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A 3D SEPARABLE COHESIVE ELEMENT FOR MODELLING THE COUPLED FAILURE IN LAMINATED COMPOSITE MATERIALS

X. Lu[1], B.Y. Chen[2], V.B.C. Tan[3] and T.E. Tay[4]

[1]Department of Mechanical Engineering, National University of Singapore, 117576, Singapore, xinlu@u.nus.edu
[2]Faculty of Aerospace Engineering, Delft University of Technology, 2629HS Delft, Netherlands, b.chen-2@tudelft.nl
[3]Department of Mechanical Engineering, National University of Singapore, 117576, Singapore, mpetanbc@nus.edu.sg
[4]Department of Mechanical Engineering, National University of Singapore, 117576, Singapore, mpetayte@nus.edu.sg

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Abstract

The interaction between matrix cracks and interface delamination is a major failure mechanism in composite laminates and has been a subject of active research in recent years. Although coupled failure behaviour of composite laminates between matrix cracks and delamination has been observed in experiments, accurate modelling of this phenomenon for application in composite structures remains challenging. In this work, a three-dimensional separable cohesive element (SCE) is proposed to enable the modelling of interaction between matrix cracking and interfacial delamination in laminated fibre-reinforced composite materials. It is demonstrated that traditional cohesive elements are incapable of modelling the coupled failure mechanisms accurately if partitioning is not allowed. The SCE may be partitioned according to the configuration and geometry of matrix cracks in adjacent plies, thus maintaining appropriate connection between plies. Physically, the original interface is split and new interfaces are formed to bond the homologous cracked solids during fracturing process. The stress concentration induced by matrix cracks and the load transfer from cracked solid elements to interface cohesive element are effectively modelled. The proposed SCE is applied to model progressive failure in composite laminates and the results are found to agree with experiments.

1. Introduction

In numerical progressive failure analysis of composite laminates, it is important to explicitly model the interaction between matrix cracking and interface delamination. Fang *et al.* [1] reported that when crack bifurcation or coalescence occurs in matrix materials, the traditional cohesive element (CE) is unable to model the load transfer between the cohesive interface and solid elements. Therefore, a two-dimensional augmented cohesive zone (ACZ) element was proposed based on the augmented finite element method. Partitioned into two sub-elements, the ACZ element could faithfully capture the stress distribution at the interface and thus provide accurate numerical predictions.

When multiple matrix cracks in adjacent plies with different fibre orientations are considered, the situation becomes more complicated. Cracks developed in different plies may cross each other at the shared interface, resulting in strong coupling between the interface and multiple matrix cracks [2]. As shown in Figure 1, if traditional CE is directly applied, the coupling effects caused by the cracks in plies are not correctly captured. Furthermore, although additional DoFs are introduced into the model due to the presence of the cracks, they are not properly constrained at the edges of the interface CE. To correctly model the coupling, a three-dimensional separable cohesive element (SCE) is required which can be partitioned into sub-elements in accordance with the crack configurations in the abutting solid elements (SEs). Subsequent damage of the partitioned cohesive interface may thus be modelled, exhibiting the coupling between matrix cracking and interfacial delamination.

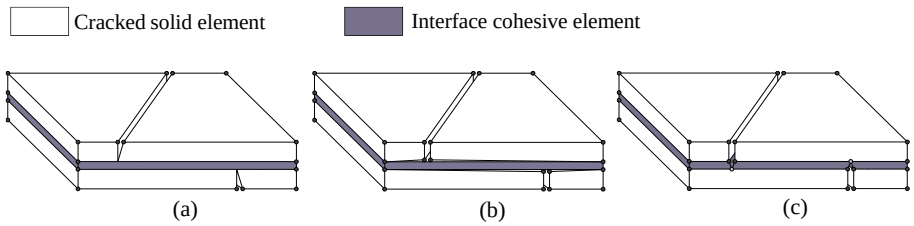

Figure 1. Three-dimensional coupling between matrix cracks and delamination: (a) two matrix cracks initiate in adjacent plies; (b) traditional CE fails to capture coupling between matrix cracks and interface failure; (c) SCE models the interaction between matrix cracking and delamination.

2. Separable Cohesive Element

2.1. Necessity for three-dimensional separable cohesive element

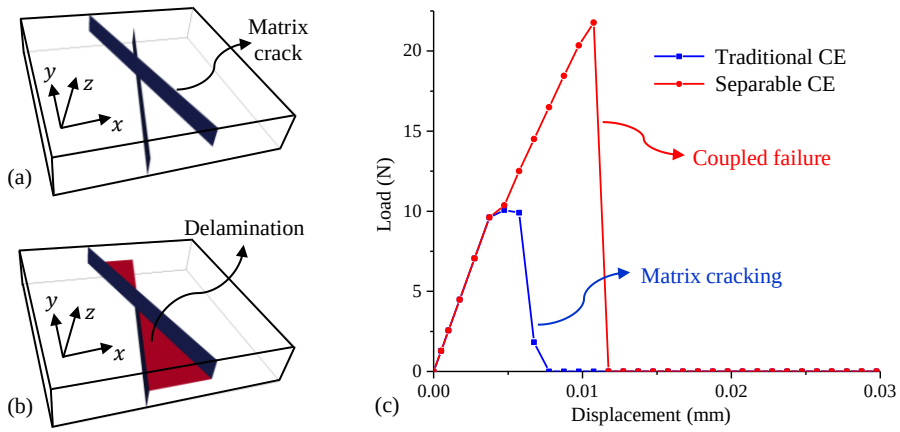

Figure 2. Comparison of numerical results between traditional CE and SCE: (a) final failure pattern of traditional CE model; (b) final failure pattern of SCE model; (c) load-displacement curves.

The necessity for SCE, is demonstrated by the test problem shown in Figure 2. In the traditional CE model, after matrix cracking has occurred, the interface remains intact and connected to the cracked SEs. Therefore, only matrix damage is predicted and no delamination is allowed. In the SCE model, however, the interface the CE is partitioned according to the crack configurations in its neighbouring SEs. The stresses released by the cracked SEs are concentrated and transferred into the triangular sub-CEs through shear deformation. Failure of these two triangular sub-CEs (delamination) and matrix cracking constitutes final fracture. Significant differences are observed from the predicted load-displacement curves of the two models. Higher strength is predicted by the SCE model compared to the traditional CE model where only matrix cracking is allowed.

2.2. Formulation of separable cohesive element

The proposed SCE is formulated based on the recently developed floating node method (FNM) [3-5]. As shown in Figure 3, two ply elements sandwich the SCE in between. By sharing the nodes from solid elements, the bottom surface of ply element I forms the top surface of the CE, while the top surface of ply element II forms the bottom surface of the CE. Nodes 1~24 are the common nodes from neighbouring SEs while nodes 25~32 are edge slave nodes and nodes 33~34 are surface slave nodes. The real and floating nodes are used to construct or partition the CE, while the slave nodes are used to ensure compatibility is preserved. Considering various crack configurations in two neighbouring plies, all the possible partitions of the SCE are obtained (Figure 4), which allows application of the SCE in general scenarios. Case 0 stands for the situation where only one crack exists in one of two abutting ply SEs; Cases I - III correspond to cases involving two cracks.

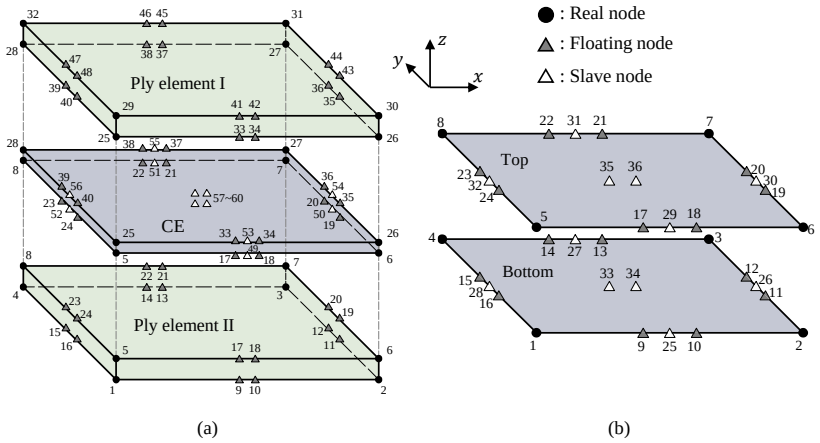

Figure 3. Floating node element (a) a two-ply laminate element; (b) the interface cohesive element.

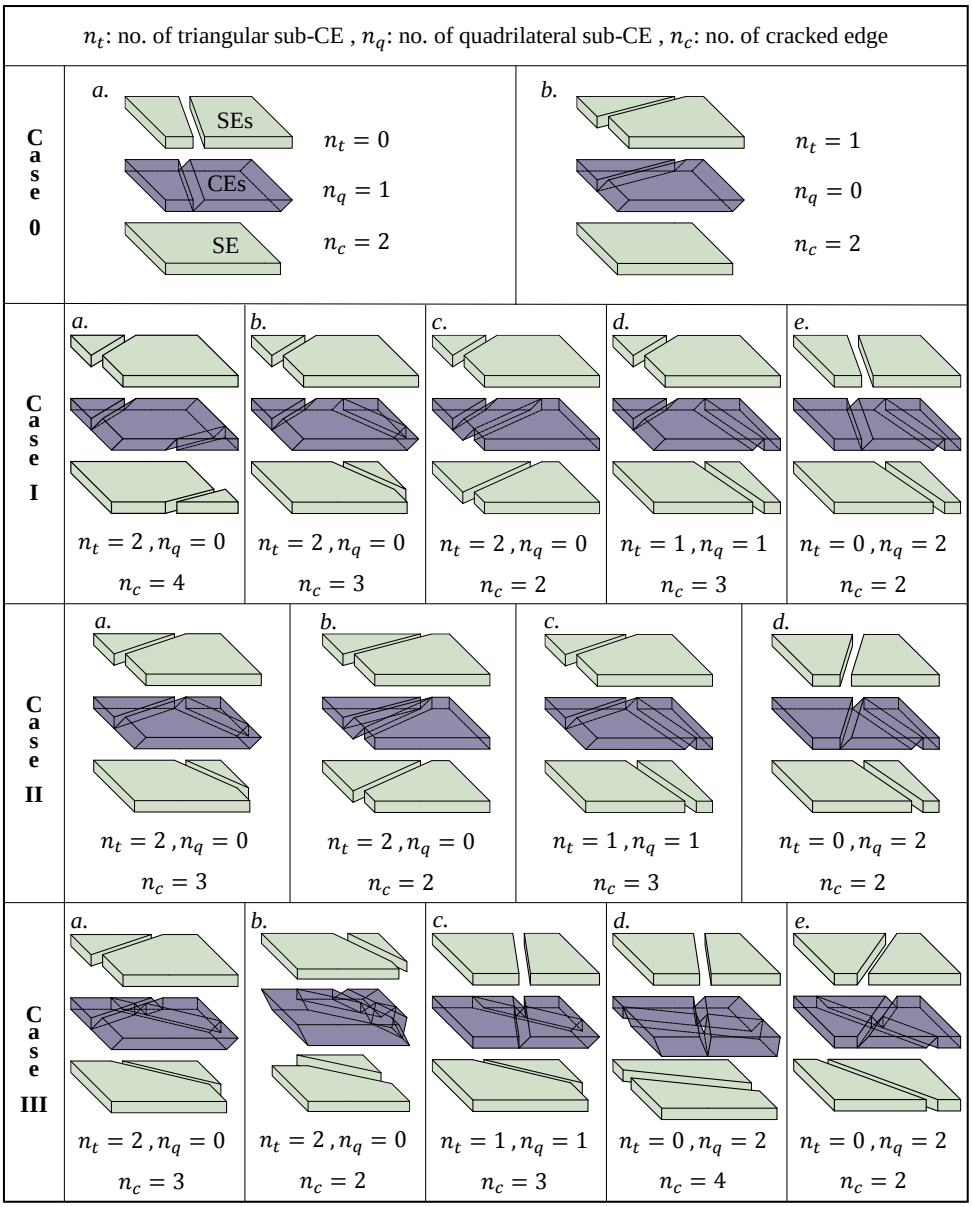

Figure 4. All the possible cases of SCE modelling interaction between matrix cracks and interface delamination.

3. Numerical Verifications

The SCE is developed in Abaqus FE software (Implicit, version 6.14) as a user-defined element. The performance of the SCE is verified through numerical simulations of tensile failure of unnotched $[30/90/-30]_s$ T300/976 laminates [6] and notched $[45_4/90_4/-45_4/0_4]_s$ IM7/8552 laminates [7].

3.1. Tensile failure of unnotched $[30/90/-30]_S$ laminate

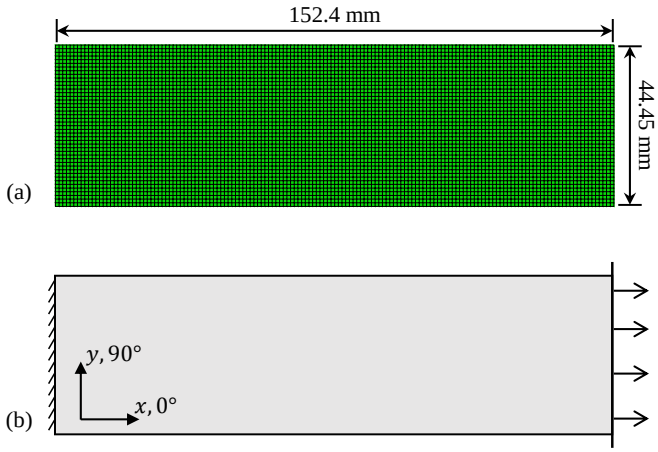

Figure 5. Unnotched laminated plate: (a) sample dimensions and FE mesh; (b) boundary conditions for unidirectional tension.

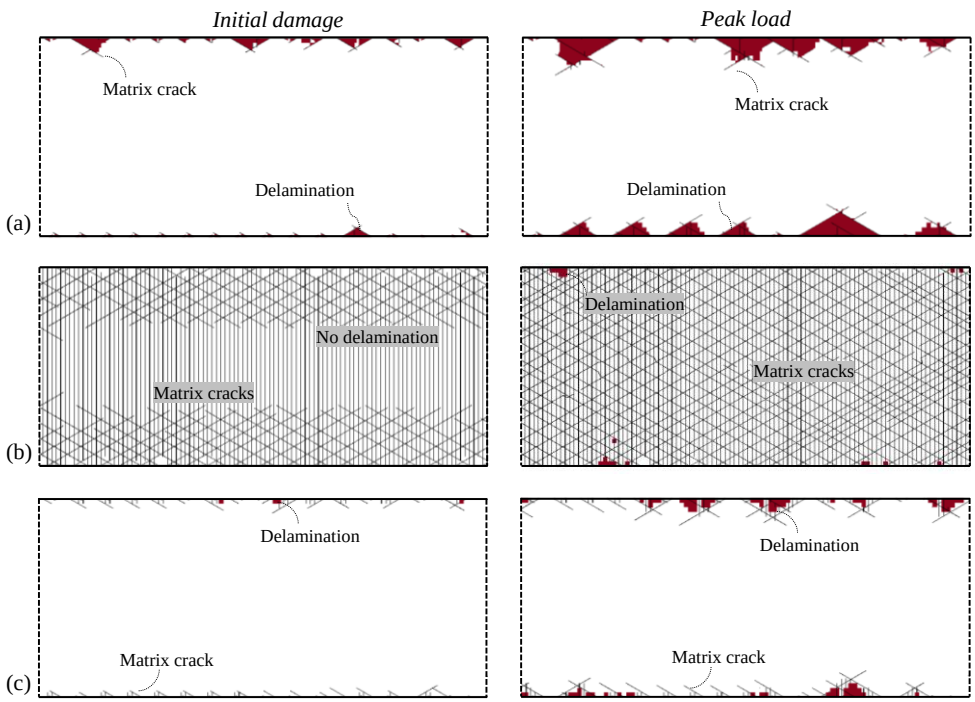

Figure 6. Numerical results of unnotched $[30/90/-30]_s$ laminate plate for initial damage (left column) and peak load damage (right column): (a) model with SCE; (b) model with traditional CE; (c) model with simplified formulation [4].

To study the coupled failure of composite laminates, the unnotched $[30/90/-30]_s$ laminate loaded in tension in [6] is modelled (Figure 5). For comparison, other than the proposed SCE, analyses with traditional CE and the approximate formulations in [4] are also performed. Adopting the SCEs in (Figure 6a), the delamination boundaries are clearly observed and compared to the experimental

results, close agreement is achieved. However, if the tradition CE are applied, extensive matrix cracks develop throughout the whole laminate at initial stage; without correctly modelling the load transfer, the induced delamination is not observed and only a small area of free-edge delamination is predicted when the peak load is reached. Although the approximate formulation avoids spurious prediction of matrix cracks, the delaminations are not accurately bounded by the cracks, which is the situation with the SCE formulation and observed experimentally.

3.2. Tensile failure of notched $[45_4/90_4/-45_4/0_4]_S$ laminate

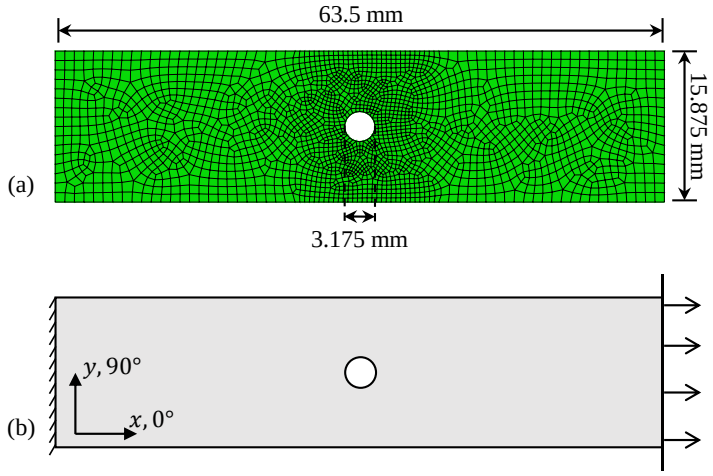

Figure 7 Open-hole laminate plate: (a) sample dimensions and FE mesh; (b) boundary conditions for unidirectional tension.

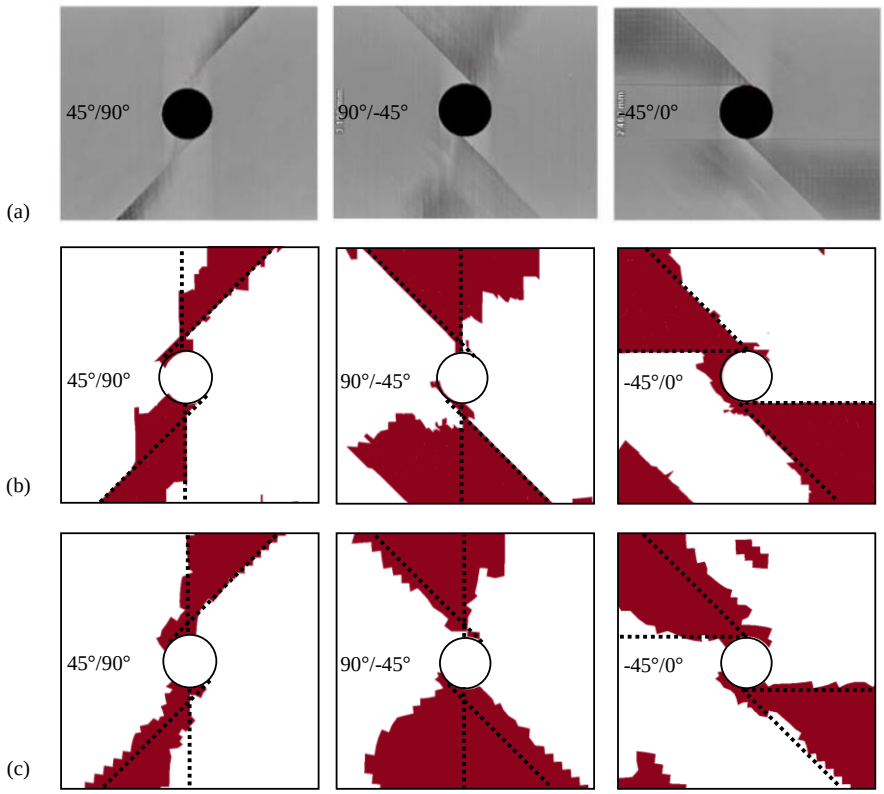

Figure 8. Comparisons of delamination patterns of $[45_4/90_4/-45_4/0_4]_s$ open-hole plate: (a) X-radiographs of delamination patterns on three interfaces; (b) simulated delamination patterns with SCE model; (c) simulated delamination patterns with traditional CE model.

The open-hole tension (OHT) of $[45_4/90_4/-45_4/0_4]_s$ laminate plate [7] is analysed in this section (Figure 7). From the experimental X-radiographs in [8], boundaries of the delamination, which align with matrix cracks, are clearly observed, indicating a coupled failure process. Employing the SCEs, the boundaries of the delamination are clearly defined and good agreement with experiment is achieved. However, if traditional CEs are adopted, the predicted delamination boundaries appear to be influenced by the FE mesh (Figure 8).

Matrix cracking triggers the onset of interface delamination, and *vice versa*. In the case where SCEs are used, the matrix cracks and delamination are better defined and the prediction patterns are in better agreement with experiments. On the other hand, in the case of conventional CEs, a large number of isolated matrix cracks, particularly at the edges, is predicted in the region away from the hole.

4. Conclusions

In this paper, the 3D separable cohesive element (SCE) is proposed for modelling the coupled failure of composite laminates. When matrix cracks initiate or propagate in the ply solid elements (SEs), the associated SCE is partitioned into several individual sub-CEs to maintain the correct bonding between the cracked solids. Depending on various crack geometries in the abutting plies, different elemental configurations are categorized and formulated for implementation in FE.

The interactions between matrix cracking and interfacial delamination can be properly modelled with SCEs. This has been demonstrated through several numerical examples, where delamination boundaries are better defined and fewer spurious matrix cracks are predicted compared to models employing only traditional CEs. For unnotched laminates, the SCE model successfully captures the predicted failure load and the local delamination induced by matrix cracks, in close agreement with experimental observations. However, the differences in employing the SCE and traditional CE are not that obvious when considering the OHT test. This may be due to the fact that damage initiation is dominated by the stress concentration at the open hole edge, and less affected by local interactions between matrix and interface delamination. Nonetheless, it is worth noting that more faithful modelling of the interaction between matrix cracking and interface damage, especially during the initial stages of damage propagation, is achieved if the SCE adopted.

From the results presented, the merit of the proposed SCE over the traditional CE and approximate CE formulations is that it provides a physically-based solution for correctly modelling interaction between matrix cracks and delamination. The kinematic compatibility is consistently enforced, leading to a more rigorous numerical formulation which is able to describe the local coupled failure mechanisms during the progressive damage process. Therefore, the SCE is a useful tool for high-fidelity modeling of failure patterns with delamination boundaries clearly bounded by matrix cracks.

Acknowledgments

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