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An improved delamination fatigue cohesive interface model for complex three-dimensional multi-interface cases

Chongcong Tao[a,b], Supratik Mukhopadhyay[b], Bing Zhang[b], Luiz F. Kawashita[b], Jinhao Qiu[a], Stephen R. Hallett[b,*]

[a] State Key Laboratory of Mechanics and Control of Mechanical Structures, Nanjing University of Aeronautics and Astronautics, Yudao Street 29, Nanjing 210016, China
[b] Bristol Composites Institute (ACCIS), University of Bristol, Queen's Building, University Walk, Bristol BS8 1TR, UK

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ABSTRACT

This work presents a cohesive interface model for predicting interlaminar failure of composite laminates under tension-tension fatigue loading. The model features improvements on previous formulations and utilizes four-integration-point elements, which offer several new advantages, while maintaining the merits of the previous single-integration-point elements. An element-based crack tip tracking algorithm is incorporated to confine fatigue damage to crack-tip elements only. A new local rate approach is proposed to ensure accurate integration of strain energy release rate from local elements. Furthermore, a dynamic fatigue characteristic length is proposed to offer a more accurate estimation of fatigue characteristic length in complex three-dimensional cases. Fatigue initiation is incorporated by using a strength reduction method, without changing the propagation characteristics. The numerical approach has been verified and validated using multiple cases and was then applied to fatigue damage development in open-hole laminates, where a good agreement between numerical analysis and experimental results was obtained.

1. Introduction

Composite laminates are seeing increasing usage due to their high specific stiffness and strength, especially in the transportation industry, where weight savings using composite materials compared to traditional metallic materials result in significant fuel consumption reduction. In addition, composite laminates can also be tailored due to their highly anisotropic behaviour and stack sequence, to provide much improved performance.

Along with all these advantages, composite laminates also come with some weaknesses. For example, multiple damage modes can exist simultaneously, making composites vulnerable to certain loads, especially on the unreinforced interfaces between plies, which can be damaged at relatively low stress, leading to severe performance degradation. Among these damage modes, delamination is usually considered the most severe [1]. Delamination can be further facilitated by manufacturing defects/damage [2], making it one of the most widely researched issues for composite laminate failure [3].

Under cyclic loads, delamination becomes more important due to its low initiation stress. Previous experiments on open hole specimens indicated a shift of failure mode from fibre dominated pull-out failure mode under static loads to delamination dominated failure modes under cyclic loads [4]. Therefore, it is of great interest to be able to simulate the initiation and propagation of delamination under cyclic loads and evaluate the fatigue life of engineering structures.

Cohesive zone models (CZM), first proposed by Dugdale [5] in 1960, have been greatly developed and recently have become quite popular and efficient for predicting delamination initiation and propagation under static loads [6,7]. In the last decade, traditional CZM has been extended to solve fatigue problems, a recent review by Bak et al. [8] covers some of the following papers. Nguyen et al. [9] and Yang et al. [10] developed the CZM approach to model generic fatigue crack growth, while Robinson et al. [11] focused on the delamination propagation in composite materials, followed by Turon et al. [12], Harper and Hallett [13], Bak et al. [14], Nojavan et al. [15] and Amiri-Rad et al. [16]. Early work of extending traditional cohesive elements to fatigue cohesive elements [12,13] required an estimation of the cohesive fatigue length ahead of the numerical crack tip, which is dependent on the geometry and loading configuration [17]. This significantly limits the applicability of these models in complex three-dimensional problems. Kawashita and Hallett [18] proposed a crack tip tracking algorithm to confine the fatigue damage accumulation to only the elements pertaining to the crack tip. This is consistent with a clear definition of crack front in linear elastic fracture mechanics, on which

* Corresponding author.
E-mail address: stephen.hallett@bristol.ac.uk (S.R. Hallett).

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the Paris law for fatigue crack growth is based. It also provides an algorithmic advantage of element-by-element fatigue crack growth, so the problem of finding a global fatigue cohesive zone length is reduced to finding a local element fatigue characteristic length. The latter can be relatively easily estimated based on the dimensions of the crack tip elements. Similar work has been done by Tao et al. [19], where crack tip tracking is realised, based on local information of elements using a virtual fatigue damage variable. Another issue related to these Paris-law-based fatigue propagation models is the over-prediction of life in fatigue initiation dominated cases, as demonstrated by May and Hallett [20]. Although a solution is provided in their later research [21], the use of a complicated two-step finite element analysis, along with an estimated initiation zone length, makes this difficult to implement for complex three-dimensional problems. It should be noted that some of the above models [11,14–17] were implemented with single-integration-point elements, since the simple relationship of one integration point to one element makes it much easier for implementation. In most static analysis though, four-integration-points elements are preferred due to their better robustness and precision. For practical purposes, it is very helpful to have a unified static and fatigue analysis tool without the need to change element type between analysis, therefore, the fatigue formulation proposed in this work is extended to four-integration-point elements, which also offers some distinctive advantages over single-integration-point elements in fatigue analysis.

In this paper, an improved four-integration-point fatigue cohesive element model is proposed. Whilst the advantages of tradition CZM approaches and single-integration-point fatigue element model are preserved, new features such as a local rate approach, a dynamic fatigue length and a new fatigue initiation approach are incorporated to further improve its applicability in complex three-dimensional problems. The improved model is then used to analyse the fatigue damage development in open-hole laminates, including both ply-level and sub-laminate level scaled tests [4,22]. An earlier formulation of the fatigue model used here was only able to model the ply-level case [23], but was unable to predict the sub-laminate case. With the new improvements in this work, a robust cohesive element model with the capability to analyse both static and fatigue damage developments in multiple cases including single-interface delamination growth (both fatigue initiation-dominated and propagation-dominated) cases and complex three-dimensional multi-interface cases without the need for model calibration is achieved.

This paper is organised as follows. In Section 2, the traditional CZM formulation is outlined, followed by a detailed description of the proposed fatigue model. The new model is validated in Section 3 using single-interface delamination growth models in terms of both fatigue initiation and fatigue propagation. In Section 4, the proposed model is applied to analyse the fatigue damage development in open-hole laminates. Finally, conclusions are drawn in Section 5.

2. Four-integration-point fatigue cohesive formulation

The fatigue cohesive formulation proposed in this paper follows on from the earlier formulations of Harper and Hallett [13] and Kawashita and Hallett [18] and is implemented in the explicit finite element software LS-Dyna. It follows an envelope loading scheme [10–13,18,19] as shown in Fig. 1. The loading is divided into two stages: smoothly ramping up from zero to peak fatigue load in stage I, and holding the load constant in stage II at its maximum value while activating the fatigue law so both static and fatigue damage can accumulate. The beginning of the second stage is marked by a fatigue initiation time t_f. The advantage of this over a cycle-by-cycle scheme is that it does not require a continual monitoring of loading and unloading hysteresis, thus offering greater computational efficiency. The number of elapsed cycles in the numerical model is equal to the product of the analysis time in the explicit solution and a pseudo (numerical) fatigue frequency f so the cycles are proportional to the elapsed analysis time.

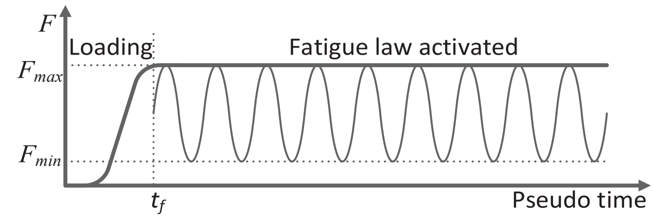

Fig. 1. Envelope loading.

The cohesive formulation described below has been implemented in the form of 8-node three-dimensional linear cohesive elements with four integration points using a user-defined material subroutine.

2.1. Static damage

In a traditional cohesive formulation, the damage propagation is driven by relative displacements between top and bottom surfaces of the element and is represented by stiffness degradation, with a single scalar damage variable D_s [6,7,24–26]. A detailed description regarding static damage can be found in Jiang et al. [7], so only a recap of some essential aspects is given below.

The driven relative displacement under mixed mode loading is referred as δ_m, which includes both mode-I (opening) and resultant mode-II (shear) components, i.e.,

$$\langle \delta_I = \delta_{33} \rangle \tag{1}$$

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

$$\delta_m = \sqrt{\delta_I^2 + \delta_{II}^2} \tag{3}$$

where δ_{33} is the out-of-plane relative displacement of the two surfaces of a cohesive element, δ_{12} and δ_{13} are in-plane transverse and longitudinal relative displacements respectively; $\langle \cdot \rangle$ is the McCauley bracket, i.e. $\langle \cdot \rangle = \max(\cdot,0)$.

A simple bilinear constitutive law shown in Fig. 2(a) is adopted here. Three basic parameters are required to define this relationship between traction forces and relative displacements: the initial stiffness K, the damage initiation relative displacement δ^0 and the failure relative displacement δ^f. The initial stiffness is typically a very large parameter to ensure a stiff connection of the two surfaces prior to damage. The initiation relative displacement is determined according to both the stiffness and the interfacial strength. The failure displacement is calculated based on the critical strain energy release rate G_c so that the area under the triangle in Fig. 2(a) equals G_c.

Under mixed-mode loading, effective values for the three parameters can be calculated based on the ratio of the two pure mode displacements δ_I and δ_{II}. For damage initiation, a quadratic damage initiation criterion applies:

$$\sqrt{\left(\frac{\sigma_I}{\sigma_{Imax}}\right)^2 + \left(\frac{\sigma_{II}}{\sigma_{IImax}}\right)^2} = 1 \tag{4}$$

where σ_{Imax} and σ_{IImax} are the interfacial strengths for mode-I and mode-II respectively. And a linear criterion is used for failure:

$$\frac{G_I}{G_{IC}} + \frac{G_{II}}{G_{IIC}} = 1 \tag{5}$$

The displacement-driven static damage variable is thus defined as:

$$D_s = \frac{\delta_m^t - \delta_m^0}{\delta_m^f - \delta_m^0} \tag{6}$$

where δ_m^t is the mixed-mode displacement at the current increment t, δ_m^0 is the displacement at damage initiation and δ_m^f is the displacement for failure. Considering the irreversibility of damage, the static damage variable at time increment t is