Composite Structures 204 (2018) 500–512

Contents lists available at ScienceDirect

Composite Structures

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

Modelling delamination migration using virtual embedded cohesive elements formed through floating nodes

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ARTICLE INFO

Keywords:
Cohesive element
Delamination migration
Floating node method

ABSTRACT

Delamination migration is a common failure mode for composite laminates and the modelling technique remains challenging. For a complete progressive failure modelling, failure modes including delamination, matrix cracking, and the interaction between them should necessarily be considered. Existing methods may be effective for delamination or matrix cracking, but the situation becomes difficult when all of these failure modes are considered together in a unified framework. In this study, a new numerical framework based on floating node method is proposed to study delamination migration problem. A few discrete cohesive cracks are inserted into one element to offer multiple optional crack paths. Crack propagation due to delamination and matrix cracking can be modelled without remeshing. Element partition is treated in a convenient way which has simplified the implementation. And severe distortion of sub-element which may arise in a traditional element partition algorithm can be avoided. The proposed method is implemented through the ABAQUS user subroutine UEL and validated by comparing with experiments. The proposed numerical method has provided a framework for the modelling of delamination migration and also explored a method to model multiple discrete cracks within one element.

1. Introduction

Delamination migration is the failure process in which delamination in between two plies migrates from one interface to another through a matrix crack and then propagate along this interface. This failure process involves at least three failure modes, delamination, matrix cracking and the interaction between them. Recently, Ratcliffe et al. [1] conducted an experiment to investigate the entire process of a single delamination migration in cross-ply tape laminates. An artificial pre-delamination between the 0°/90° interface is formed by inserting a PTFE before curing. The external loading controlled by prescribed displacement is applied at the middle of the specimen, and the delamination is promoted to propagate along the interface until reaching a point where the crack tip migrates into the 90° ply. The crack continues to propagate as a matrix crack to the adjacent 90°/0° interface and forms a new delamination along this interface. The relationships between the location of migration and the load offsets are investigated. Pernice et al. adopted the same testing setup to investigate delamination migration in angle-ply laminates [2]. Delamination migration was also observed in other experimental investigations [3–6].

Many advanced numerical methods have been developed to model structures with complex geometry [7–9]. In the modelling of delamination migration of composite laminates, the interlaminar, intralaminar failures and the interaction between them are involved. These failure modes are essentially crack propagation problem which is one of the most common types of failure mechanism in engineering. Existing numerical methods for crack propagation can be divided into two categories, i.e., linear elastic fracture mechanics (LEFM) [10,11] and nonlinear cohesive zone based crack model [12–16]. In LEFM, stress singularity in the vicinity of crack tip is involved and extremely refined mesh around crack tip is often used. Singular finite element [17,18] or enriched element [19–23] can also be used in front of crack tip in order to calculate the stress intensity factors (SIFs) [24,25]. However, the determination of SIFs in anisotropic material is mathematically complex, so cohesive elements (CE) is widely used in the modelling of composite laminates. When the CE method is used, the crack is characterized based on proper traction separation law and the stress singularity is eliminated. The initiation and propagation of crack are related to material fracture energy and strength obtained from laboratory testing. The benefit of using this method is that the numerical prediction is more accurate [26]. However, this method relies heavily on the *a priori* knowledge of crack path, i.e. CEs should be placed on the

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https://doi.org/10.1016/j.compstruct.2018.07.120
Received 15 May 2018; Received in revised form 13 July 2018; Accepted 30 July 2018

anticipated crack propagation path [16].

A significant advance occurred with the emergence of the extended finite element method (XFEM) for cohesive crack [27,28], in which extra nodal degrees of freedom (DOFs) may be introduced to represent a strong discontinuity within an element. Zhang and Bui studied cohesive crack problem by using XFEM, and two new solution procedures based on Newton-Raphson method were proposed for the nonlinear system of equations [28]. Crack path is determined by proper criterion and arbitrary crack path can be modelled. For composite laminates, delamination occurs along the ply interfaces but matrix crack is related to the loading condition and constraints. Hu et al., modelled delamination migration of composite laminations by using an integrated XFEM-CE method, where delamination is modelled by CEs and matrix crack is handled by XFEM [15]. Recently, a floating node method (FNM) proposed by Chen et al. [29,30] has gained attention. Instead of using extra nodal DOFs, the method employs a few “floating” nodes which are activated if an element is cut by a crack. The FNM has been applied to model delamination migration in both two and three dimensional composite laminates [31–34,35]. As demonstrated in [29], FNM has overcome some limitations that may exist in XFEM, i.e., (1) the implementation is complicated as blending elements are generally required to connect with standard elements (it may be overcame by introducing the shifted Heaviside enrichment, such as in [15]); (2) the determination of crack tip enrichment for anisotropic material is generally complicated; (3) the integration strategy has a strong impact on the numerical accuracy; (4) the mapping of a crack from natural space to physical space will change it from straight to curve which is physically inconsistent. More detailed comparisons between the FNM and XFEM are found in [29].

A difficulty in the implementation of XFEN and FNM is element partitioning. In XFEM, the cracked element is partitioned into several sub-elements for the purpose of numerical integration. On the other hand, in FNM, the cracked element is also partitioned to form standard sub-elements to forming the new boundary of the crack. For the case where crack path is arbitrary element partition is quite cumbersome but still very important for numerical accuracy. Numerical methods such as Delaunay triangulation is employed and the implementation becomes complex [15]. For the case where crack is very close to element node, the predicted crack path should be slightly adjusted to avoid the generation of distorted sub-element from partition [15,29]. Due to this difficulty, some researchers chose to use other more conventional methods such as adaptive remeshing to modify the local mesh connectivity to represent the crack. In these methods, the crack is assumed to propagate along element edges as shown in Fig. 1. When an edge is ready for fracture, the end node of the edge is split into two so that this edge can be separated [36]. The adaptive remeshing technique is simple and robust for the modelling of crack. The shortcoming is that there are only few crack path candidates which depends on the location of crack tip, as illustrated in Fig. 1 (the number of crack candidates could be seven or three depending on the crack tip location). In this study, a new virtual embedded cohesive element technique (VECET) is proposed based on the FNM. A few cohesive cracks are inserted in front of the matrix crack tip as propagation candidates, and only one of them will be activated depending on the stress state or fracture criterion. These virtual cracks are modelled by the CEs, of which the element nodes are automatically superposed floating nodes (FNs). The positions of these FNs are calculated through a simple algorithm and crack propagation can be modelled without remeshing. These CEs are placed through a simple algorithm and element is also partitioned by them. Delamination is modelled by using CEs placed on the material interface between plies. In order to consider the interaction between delamination and matrix cracking, a modified CE with a few FNs on the element edges is proposed. These FNs are used to partition the CE into a few parts to connect delamination and matrix crack such that the delamination path can kink into matrix to form delamination migration once certain criterion is met.

2. Modelling strategy

2.1. Matrix crack

Matrix crack takes place in the 2–3 plane of a ply in composite laminates, hence the material property is considered to be transversely isotropic. In a finite element (FE) model, all the cracks are cohesive cracks and each crack tip is always kept on element edge. For a matrix crack, six candidate cracks are inserted around the original crack tip, and the other tips of the candidate cracks are located at the element edges, as shown in the left of Fig. 2. Since more crack candidates are used in this strategy compare with the adaptive mesh remeshing method as shown in Fig. 1, and hence this method provides more precise description of crack path trajectory.

The initiation and direction of the crack path can be determined by an appropriate criterion such as the maximum principle stress criterion for a transversely isotropic case. Once the direction of the crack path is determined, the candidate CE closest to the predicted path is chosen as the crack propagation path and the end of the chosen CE is the new crack tip, as shown in Fig. 3. Once the crack path is chosen, the other embedded CEs within this element are kept intact and hence inactive. In the meantime, a new group of virtual embedded CEs will be inserted in front of the new crack tip. This process is repeated until the matrix crack reaches another ply interface where delamination will take place. The inserted CEs are intended to provide more possible crack paths but only one is activated, hence this method is termed as virtual embedded cohesive element technique (VECET).

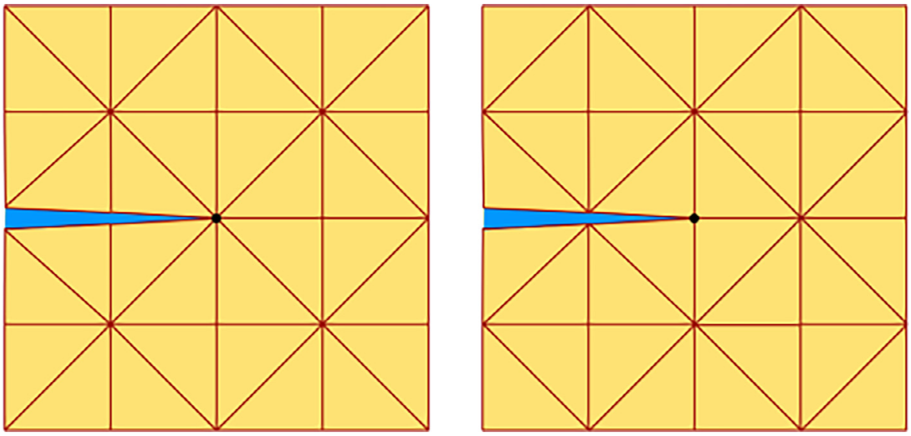

Fig. 1. The adaptive meshing technique for crack propagation. There are seven (left) or three (right) propagation path candidates.