K, which is usually considerably larger than surrounding materials to ensure a stiff connection between two faces of the interface before damage. The penalty stiffness together with the interfacial strength, σ_0, defines the damage onset displacement jump δ_0.

When interface elements are loaded to a certain point, damage onset is assumed. Under pure Mode-I or Mode-II situation, damage initiates when corresponding displacement jump reaches δ_0 or the traction force reaches the interfacial strength. Under mixed-mode loading, damage onset is determined by the following quadratic damage criterion and the critical displacement jump and traction force are recorded as onset values [4,7,8].

$$\sqrt{\left(\frac{\langle\sigma_{11}\rangle}{\sigma_n}\right)^2+\left(\frac{\sigma_{12}}{\sigma_s}\right)^2+\left(\frac{\sigma_{13}}{\sigma_t}\right)^2}\geq 1 \tag{1}$$

where $\langle\rangle$ is the MacAuley bracket, defined as $x = 1/2(|x|+x)$, σ_{11} is the normal traction force, σ_{12} and σ_{13} are the shear traction forces. σ_n, σ_s and σ_t are the corresponding interfacial strengths.

Once damage is onset, interface elements enter a softening zone where the stiffness of the elements is gradually reduced to 0. During this damage propagation process, the energy dissipated by an interface element must equal the fracture energy of the material to ensure an accurate simulation of damage propagation. Under single mode loading, this is achieved by simply equating the area under traction-displacement curve to the corresponding fracture toughness. Under mixed-mode loading, an equivalent displacement jump is defined as Eq. (2) to drive the damage process [4,7,8].

$$\delta = \sqrt{\langle\delta_{11}\rangle^2+\delta_{shear}^2} \tag{2}$$

in which δ_{11} is the mode-I displacement jump, which is perpendicular to the fracture plane; δ_{shear} is the displacement jump in shear mode, which is parallel to the fracture plane and is defined as [4,7,8]:

$$\delta_{shear} = \sqrt{\delta_{12}^2+\delta_{13}^2} \tag{3}$$

A mixed-mode energy criterion is then applied to obtain the fracture energy under mixed-mode loading. In this case the following B-K criterion [13] is applied:

$$G_{mix} = G_{IC} + (G_{IIC} - G_{IC})B^{\eta} \tag{4}$$

where η is a material parameter ranging from 1 to 2, G_{IC} and G_{IIC} are fracture toughness of mode-I and mode-II respectively and B is the B-K parameter, calculated as:

$$B = \frac{\langle\sigma_{11}\rangle\langle\delta_{11}\rangle}{\langle\sigma_{11}\rangle\langle\delta_{11}\rangle+\sigma_{12}\delta_{12}+\sigma_{13}\delta_{13}} \tag{5}$$

It should be noted that the implemented mixed-mode criterion can be easily switched to other criteria according to different types of materials used.

In the bilinear formulation, a linear softening law is applied to gradually degrade the stiffness to simulate the damage propagate process. Under quasi-static loading, a scalar static damage variable, d_s, is used to record the accumulated static damage [3,4]:

$$d_s = \frac{\delta_f(\delta-\delta_0)}{\delta\left(\delta_f-\delta_0\right)} \tag{6}$$

where δ_f is the relative displacement jump at final failure, which is determined by the fracture energy of the material and the characteristic length of the interface element, L_c: