ANALYSIS OF DELAMINATION MIGRATION IN LAMINATED COMPOSITES USING CONVENTIONAL AND MESH-INDEPENDENT COHESIVE ZONE MODELS

M.F. Pernice\textsuperscript{1}, L.F. Kawashita\textsuperscript{2*}, S.R. Hallett\textsuperscript{1}

\textsuperscript{1}Advanced Composites Centre for Innovation and Science, University of Bristol, Bristol BS8 1TR, UK
\textsuperscript{2}School of Engineering, Cardiff University, Cardiff CF24 3AA, Wales, UK
* Corresponding author (KawashitaL@cardiff.ac.uk)

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1 Introduction

The use of carbon fibre-epoxy composites in aerospace structures can enable significant weight savings and crucial reductions in fuel consumption. However, the design of high-performance laminated structures still relies heavily on empirical rules, particularly in the consideration of damage tolerance and fatigue life. The main reason is the complex progressive damage behaviour of these materials, which are made of relatively brittle fibres and matrices with intricate layups and geometries. In order to predict the correct macroscopic behaviour of the structure in the presence of damage, it is necessary to consider the various mesoscopic damage mechanisms individually, i.e. delamination, matrix cracks and fibre failure, as well as the various interactions between them [1].

One of the most challenging damage mechanisms to model in laminated composites is the so-called ‘delamination migration’ which happens when a delamination propagates through a ply and reaches a neighbouring interface resulting in the propagation of damage through the thickness of a laminate. Delamination migration is difficult to model using traditional Cohesive Zone Models (CZM) and the Virtual Crack Closure Technique (VCCT) because it involves large numbers of cracks with locations which cannot be known a priori [2].

In the present work delamination migration in aerospace-grade carbon fibre-epoxy laminates has been investigated experimentally and numerically using both the traditional CZM formulation as well as a novel mesh-independent implementation based on the automatic introduction of additional degrees of freedom [3].

2 Experimental Methods

The test case studied in this work was a modified Double Cantilever Beam (DCB) specimen with a $\pm \theta$ ply interface at the midplane to promote delamination migration [4]. This test was chosen because it allows the complex delamination migration patterns to be observed directly at the end of the test without the need for complex instrumentation. Thus, it provides a simple validation case for Finite Element Analyses results. To promote delamination migration, the usual unidirectional (UD) layup of DCB specimens was modified by introducing a sequence of angle plies at the midplane of the specimen. The layup used in this work (from bottom to top ply) is given by:

$$[(+\theta_2, -\theta_2)_2, 0, 90, 90, 0 (-\theta_2, +\theta_2)_2]_A \quad (1)$$

where 0 is the specimen length direction, 90 is the width direction and angles are measure in anticlockwise direction. The ply angle $\theta$ considered here was 60 degrees. The subscript “A” in (1) denotes anti-symmetry of the stacking sequence.

This layup was designed in order to promote multiple delamination migrations within the central 8 ply blocks oriented at $\pm \theta$, while initially providing two balanced and symmetric arms in the specimen. A 0-degree ply was introduced in the layup after the central block of angle plies to stop the delamination migration and prevent the arms from breaking off. A fluoro-polymer film was used to create a pre-crack along the plane of anti-symmetry at one end of the specimen. The laminates were made of Hexcel...
IM7/8552 UD pre-preg material and manufactured as larger plates. These were laid by hand on a flat plate and cured in an autoclave, following the curing cycle specified by the pre-preg supplier. The average cured ply thickness was 0.125 mm. Specimens of 20 mm by 150 mm were cut from the plates and tested according to the ASTM-D5528-01 standard. Figure 1 shows a DCB specimen at two successive stages during the test. Initially, extensive amount of fibre bridging between the ±60° plies was observed (Figure 1-a), followed by migration of delamination to a neighbouring interface (Figure 1-b).

Photographs were taken of the fracture surfaces after each test in order to characterise the patterns of delaminations and matrix cracks. An example is shown in Figure 2. These patterns were reproducible between repeats of the same test albeit with some amount of variation in the migration location.

3 Numerical Models

The modified DCB specimen described in the previous section was modelled for the analysis of delamination migration. The software Abaqus/Explicit was used in all finite element analyses. Full 3D ply-level models of the DCB specimens were analysed using hexahedral continuum elements (C3D8) to represent each ply block individually. The orthotropic elastic constants for the UD plies investigated are shown in Table 1. Delaminations were modelled with layers of 8-noded cohesive elements (COH3D8) being placed between plies and two different strategies were used for modelling transverse matrix cracks as detailed below.

3.1 Conventional cohesive elements

The baseline methodology was to introduce pre-defined matrix crack paths using standard cohesive elements (COH3D8) [4]. This strategy has proven effective when the patterns of matrix cracks can be determined by the presence of stress concentrations, e.g. in the analysis of open-hole tests [1]. However, to model the angle-ply DCB tests this methodology required very complex meshing and the use of surface interactions when placing cohesive elements between non-coincident meshes.

For clarity, only the lower arm of the specimen is shown in Figure 3. The mesh was refined along the first 40 mm of the specimen length starting from the tip of the pre-crack, with in-plane element lengths in this zone being about 0.25 mm. This region also contained potential paths for transverse cracks as shown in the detail of Figure 3. Assumptions had to be made regarding the location and density of these pre-defined crack paths; they were made equally-spaced within each ply and vertical through the thickness. Figure 4 shows the bands of cohesive elements forming potential crack paths within the central angled plies (with one ply being shown for reference).

All delamination planes and pre-defined crack paths were assumed to exhibit the same cohesive properties which are shown in Table 2. These values were obtained based on experimental observations as described in [5, 6]. This method, however, was not able to predict delamination migration. FE results after full delamination of the refined mesh region are shown in Figure 5. It can be seen that delamination is predicted only along the specimen mid-plane without migrating to any other interface. These results are not in agreement with experimental observations and the possible reasons for this are discussed further in the next sections.

3.2 Mesh-independent cohesive cracks

An alternative to the use of pre-defined crack paths has been proposed recently [3] based on the use of a user-defined element formulation (VUEL) with an embedded cohesive formulation and extra degrees of freedom which is capable of modelling arbitrary cohesive cracks.

The procedure is illustrated in Figure 6. When the element is ‘undamaged’ it behaves as an 8-noded fully-integrated linear isoparametric hexahedral. The usual notation for the composite material coordinate system is used here, where 1 is the fibre direction and 3 is the out-of-plane direction. If the stress criterion for damage initiation is satisfied at any integration point within the element with respect to the local plane 1-3, then a cohesive crack will be introduced. The quadratic initiation criterion from [5] is used here, i.e.
Analysis of delamination migration in laminated composites using conventional and mesh-independent cohesive zone models

\[
\left( \frac{\sigma_{12}}{\sigma_{12}^{\text{max}}} \right)^2 + \left( \frac{\sqrt{\sigma_{12}^{2} + \sigma_{23}^{2}}}{\sigma_{12}^{\text{max}}} \right)^2 = 1 \quad (2)
\]

where \( \sigma_{12}^{\text{max}} \) and \( \sigma_{23}^{\text{max}} \) are the cohesive strengths in mode-I and mode-II, respectively, and \( (*) \) denotes the McCauley operator.

The introduction of a strong discontinuity within the element requires the introduction of new degrees of freedom (or 'extra nodes') which in the present work are part of the user-defined element formulation. The original element is then 'triangulated' in the plane 1-2 so that the hexahedral domain is divided into pentahedral sub-domains that follow the new crack path. The integration scheme is modified accordingly, which requires the projection of state variables from the original element to the new pentahedral sub-elements.

Cohesive segments are then introduced along the fracture plane. The cohesive law is evaluated at a single cohesive integration point for each pair of quadrilateral sub-element boundaries. The mixed-mode, linear-softening cohesive law presented in [5] is used here. The mode ratio is estimated at every time step by the ratio between the opening displacements in modes I and II, \( \delta_i \) and \( \delta_u \) respectively, and the effective mixed-mode softening law is computed by interpolation between the two modes as shown in Figure 7.

The power-law propagation criterion is used here, i.e.

\[
\left( \frac{G_i}{G_{\text{IC}}^i} \right)^n + \left( \frac{G_u}{G_{\text{IC}}^u} \right)^n = 1 \quad (3)
\]

where \( G_{\text{IC}} \) and \( G_{\text{IC}}^i \) are the critical strain energy release rates for pure modes I and II respectively. The power-law coefficient \( n \) is found by fitting experimental data from mixed-mode tests. This coefficient was set to 1 in this work, which gives a good fit for the material under consideration [5]; in this case equation (3) will retrieve a linear interaction criterion.

In the proposed model the direction of crack propagation is determined directly from the local fibre orientation. Moreover, through the thickness the crack will follow the local 3-direction and consequently will be orthogonal to the ply surface as shown in Figure 8.

The assumption of orthogonal through-thickness cracks is valid for in-plane tensile loading. However, in the presence of compressive and/or shear stresses the fracture planes may be 'slanted' at certain angles which will depend upon the local stress state at the time of initiation. The orientation of the fracture plane is important because it affects the definition of modes I and II components, e.g. in equations (2) and (3) and Figure 7. In this work it is assumed that the fracture surfaces are parallel to the 3-direction, as shown in Figure 8. However the consideration of arbitrary orientations may be necessary in the analysis of angle-ply DCB tests as will be discussed later.

In order to make the computational costs more manageable, in this work only a small portion of the specimen was modelled with user-defined elements, namely only the four central angle plies along the first 40 mm of the specimen length (measured from the initial pre-crack front) as shown in Figure 9. The remainder of the specimen was modelled with standard continuum elements. The in-plane element sizes for the user-defined elements were 1 mm×1 mm and the mesh coarsened gradually away from this region. The through-thickness discretisation is shown in Figure 10. A single element was used through the thickness of each of the four central plies. Standard cohesive elements were used to model delamination only along the three interfaces between the four central angled plies (Figure 10). The remaining plies were modelled using only four elements through the thickness of each arm, and assigning homogenised material properties for the corresponding sub-laminates as shown in Figure 10.

As described in [3], a minimum crack spacing parameter must be defined because every user-defined element only supports a single discontinuity. This parameter must be larger than the minimum in-plane element size for the mesh being analysed. In the present work this element size is 1 mm×1 mm, and therefore a minimum crack spacing of 1.5 mm has been adopted throughout. The DCB tests were simulated using mass-scaled dynamic explicit solutions, and material densities were scaled by a factor of 10^5. The run time for each
analysis was in the range 12h-48h when running on a single 3 GHz CPU.

Figure 11 shows the patterns of matrix cracks and interfacial damage for a crosshead displacement of 12 mm. These results refer to the baseline case where the same set of cohesive properties (Table 2) is assumed for both delamination and transverse cracks. It can be seen that the mesh-independent methodology predicted the initiation of very large numbers of matrix cracks. However, it should be noted that the crack paths shown in Figure 11 also include cracks which are partially ‘closed’, i.e. where the cohesive segments have not failed completely. Eventually, some of these cracks progressed up to complete failure allowing delaminations to jump between interfaces. The colour plots in Figure 11 show contours of the scalar damage variable for each delamination plane. It can be seen that the crack front along the central interface is irregular. Damage is also observed along the two neighbouring interfaces, with a higher extent of damage being observed in the 'lower' interface in comparison with the 'upper' interface. As the number of nucleating cracks increased, numerical instabilities were observed in the models. These were characterised by high-frequency oscillations in the loads and displacements predicted by the FE solution. The simulations were stopped when the numerical 'noise' became excessively high in comparison to the 'quasi-static' values of interest.

In order to investigate the factors affecting the nucleation of matrix cracks, a parametric study was performed on the cohesive strengths assumed for the transverse cracks. While maintaining all critical strain energy release rates constant, and without modifying the delamination properties, the cohesive strengths for the user-defined elements were varied within a certain range shown in Figure 12. The number of matrix cracks as well as the tendency for delamination to migrate between interfaces were found to be strongly sensitive to the assumed strength values. At the top of the range, where \( \sigma^\text{max} = 120 \, \text{MPa} \) and \( \sigma^\text{max} = 130 \, \text{MPa} \), the mesh-independent crack model ceased to predict delamination migration between interfaces, with only a minor number of transverse cracks initiating. This study shows the importance of capturing the initiation of transverse cracks with accuracy in order to predict the progressive damage behaviour of laminated composites. Work is ongoing on understanding the influence of the assumed through-thickness fracture angle on the delamination migration behaviour.

4. Conclusions

Experimental and numerical studies of the phenomenon of 'delamination migration' in laminated composites have been presented. This phenomenon involves delamination and intra-ply damage and its analysis via the finite element method is indeed very challenging. Two analysis approaches have been presented and discussed. The first, based on the \textit{a priori} definition of matrix crack paths using cohesive elements, required very complex meshes and assumptions of crack location. This method did not predict crack migration which was not in agreement with experimental observations. The second was a mesh-independent cohesive crack model, where matrix cracks were allowed to nucleate and propagate automatically based on standard cohesive zone law assumptions. This method could be applied to regular structured meshes and predicted delamination migration and the appearance of multiple matrix cracks, although the locations and damage sequence have yet to be fully validated in a quantitative sense. Further development is necessary for this but the mesh-independent crack model has the potential to offer simple and effective analyses of complex damage mechanisms in laminated composites.

Acknowledgments

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References

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Table 1. Elastic constants for UD plies.

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<th>Property</th>
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<td>$G_{13}$</td>
<td>5.17</td>
</tr>
<tr>
<td>$G_{23}$</td>
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Table 2. Cohesive properties.

<table>
<thead>
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<tr>
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</tr>
<tr>
<td>$K_{II}$</td>
<td>$1.75 \times 10^5$ [N/mm³]</td>
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Fig. 1. A DCB specimen at two successive stages during the test: a. initial fibre bridging; b. delamination migration.

Fig. 2. Photograph of the fracture surfaces of an angle-ply DCB specimen. Red lines indicate the delamination migration events within the four central blocks of \(\pm 60^\circ\) plies until the 0° ply is reached.

Fig. 3. FE mesh of the lower half of the specimen with detail of the mesh refinement.

Fig. 4. Detail of the potential crack paths.
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Fig. 5. FE results using conventional cohesive elements.

Fig. 6. Modelling cohesive cracks via the introduction of extra degrees of freedom.

Fig. 7. Mixed-model cohesive zone law.

Fig. 8. Transverse matrix cracking in 3D.

Fig. 9. FE mesh showing the zone of refinement.

Fig. 10. Specimen layup and through-thickness mesh discretisation.
Fig. 11. Patterns of matrix cracks and delamination using the baseline set of cohesive properties.

Fig. 12. Patterns of matrix cracks observed when varying the intra-ply cohesive strengths.