Modelling the effect of Gaps and Overlaps in Automated Fibre Placement (AFP) manufactured laminates

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1 Introduction
The Automated Fibre Placement (AFP) process shows great potential for efficient manufacturing of large composite structures. An AFP machine consists of a computer controlled robotic arm with a placement head (refer to Fig. 1) that lays bands of pre-preg strips (slit tape) onto a mould in order to construct the layup. The pre-preg strips are relatively narrow (~6mm) tapes. Due to the complexity of the tape laying process, gaps and overlaps as shown in Fig. 2 can be introduced between the adjoining tapes. These gaps and overlaps can cause a reduction in strength as compared with pristine conditions. It is important to understand how the size and distribution of such gaps and overlaps influence the strength and failure development. There are a large number of different combinations and permutations for gap and overlap defect types, and finite element modeling is an effective way to understand the interactions of these defects and provide guidelines to the tolerance of gaps and overlaps. Previous modeling work on gaps and overlaps by Cairns et al [2], Sawicki and Minguet [3] and Turoski [4] demonstrated the ability to simulate the failure with gaps and overlaps. However their models did not capture all the detailed features of gaps and overlaps in composites and are quite labour intensive. In this work 3D meshing tools were developed to automatically generate ply-by-ply models with gaps and overlaps. Cohesive elements for potential intra-ply splits and inter-ply delamination were also generated in the models. Models with various sizes and distribution of gaps and overlaps were built to predict the reduction of strength as a function of the magnitude and type of the defects. Results of gap and overlap models were used to guide the experimental characterization of simulated AFP process defects, manufactured by hand layup from pre-preg tape.

2. Features of gaps and overlaps in composites
To investigate the features of gaps and overlaps, trial specimens using IM7/8552 pre-preg with layup [45/90/-45/0]_2S were made by hand and autoclave cured at the University of Bristol. During the cure process two variants on the top surface of the specimens were used, one with soft tooling and one with hard tooling. The soft tooling used only release film, a layer of breather material and the vacuum bag. The hard tooling used a flat Aluminum plate in addition to the release film and breather material. The specimen made with hard tooling has a constant thickness despite the existence of gaps and overlaps while the specimen made with soft tooling has decreased thickness at gaps and increased thickness at overlaps, as shown in Fig. 3.

The specimens were then sectioned perpendicular to the path of the gaps and overlaps. Fig. 4 gives typical images of the sectioned gaps and overlaps. From the sectioned images, it was found that overlapping plies merged at the overlap zone and plies at gaps have a tendency to flow into and fill the gaps. In the case of gaps and overlaps being superimposed, the resin rich area and ply merging phenomena are enhanced.

Based on the above observations, the simplified features for gaps and overlaps models were proposed as shown in Fig.5. For the gaps models, the ply has a length of Agap to flow into the original gap. Away from the gap the ply within length Bgap was thinned down due to part of the ply material flowing into the gap. At the tip of the ply in the gap is a resin rich pocket with a length of Rgap. The thinnest part of the resin area has a minimum thickness of Hmin. In overlap models, there is a transition area with length Aoverlap between the single ply and overlapped plies. A simplified interface was put between the two overlapped plies. The overlapped plies have a total increased thickness of Hoverlap as compared with a single ply. Both the ply thin down shape in
the gap models and ply transition shape from single to overlapped plies follow cosine functions.

For models with soft tooling, the ply thickness away from the regions influenced by gaps and overlaps is the same as in the pristine condition. Therefore the overall laminate thickness decreases at locations with gaps and increases at locations with overlaps. For models with hard tooling, the overall laminate thickness needs to remain constant, as for the pristine condition. Therefore the ply thickness over gaps need to be increased and thickness over overlaps need to be decreased. As fibres in 0° plies bridge over regions with gaps and overlaps and cannot flow along the paths of gaps and overlaps, changes of thickness are evenly averaged only to every non-0° ply. The thickness of 0° plies is not influenced by gaps and overlaps, i.e. the ply thickness of 0° plies over gap and overlap regions remains the same as the pristine condition. For plies with changed thickness, the fibre direction modulus is also changed due to the variation of fibre volume fraction. The in-situ ply modulus in the fibre direction is simplified as a function of the in-situ ply thickness:

\[
E_{11}(T) = (E_{11} \times T_o + \max(0,(T-T_o))) \times E_{22})/T
\]

where \(T\) is the in-situ ply thickness, \(T_o\) is the pristine ply thickness, \(E_{11}\) and \(E_{22}\) are pristine ply moduli and \(E_{11}(T)\) is the in-situ ply modulus in the fibre direction.

The shear, transverse and through-thickness moduli of the plies are not influenced by gaps and overlaps, i.e.

\[
E_{22}(T) = E_{22}, \\
E_{33}(T) = E_{33}, \\
G_{12}(T) = G_{12}, \ G_{13}(T) = G_{13}, \ G_{23}(T) = G_{23}
\]

Where \((T)\) denotes the in-situ condition.

3. Meshes for gaps and overlaps models

In order to put intra-ply cohesive elements along the fibre direction to capture the splitting development in differently orientated plies, in-plane meshes for the gaps and overlaps models consist of unit cell meshes as shown in Fig. 6. The diagonal angle of the unit cell mesh can be adjusted to be applicable to different oriented plies. For instance a quasi-isotropic layup consisting of 0°, 90° and ±45° plies uses the unit cell mesh as shown in Fig. 6a. For a layup consisting of 0°, 90° and ±30° plies, the unit cell mesh is shown as Fig. 6b.

By inputting the unit mesh size, the dimension of each ply and the spacing of pre-defined splits in the plies, the meshing tools can generate the basic mesh for each oriented ply. Cohesive elements for intra-ply splits are put at interfaces between different colored areas.

The distribution of gaps and overlaps within a ply can be expressed by an array \([\text{no. of ply}, x_o, y_o, \text{gap or overlap size}]\), where ‘no. of ply’ identifies the ply in which to put gaps and overlaps, \((x_o, y_o)\) are the in-plane coordinates of the centre, and ‘Gap or overlap size’ defines the size. Positive value of the size represents an overlap and negative size means a gap.

By inputting the stacking sequence and distribution of gaps and overlaps, the meshing tool generates the meshes with defects. Cohesive elements are generated between plies to capture potential delaminations. For the model with the hard tooling condition, the ply thickness was automatically adjusted based on the assumption in section 2 to get constant laminate thickness at regions with gaps and overlaps. For the soft tooling model the plies were assumed to have less thickness reduction or increase due to the flexible upper surface. Fig. 7 gives an example of such a mesh with layup \([45/90/-45/0]_s\) and gap distribution array as:

\[
[3, x_o, y_o, 2] \\
[7, x_o+10, y_o+10, 2] \\
[11, x_o+20, y_o+20, 2] \\
[14, x_o, y_o, 2] \\
[18, x_o+10, y_o+10, 2] \\
[22, x_o+20, y_o+20, 2]
\]

The overlap distribution array is:

\[
[3, x_o, y_o, -2] \\
[7, x_o+10, y_o+10, -2] \\
[11, x_o+20, y_o+20, -2] \\
[14, x_o, y_o, -2] \\
[18, x_o+10, y_o+10, -2] \\
[22, x_o+20, y_o+20, -2]
\]

Meshes with gaps and overlaps as shown in Fig.7 were then stacked up with the meshing tool to form a laminate model as shown in Fig. 8. with cohesive elements generated between plies to capture the potential delaminations. For Cut-section views of the model in Fig. 8a, show the existence of gaps and overlaps in the model. Fig. 8b. gives close 3D views of the gaps and overlaps in the model.

4. Failure Criteria
Cohesive elements inserted in gaps and overlaps models for intra-ply splitting and inter-ply delamination used a strength based initiation and fracture energy based propagation criterion [5]:

\[
\left( \frac{<\sigma_1>}{\sigma_{1 \text{max}}} \right)^2 + \left( \frac{<\sigma_2>}{\sigma_{2 \text{max}}} \right)^2 = 1
\]  

(2)

\[
<\sigma_1> = \begin{cases} 
\sigma_1 & \sigma_1 > 0 \\
0 & \sigma_1 \leq 0 
\end{cases}
\]

\[
\left( \frac{G_I}{G_{IC}} \right) + \left( \frac{G_{II}}{G_{IIIC}} \right) = 1
\]

(3)

Where \(\sigma_1\) and \(\sigma_2\) are mode I and mode II stress, \(\sigma_{1 \text{max}}\) and \(\sigma_{2 \text{max}}\) are mode I and mode II maximum stress. \(G_I\) and \(G_{II}\) are mode I and mode II fracture energy, \(G_{IC}\) and \(G_{IIIC}\) are critical energy release rates for mode I and mode II respectively.

The Weibull statistical failure criterion in Eq. (4) [6] which integrates stresses over the entire model is implemented within the ply solid elements to capture the fibre tensile failure.

\[
\sum_{i=1}^{\text{No. Solid Elements}} V_i \left( \frac{\sigma_i}{\sigma_{\text{unit}}} \right)^m = 1
\]

(4)

Where \(\sigma_{\text{unit}}\) is the unidirectional failure strength of one unit volume material and \(m\) is the Weibull modulus. \(\sigma_i\) and \(V_i\) are elemental longitudinal tensile stress and volume respectively.

The ply solid elements are orthotropic and elastic. When the fibre failure criterion in Eq. (4) is satisfied, the element with the maximum fibre direction stress loses its load carrying capability and is removed from the model. The load is automatically redistributed to other remaining elements by the FEA program. With the loading continuing, stresses keep increasing until the Eq. (4) is satisfied again, then a further element with the maximum longitudinal tensile stress in the model at this time step is removed. In this way, the progressive damage propagation in gaps and overlaps specimens is simulated.

For compressive failure, the simple maximum stress failure criterion as in Eq.(5) was used.

\[\sigma_{11} > X_c\]

(5)

Where \(\sigma_{11}\) is the fibre direction stress, \(X_c\) is the compressive strength of plies. When the fibre direction stress exceeds the compressive strength, the specimen was taken to experience a sharp failure.

5. Comparison of models for hard tooling and soft tooling condition

To compare the difference of models for hard tooling and soft tooling condition, the layup and defect distribution as shown in Fig. 9, were used. In the configuration of Fig. 9, 2mm wide gaps and overlaps were generated simultaneously by shifting a strip of 6mm wide tape. Cut section views of the layed-up models for hard tooling and soft tooling are compared in Fig. 9b and c. To enhance the visibility, the ratio in the thickness direction of the section was increased so that the ply waviness inside the laminate looks more severe than the actual case. It can be seen that the model for hard tooling has a flat top surface and the model for soft tooling has an undulating surface. The ply waviness in the hard tooling model is less than that in the soft tooling model.

Gross section stress vs. tensile strain curves of the two models are compared in Fig.10, in which the hard tooling model has an obviously larger failure initiation stress and final failure stress. The failure initiation location can be identified both in-plane and in the through-thickness direction in the model, as shown in Fig. 11. This comparison suggests that hard tooling can help reduce the ply waviness at gaps and overlaps and thus increase the tolerance to such defects.

6. Batch analysis of gaps and overlaps models

To test the reliability of the meshing tool, pristine models were firstly created and simulated in both tension and compression. The pristine models failed by delamination in tension and by fibre failure in compression. Table 3 gives the comparison of test results for the pristine specimen with the results predicted by the models. The good agreement between tests and models for the pristine layup in both tension and compression cases suggests that distribution of cohesive elements for splitting and delamination and failure criteria for cohesive elements and fibres are reasonable.
A series of defect models with layup [45/90/-45/0]_3S were then created using the meshing tools and simulated in both tension and compression. Each of the plies is 0.25mm thick and the total laminate thickness is 6mm. Materials for the layups are IM7/8552 with the material properties listed in Table 1 for plies and Table 2 for cohesive elements. The influence of isolated defects was firstly investigated. In the defect models, either gaps or overlaps were placed only in the 90° plies as shown in Fig. 12, 45° plies and -45° plies with or without stagger. The modeling demonstrated that overlaps without stagger have the largest predicted knock-down on the strength compared with gaps and overlaps with stagger. Defects in the 45° or -45° plies have a larger effect on the failure than defects in the 90° plies. Defects in 45 ply and -45 ply have a similar effect on the failure.

Another series of gaps and overlaps models with layup [45/90/-45/0]_3S and defects only in the -45° plies were then created to investigate the influence of defect size, stagger repeat and stagger distance. This series of models include only gaps or overlaps in -45° plies with positive stagger distance as shown in Fig. 13a, negative stagger distance as shown in Fig. 13b and combination of gaps and overlaps in -45° plies with negative stagger distance as shown in Fig. 13c. Based on the assumption that the defect features in all combination of gaps and overlaps models are the same, all studied cases with defects only in -45° plies failed by delamination in tension and by fibre failure in compression due to the stress concentration at the waviness caused by the gaps and overlaps. It was further found that negative stagger distance has the largest influence on the failure of the defect models. Defect size, stagger repeat and positive stagger distance have a minor influence on the failure. For the tension cases with negative stagger distance and the same defect size, the influence of Overlaps is greater than Gaps with Gaps+Overlaps in combination having the least effect. For cases of compression with negative stagger distance and the same defect size, the influence of Gaps is greater than Gaps+Overlaps in combination with Overlaps having the least effect.

To investigate the influence of interacting defects, models with overlapping gaps and overlaps, i.e. defects in the 45, 90 and -45 plies, were created. At the in-plane cross-over point these defects give rise to a “stack up” of the gaps or overlaps as shown in Fig. 14a. For the stacked up gaps and overlaps models, three cases of the cross-over centre of the defects were considered: close to either edge and at the centre of specimen, as shown in Fig. 14c and d. Results were generated for both tension and compression loading, as shown in Table 4. The specimens failed by delamination in all tension cases and by fibre failure in all compression cases. Comparison in Table 4 also shows that the interacting gaps have a greater strength knock-down than the overlaps in both tension and compression. When the cross-over centre of gaps and overlaps is close to either edge of the specimen, the influence of defects is increased compared with the defects in the centre. This conclusion will be validated against experimental results in the future.

7. Summary and discussion

A sophisticated meshing tool has been developed to automatically create complex models of gaps and overlaps specimens. This meshing tool makes it easy to create series of defect models with various combinations and permutations of gaps and overlaps, hence to systematically investigate the influence of defect size and distribution on the strength knockdown of the specimens. Cross-section views of gaps and overlaps in the models generated automatically from a set of predefined parameters showed very good agreement with views of manufactured specimens. Both tensile strength and compressive strength knockdown of the specimen are encouraging, though they still need to be verified again tests in future. With detailed finite element analysis such as this it will become possible to generate guidelines for the tolerance of specimens made by AFP to gaps and overlaps.

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References
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Tables

Table 1  Fibre material properties of IM7/8552(1=fibre direction)

<table>
<thead>
<tr>
<th>$E_{11}$ (GPa)</th>
<th>$E_{22}=E_{33}$ (GPa)</th>
<th>$G_{12}=G_{13}$ (GPa)</th>
<th>$G_{23}$ (GPa)</th>
<th>$v_{12} = v_{13}$</th>
<th>$v_{23}$</th>
<th>$a_{11}$ (°C$^{-1}$)</th>
<th>$a_{22}$=$a_{33}$ (°C$^{-1}$)</th>
<th>$m$</th>
<th>$\sigma_{unit}$ (MPa)</th>
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<td>161</td>
<td>3.98</td>
<td>5.17</td>
<td>0.32</td>
<td>0.436</td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>41</td>
<td>3131</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</table>

Table 2. Cohesive material properties of IM7/8552

<table>
<thead>
<tr>
<th>GIC (N/mm)</th>
<th>GIIC (N/mm)</th>
<th>Mode I Yield Stress (MPa)</th>
<th>Mode II Yield Stress (MPa)</th>
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<tr>
<td>0.2</td>
<td>1.0</td>
<td>60</td>
<td>90</td>
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Fig. 1. Automated Fibre Placement head[1]
Fig. 2. Schematic gap and overlap between adjoining tapes

Fig. 3. Cut-section view of gaps and overlaps trial specimens with soft and hard tooling

Fig. 4. Sectioned views of gaps and overlaps in trial specimens

Fig. 5. Simplified features of gaps and overlap models

Fig. 6. Unit cell for the meshes of gaps and overlaps models
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Fig. 7. Meshes with layup [45/90/-45/0]₃s, and cut-section views of distributed gaps and overlaps

Fig. 8. Gaps and overlaps model with a stacking sequence [45/90/-45/0]₃s
a. defects distribution

b. cut-section view of the model for hard tooling

c. cut-section views of the model for soft tooling

Fig. 9. Comparison of cut-section views of models for hard and soft tooling, thickness changes magnified

Delamination initiation        delamination propagation

Fig. 11. Failure (delamination) initiation and propagation within the hard tooling model

Gaps or overlaps only in 90° plies

Fig. 12. Gaps and overlaps only in 90° plies with or without stagger

Fig.10. Comparison of failure stresses of hard tooling and soft tooling models
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Fig. 13. Defect seeds only in -45° plies

Fig. 14. Stacked up defects in the inner-most plies