

# EFFECT OF GAPS INDUCED BY TOW MISALIGNMENT IN COMPOSITE STRUCTURES FABRICATED WITH AUTOMATED FIBER PLACEMENT METHODS

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## Abstract

Automated fibre placement (AFP) is a method used to create large or complex composite parts. While it has its advantages, it also leads to defects in the material which are not seen in other methods. One of these defects is the appearance of side-to-side gaps, which have been examined using finite element software. By varying the number of gaps, their width, and their angle with respect to the loading axis, the effects of gaps on the strength of composite coupons has been obtained. Gaps at 45° seem to have negligible effects in most cases while gaps at 0° and 90° can lead to strength reductions of over 10%. The combination of several of these gaps into one coupon had no effect in tension but in compression there was a reduction in strength of 4.6%, the highest for any coupon with only 4 gaps.

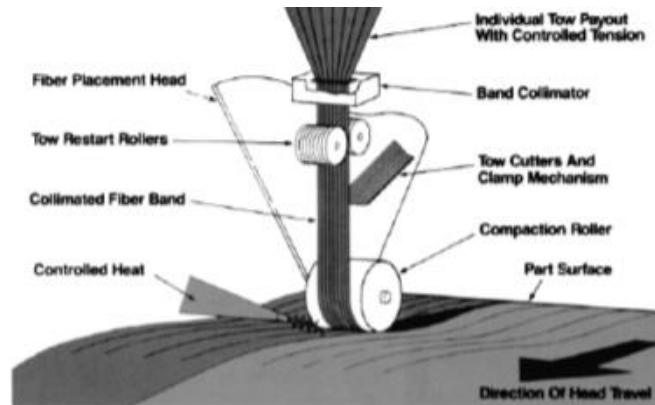
## 1. Introduction

In industries such as aerospace and high end automotive, the use of composite parts is consistently increasing to replace conventional metal parts. There are many benefits to using composite materials, but due to their more complex nature, getting parts certified is a slow process. This is especially true in aerospace where the regulations are extremely strict. In this industry it is common to use the automated fibre placement (AFP) method to make large or complex parts. While this method allows for the creation of parts that would otherwise be unfeasible by hand layup, it also comes with defects which would not be seen in other methods. The effect of many of these defects are still not understood fully. This leads to hefty safety factors regarding defects, which then leads to increased production times and a higher difficulty when certifying parts. If composite parts are to be used more frequently in large aerospace structures, then AFP is the most promising manufacturing technique and its defects must be further understood. This paper aims to further the understanding of these defects, specifically side-to-side gaps, by running simulations using the finite element method.

### 1.1. Automated Fibre Placement (AFP)

The automated fibre placement method uses a machine to place thin strips of composite prepreg onto a mould according to a program which a user must set up. There are diverse types of AFP machines, but the idea is always the same. The composite prepreg is stored in rolls and loaded into the AFP head (see figure 1). The composite strips in the rolls are called tows. The tows are pulled through the head and pressed to the mould with a compaction roller. The tows are heated at the point of contact to increase

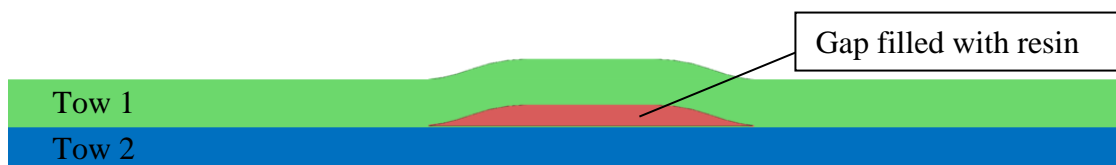
tackiness. Multiple tows are placed at the same time and on newer machines each tow can be cut and restarted separately. Tows are typically 1/4 inch or 1/8 inch wide [1]. The width of the combined tows is called the bandwidth. The AFP machine continues to place the tows until one ply is complete and then moves on to the next ply. This is repeated until the full part has been made.



**Figure 1.** Example of AFP head applying tows to a mould [2]

## 1.2. Side-to-Side Gaps

While AFP is a great method of manufacturing, it also has its disadvantages. One of which is the appearance of defects that are not present in other methods. Some examples of these defects are twisted tows, tow overlaps, tow gaps, tow wrinkling, etc. In this paper the effect of side-to-side gaps will be examined. A side-to-side gap happens when two adjacent tows are misaligned with respect to each other, leaving a space between them. This can be seen in figure 2. This type of defect occurs most often when there is a curvature to the part or when the machine is programmed to perform fiber steering. It can also occur in simple straight sections between two passes of the AFP head. During the cure cycle this space gets filled in with matrix from the surrounding tows. There is also a different behavior if using hard tooling (caul plates on both sides) or soft tooling (vacuum bag). If soft tooling is used, then ply waviness is introduced into the part. This happens because the plies above or below the gap get pushed into the open space. In the case of hard tooling the total thickness of the part remains constant so there is less or no ply waviness at all. This paper will only study simulations for coupons which would be made from hard tooling, meaning no ply waviness



**Figure 2.** Top view of gap geometry

Little research has been done to study gaps compared to other aspects of composites. Research that has been done does not examine gaps of this shape. Typically, an entire tow is removed leaving a rectangular gap which runs through the entirety of the coupon. In 2011 an experimental study was conducted to study these types of gaps [3]. The coupons all had two tows removed directly on top of each other at the center of the part. The gaps were 3.175 mm wide and 0.424 mm thick. The coupons were also made with soft tooling meaning that there was some ply waviness. The results of these tests

were that the gaps had minimal effect. in tension, compression, and shear with longitudinal gaps as well as shear with transverse gaps, the reduction in strength was 3% or less. This concluded that a single gap may not have a large effect but coupons with additional gaps should be studied.

In 2015 another study was done which built on this idea [4]. Finite element simulations were done in tension and compression for coupons made by hand tooling. Again, the gaps ran through the entirety of the part and were two plies thick. Each gap was 2 mm wide by 0.5mm thick. Different staggering sequences were tested with 6 gaps, and the gaps were put in 90° plies for some tests and in 45° plies for others. These tests led to some interesting results. Several of the configurations generated reductions in strength between 10% and 25%. While 6 gaps that are two plies thick may seem unreasonably high for certain industries, it still demonstrates that more gaps will have a larger effect.

## 2. Material and Methods

### 2.1. Required Material properties

The material used was a carbon/peek composite. Because of a confidentiality agreement the properties of the material cannot be shared. The required properties for the simulations can be seen in below.

**Table 1.** Properties used for finite element model

Elastic lamina properties (required for composite prepreg and neat resin)						
Symbol	$E_1$	$E_2$	$\mu$	$G_{12}$	$G_{13}$	$G_{23}$
Detail	Longitudinal elastic modulus	Transverse elastic modulus	Poisson's Ratio	Shear elastic modulus	Shear elastic modulus	Shear elastic modulus
Hashin damage properties (required for composite prepreg and neat resin)						
Symbol	$\sigma_{T1}$	$\sigma_{C1}$	$\sigma_{T2}$	$\sigma_{C2}$	$S_1$	$S_2$
Detail	Longitudinal tensile strength	Longitudinal compressive strength	Transverse tensile strength	Transverse compressive strength	Longitudinal shear strength	Transverse shear strength
Hashin damage evolution properties (required for composite prepreg and neat resin)						
Symbol	$G_{LT}$	$G_{LC}$	$G_{TT}$	$G_{TC}$		
Detail	Longitudinal tensile fracture energy	Longitudinal compressive fracture energy	Transverse tensile fracture energy	Transverse compressive fracture energy		
Cohesive behavior properties (required for cohesive properties between plies)						
Symbol	$K_{NN}$	$K_{SS}$	$K_{TT}$			
Detail	Normal stiffness coefficient	In plane shear stiffness coefficient	out of plane shear stiffness coefficient			
Damage initiation properties (required for cohesive properties between plies)						
Symbol	$\sigma_N$	$\sigma_S$	$\sigma_T$			
Detail	Normal strength	in plane shear strength	out of plane shear strength			
Damage evolution properties (required for cohesive properties between plies)						
Symbol	$G_I$	$G_{II}$	$G_{III}$			
Detail	Normal fracture energy	in plane shear fracture energy	out of plane shear fracture energy			

### 2.2. FEA Model

The software used for the simulations was Abaqus Unified FEA. To capture any out of plane loads or ply separation, each ply was modeled as a separate part and then stuck together with cohesive elements.

### 2.2.1. Modeling the Gap

The gap in the model has been simplified. The gap is modeled as a trapezoid instead of having the curved shape that was shown before in figure 4. In reality, the tow is misaligned meaning there is some fibre steering that occurs. Right beside the gap there should also be an overlap region. For these simulations it is assumed that these two aspects will have negligible effects when compared to the gap. The material of the gap is that of neat resin. Particular care has been taken to avoid having edge effects. A paper in 1996 plotted stress concentration as a function of distance from the edge of a coupon [5]. From these results, it was concluded that a leaving at least a distance of two times the thickness of the coupon between a gap and the edge of a coupon would be appropriate.

### 2.2.2. Model Boundary Conditions

The boundary conditions for a coupon in tension can be seen in figure 3. One end of the coupon has the entire face constrained in the X direction. There are also three points which are constrained (two in Y and one in Z) to prevent the coupon from rotating while still allowing it to grow and shrink due to Poisson effect. The other end of the coupon has the exact same conditions except instead of having the face fixed, a displacement in X is applied. For compression tests the top and bottom faces are fixed in Y to avoid buckling, and the constraints on the three points at each end are removed.

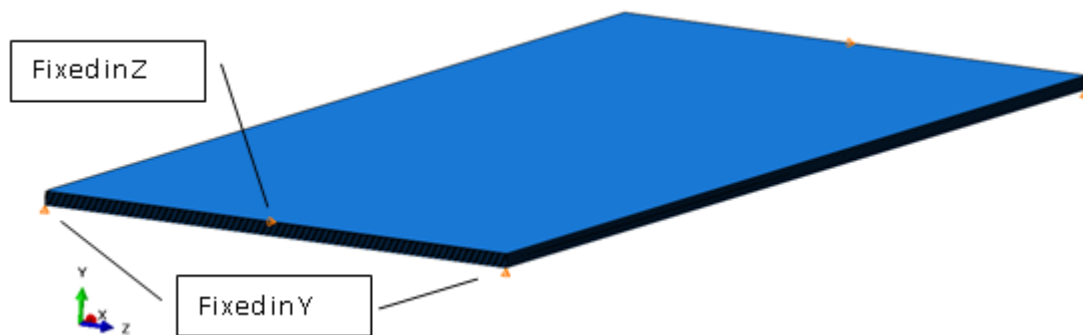


Figure 3. Model coupon with fixed points shown.

### 2.2.3. Model Mesh

Continuous shell elements with enhanced hourglass control. Plies which contained gaps had to be segmented to keep the mesh as uniform as possible. As can be seen in figure 4, the region around the gaps have an irregular pattern. To obtain valid results, the elements in this region were smaller. A mesh sensitivity analysis was conducted to ensure the element sizes chosen for the entire part would be small enough to give an appropriate solution. On average the model contains 112000 nodes.

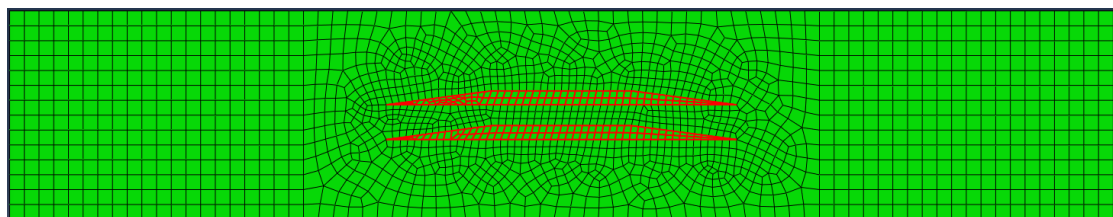


Figure 4. Top view of model mesh for a 0° ply with two gaps. Gaps highlighted in red

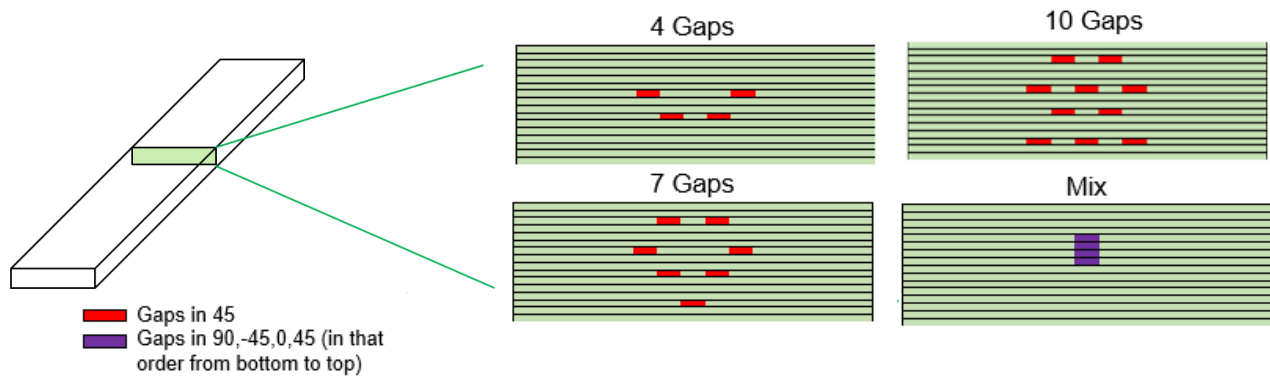
### 2.3. Test Plan

The variables that were examined in these simulations were; number of gaps, angle of the gaps in the coupon, and width of gaps. Table 2 shows how each variable was studied.

**Table 2.** Finite element test matrix

		Gap details							
		45° ply gaps		0° ply gaps		90° ply gaps		mixed ply gaps	
		0.05" width	0.1" width	0.05" width	0.1" width	0.05" width	0.1" width	0.05" width	0.1" width
Number of gaps	4	FEA	FEA	FEA	FEA	FEA	FEA	FEA	no FEA
	7	FEA	FEA	FEA	FEA	FEA	FEA	no FEA	no FEA
	10	FEA	FEA	FEA	FEA	FEA	FEA	no FEA	no FEA

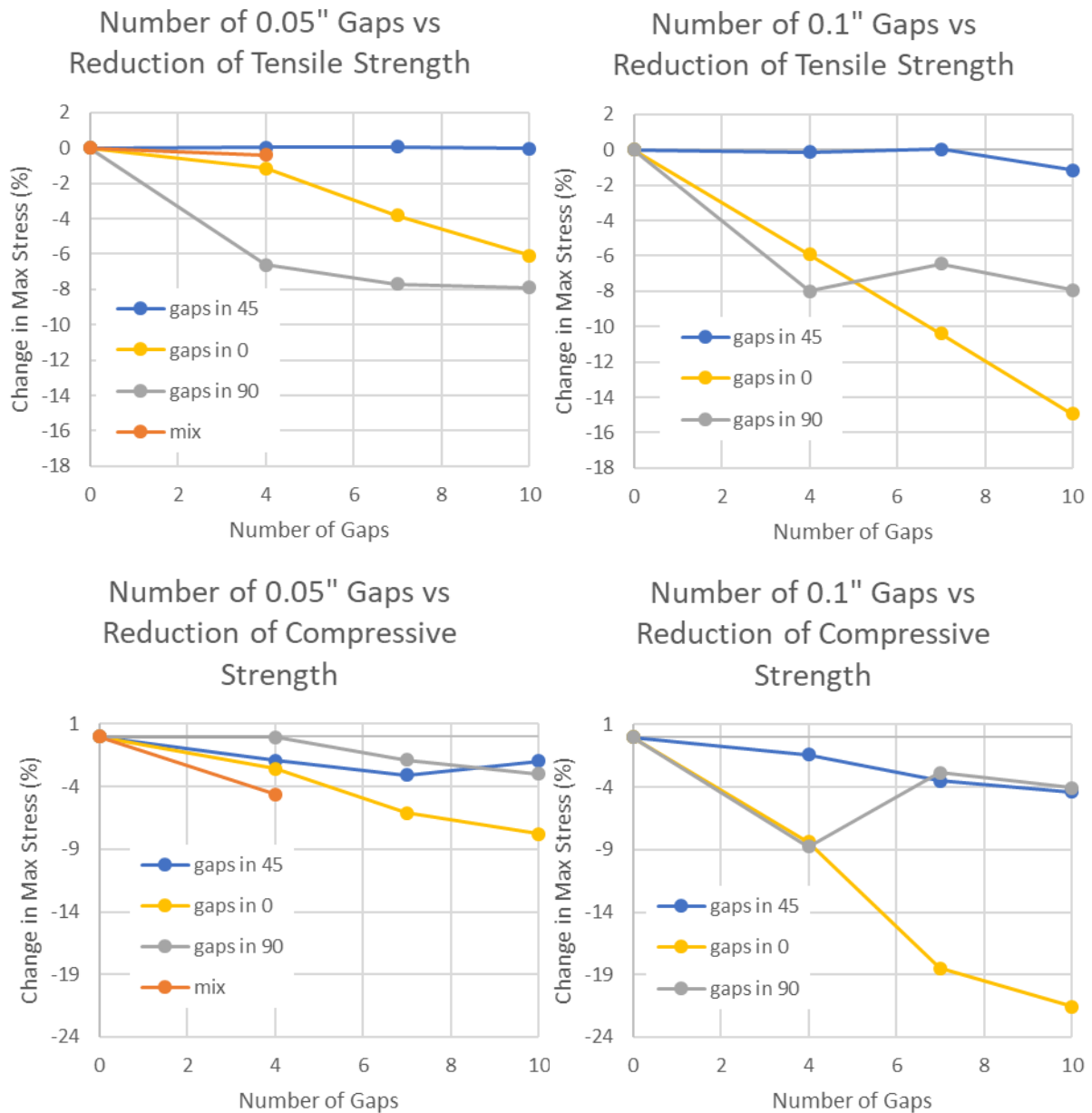
An example of the orientation of the gaps can be seen in figure 5. The figure shows cross sections of coupons with different amounts of gaps. The red and purple rectangles denote the locations of gaps which are coming out of the page at an angle as defined by the legend. The figure shows coupons with gaps in 45° plies, as well as the coupon with mixed gaps. The coupons with gaps in 0° plies and in 90° plies are like the 45° case except that the gaps are moved up or down to the appropriate plies.



**Figure 5.** Coupon cross section showing location of gaps for different tests

### 3. Results

This paper examines the ultimate stress of the coupons and the failure modes. These were compared to a pristine coupon. The changes in maximum stress can be seen in Figure 6.

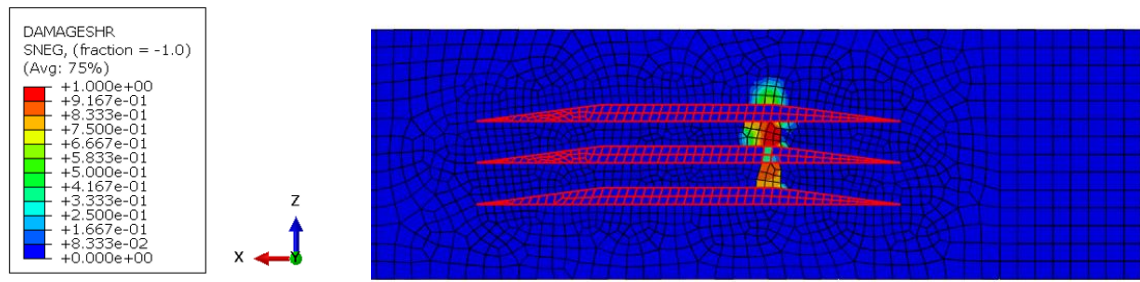


**Figure 6.** Finite element analysis results

## 4. Discussion

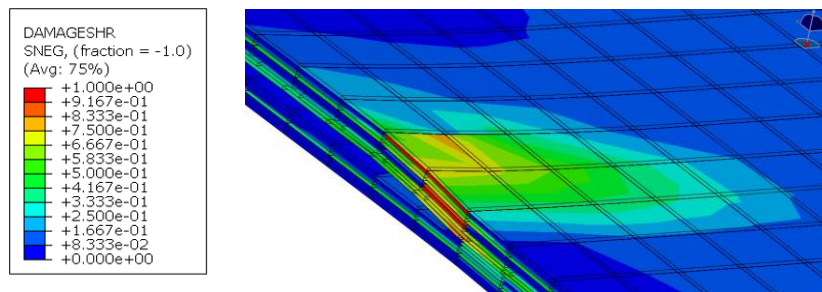
### 4.1. Tension Discussion

When gaps are placed in the 45° plies there is no effect until we hit the extreme case of 10 gaps of 2.54mm width. Even in this case though there is less than 2% reduction in strength. When gaps are placed in the 0° plies there seems to be a linear trend of decreasing strength. The reduction in strength gets to be as high as 15%. All the 0° gap coupons as well as the only 45° gap coupon with lower strength failed due to fiber damage in the gap area. Figure 7 shows an example of the failure initiation with gaps highlighted in red.



**Figure 7.** Failure initiation around gaps

The coupons with gaps in the 90° plies have a stranger behavior. There seems to be somewhat of an inverse function with the asymptote around -8% change in strength. These coupons failed due to ply delamination close to the area with gaps. This could explain why adding more gaps does not affect the strength that much. The ply delamination is what ultimately leads to failure. This means that once the delamination happens, it does not matter how many gaps there are. If 4 gaps are enough to cause delamination then adding more gaps won't change the results by much, the ply delamination initiates at around the same load in the cases tested. Figure 8 shows an example of the ply separation.



**Figure 8.** ply delamination in coupon with gaps in 90° ply

The coupon with gaps in the mixed case had negligible effect, less than -1% change in strength. This test was a worst-case scenario to see if the interactions between adjacent plies with gaps at different angles could create a notable effect that otherwise wouldn't be seen.

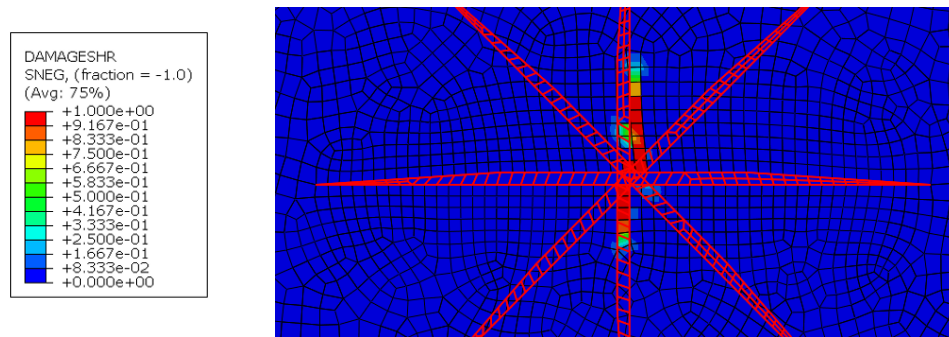
#### 4.2. Compression Discussion

All the coupons failed due to fibre compression damage. The gaps in 45° plies have an effect in compressive tests that they did not have in tension tests. All coupons still have less than 5% reduction in strength. The coupons with 0° gaps act the same in compression as they did in tension. There is an approximate linear trend of decreasing strength once again. The reduction in strength is larger than the tension case. The coupons with 90° gaps no longer have ply delamination like they did in the tension tests. This is most likely due to the new boundary conditions which hold the top and bottom faces. This could also be why the effects of the gaps are less than in the tension case. The failure now is initiated by fiber compression failure in the 0° ply around the gap area. It is important to note that the coupon with 4 2.54 mm gaps has the largest reduction in strength. This is unexpected and means that the orientation of the gaps also plays a role in the failure of the coupon. The coupons with 7 and 10



gaps have the gaps more spread out thus spreading the effects of the gap more uniformly over the cross section.

The coupon with the mixed gaps has the worst effect out of all the compression tests with 4 gaps. There is only one data point, but it's result shows that there is a need for further simulations. The coupon has a change in strength of -4.6%. Figure 9 shows the damage initiation. The gaps in the surrounding plies are highlighted to show their location in relation to the damage.



**Figure 9.** Failure initiation of coupon with gaps in multiple plies. Gaps shown are in different plies.

## 5. Conclusion

With the results of this paper, some conclusions can be drawn about gaps. First, coupons containing gaps react differently to different angles of gaps. Gaps in plies at 45° have the lowest effect, having at most 4% reduction in strength but often having no effect at all. 0° gaps have a negative effect that is linearly increasing, consistently lowering the strength of the coupon as more gaps are added. In the extreme cases the strength of these coupons drops more than 15%. Coupons with gaps in 90° have the strangest behavior. Having a significant change in strength from 0 to 4 gaps but then reaching a plateau where more gaps seem to have no further effect. Many of the coupons with 90° gaps reach a reduction in strength of around 8%. The mixed gap configuration shows negligible effect in tension but has the largest effect of any coupon with 4 gaps in compression, having a reduction of 4.6%. This shows that gaps do interact with one another when placed close enough. More tests with mixed gap orientations should be done. The results of all these simulations also show that increasing the width of a gap also increases the reduction in strength. Physical test should be done to validate or update this model. For now, though, these results help to guide future work.

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