MODELING DELAMINATION MIGRATION IN MULTI-DIRECTIONAL COMPOSITE LAMINATES

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Abstract

Progressive damage and failure in composites are generally complex and involve multiple interacting failure modes. Depending on factors such as lay-up sequence, loading and specimen configurations, failure may be dominated by extensive matrix crack-delamination interactions, which are very difficult to model accurately. The present study further develops an integrated extended finite element method (XFEM) and cohesive element (CE) method for three-dimensional (3D) delamination migration in multi-directional composite laminates, and validates the results with experiment performed on a double-cantilever beam (DCB) with multi-directional lay-up. The interaction between matrix crack and delamination is achieved by enriching the nodes of cohesive element. Matrix crack initiation and propagation can be predicted and delamination migration is also observed in the results.

1. Introduction

Delamination in general laminated structures often involve multiple crack fronts which may migrate between different plies. Ratcliffe *et al.* developed an experimental test to study delamination migration in cross ply laminates[1]. Pernice *et al.* extended the test set up for different stacking sequences and conducted numerical simulation to discuss the mechanisms that govern delamination growth and migration[2, 3]. Canturri *et al.* investigated the delamination propagation processes, and discussed the impact of stacking sequence on delamination migration[4].

According to the previous study, it is found that delamination migration combines two main failure modes, which are interface delamination and matrix fracture. For such complex progressive failure mode, suitable modeling tecnique is desired. Cohesive elements (CEs) are proven to be useful on the simulation of delamination[5, 6, 7]. The interface between plies in front of crack tip is modeled as cohesive zone, and the mechanical behaviors are characterized by using cohesive traction separation law. In order to overcome the necessity to remesh repetitively, the extended finite element method (XFEM) has been proposed for crack propagation in composites[8,9]. Since XFEM introduces Heaviside function enrichments to simulate weak and strong discontinuities explicitly, the new generated crack segments do not require remeshing with improved computational efficiency. With the development of the XFEM, a shifted basis enrichment was proposed[10,11,12], many advantages by using the shifted basis enrichment especially in post processing were reported and discussed[10].

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In previous studies, Tay *et al*. proposed an integrated XFEM-CE method to study the interaction between delamination and matrix crack[13,14,15]. In the integrated XFEM-CE method delamination is modeled by CE while matrix crack is modeled by using XFEM. It is found that CE nodes should also be enriched to account for the interaction between matrix and interface. In this study, a delamination migration problem for a laminate with plies of different orientations is studied in detail computationally and experimentally. The integrated XFEM-CE method is employed to analyze the problem numerically. The matrix crack is modeled as cohesive crack and shift basis enrichment is used, so the formulation of XFEM is upgraded accordingly. The method is implemented by using ABAQUS® subroutine UEL[16]. The Hashin criterion[17] is adopted for the initiation of matrix crack while a quadratic interactive criterion is used for the 3D mix-mode cohesive cracks. Numerical simulation results are compared with experimental tests conducted on double cantilever beams (DCB).

2. Fundamental formulation

In a standard XFEM formulation, the Heaviside enrichment function and the crack tip enrichment functions are introduced to represent discontinuities and crack tip fields, respectively. However, the crack tip enrichments based on analytical solutions do not exist for 3D anisotropic materials, the present approach therefore only employs the Heaviside function enrichment for modeling the displacement jump across a matrix crack. This study employs a so-called shift basis interpolation[10, 11] for XFEM given by

$$u = \sum N_i \left[u_i + (H - H_i) a_i \right] \tag{1}$$

where H_i is the value of Heaviside function on node i.With this shift, the value of the enrichment function becomes zero at all the nodes, so the nodal variable u_i equals to real displacement on node i, thereby facilitating the post-processing. In order to account for the interaction between matrix cracks and delamination, the cohesive elements at the interface should also be enriched. Displacement field in top surface and bottom surface in cohesive element can be specified by

$$u^{top} = \sum N_i \left[u_i^{top} + (H - H_i^{top}) a_i^{top} \right] \tag{2}$$

$$u^{bot} = \sum N_j \left[u_j^{bot} + (H - H_j^{bot}) a_j^{bot} \right] \tag{3}$$

where the superscripts “^{top}” and “^{bot}” represent variables in top surface and bottom surface respectively.

In addition, the values of H_i and H are equal to each other in the blending element, hence the displacement fields in the blending elements are simplified into

$$u = \sum N_i u_i \tag{4}$$

In this way, the implementation of blending elements is generally simplified. However, the value of Heaviside function is discontinuous in the reproducing elements, so that element partition is necessary to enable integration over the elements.

Considering matrix crack as cohesive crack and introduce relative crack separation $\boldsymbol{w} = \boldsymbol{u}^{+} - \boldsymbol{u}^{-}$, the weak form of equilibrium equation is specified by

$$\int_{\Omega} \boldsymbol{\sigma}^{\mathrm{T}} : \boldsymbol{\varepsilon}(\delta \boldsymbol{u}) \mathrm{d}\Omega + \int_{\Gamma_{\mathrm{coh}}} \boldsymbol{t}^{\mathrm{T}} \cdot \boldsymbol{w}(\delta \boldsymbol{u}) \mathrm{d}\Gamma_{\mathrm{coh}} = \int_{\Gamma_t} \boldsymbol{F}^{\mathrm{T}} \cdot \delta \boldsymbol{u} \mathrm{d}\Gamma_t \tag{5}$$

and the relationship between traction $\boldsymbol{t}$ and separation $\boldsymbol{w}$ is defined by cohesive law, which also governs the matrix crack propagation. In the cohesive zone theory, the crack-tip stress singularity from the Linear Elastic Fracture Mechanics (LEFM) is eliminated, and the complex procedures for the calculation of stress intensity factors are avoided.

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3. Experimental study and modeling

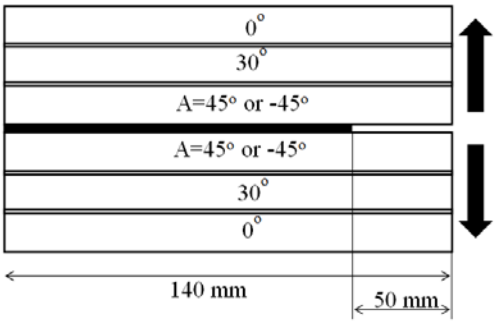

Fig. 1 Configuration of the DCB test specimen

A set of double cantilever beam (DCB) tests are conducted to study delamination migration. The test focus on two sets of stacking sequence i.e. [0,30,45]s and [0,30,-45]s. The configuration of the $[0,30,45]_s$ and $[0,30,-45]_s$ specimens is illustrated in Fig. 1. The specimens are tested in the Instron 8874 uni-axial tabletop servo-hydraulic testing system, with the loading speed set at 1mm/min. For both tests, the original delamination in the center interface eventually migrates to the $30^o/0^o$ interface and propagates until total separation. Specimens after test are shown in Fig. 2(a) and (b).

(a) [0^o,30^o,45^o]s (b) [0^o,30^o,-45^o]s

Fig. 2 Delamination propagation and migration in the specimens after test

In order to better simulate the whole tests conducted, the impact due to the cooling down process from curing temperature to room temperature is considered. The curing temperature and room temperature are chosen as 141 ^oC and 21 ^oC, respectively. The deformation due to the thermal residual stress is shown in Fig. 3(a) and (c), where the sub figure (a) is the numerical prediction for [0,30,45]s specimen while the sub figure (c) is for the [0,30,-45]s specimen. It is found that the pre-delamination ends of the both specimens are predicted to warp as a result of thermal loading, and the numerical predictions agree well with the experimental observations.

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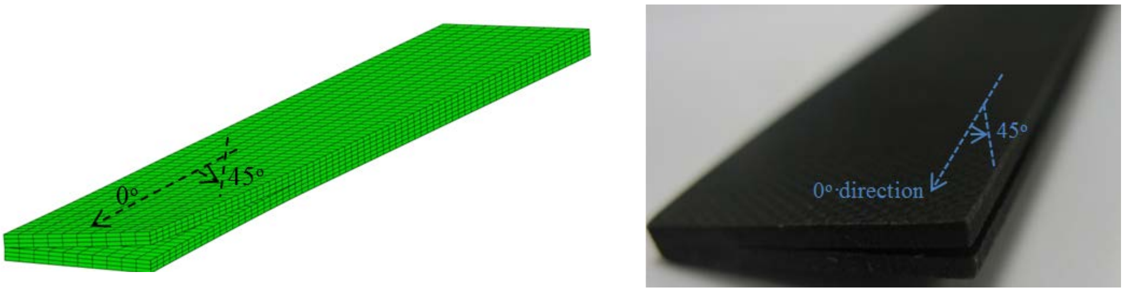
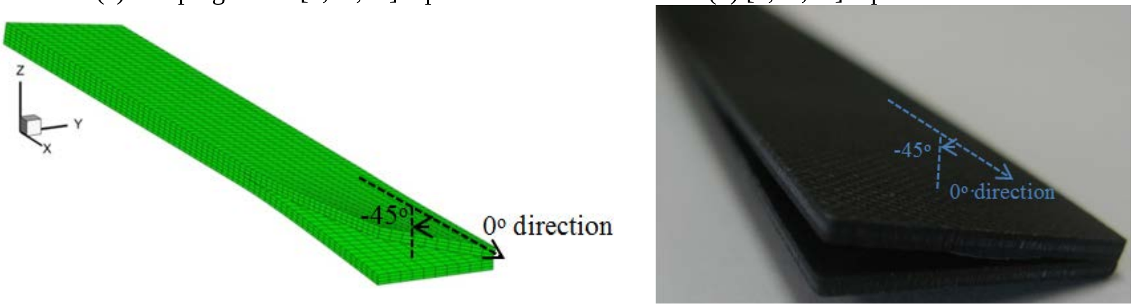


(a) Warping of the [0,30,45]s specimen (b) [0,30,45]s specimen before test



(c) Warping of the [0,30,-45]s specimen (d) [0,30,-45]s specimen before test

Fig. 3 Post-curing warping and the numerical prediction

The specimen deformation during modeling is shown in Fig. 4, and the experimental observation during test is given in Fig. 5 as a reference. It can be seen that the matrix crack is explicitly modeled by the present method and delamination migration is predicted.

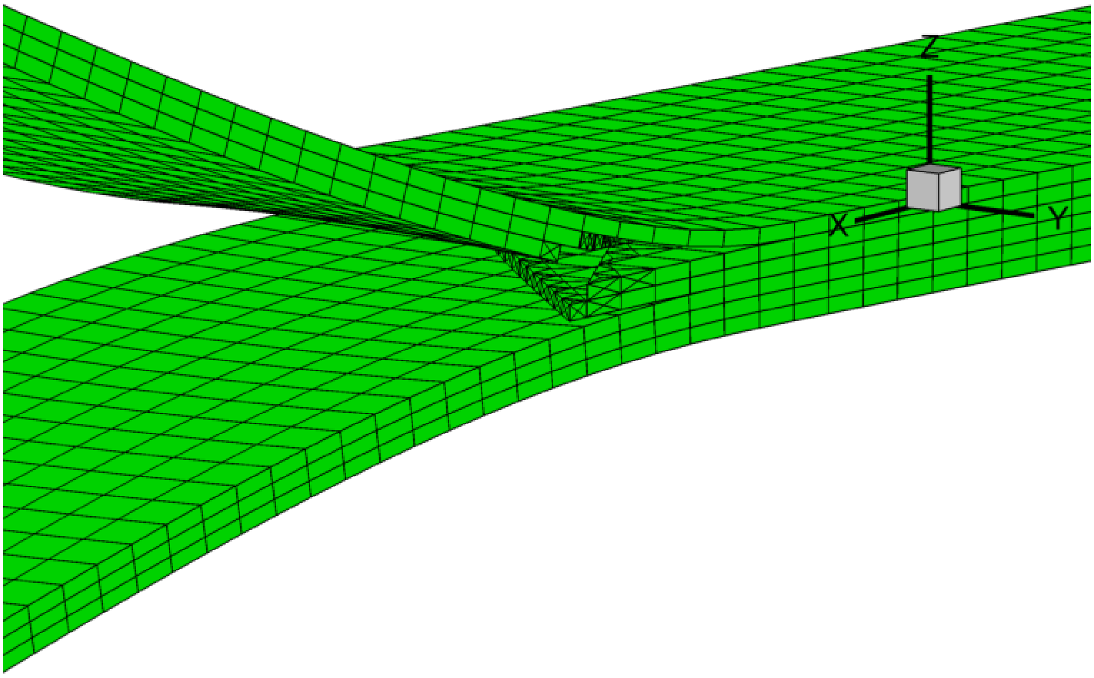


Fig. 4 Specimen deformation of the [0,30,45]s laminate during modeling

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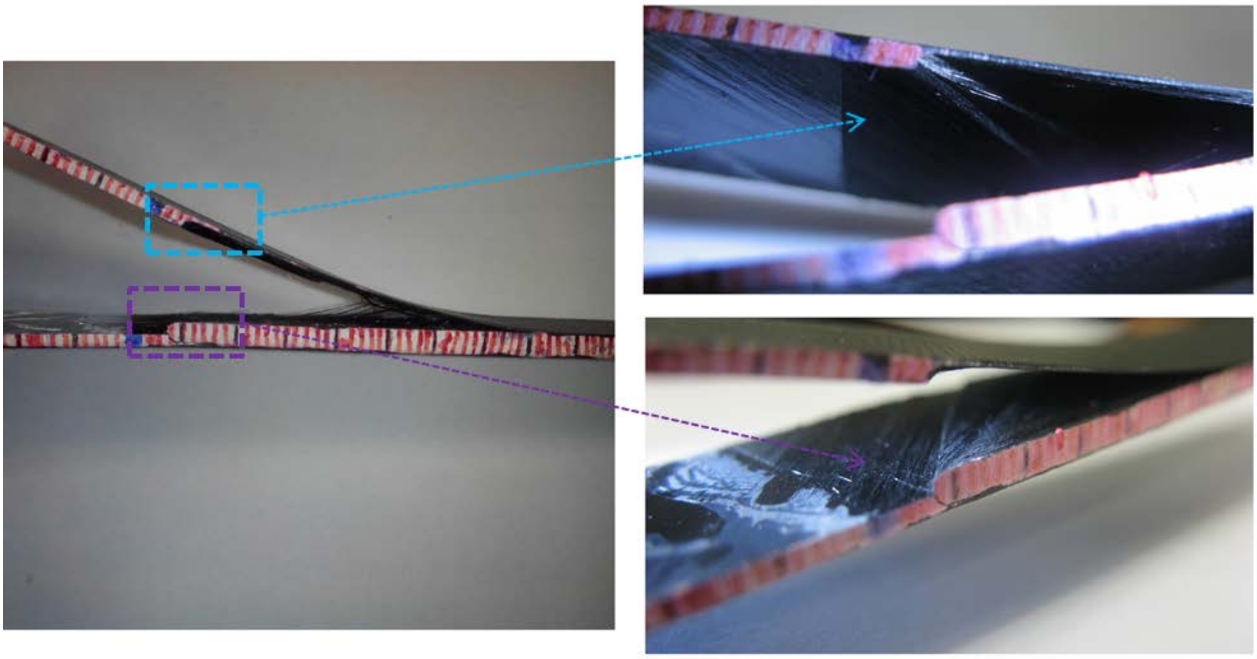

Fig. 5 Specimen deformation of the [0,30,45]s laminate after test

4. Conclusions

In this study, an integrated extended finite element (XFEM) and cohesive element (CE) method for the modeling of progressive damage of three dimensional (3D) multi directional composite laminates is further developed. The element nodes of CEs are also enriched with Heaviside function to allow element split and the subsequent delamination migration. The delamination migration in composite can be simulated by using the proposed method and the numerical predictions agree with the experimental observations which validated the proposed XFEM-CE method. The proposed numerical method provides a platform for the realistic simulation of composite laminate progressive damage.

Acknowledgments

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