AUTOMATED FIBER PLACEMENT DEFECT IDENTITY CARDS: CAUSE, ANTICIPATION, EXISTENCE, SIGNIFICANCE, AND PROGRESSION

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ABSTRACT

Automated Fiber Placement (AFP), a major composite manufacturing process, can result in many defects during the layup process that often require manual corrective action to produce a part with acceptable quality. These defects are the main limitation of the technology and can be hard to categorize or define in many situations. This paper provides a thorough definition and classification of all AFP defects. This effort constitutes a comprehensive and extensive library relevant to AFP defects. The defects selected and defined in this work are based on understanding and experience from the manufacture and research of advanced composite structure. Proper classification of these defects required an in-depth literature review and consideration of various viewpoints ranging from designers, manufacturers, analysts, and inspection professionals. Collectively, these sources were utilized to develop the most accurate view of each of the individual defect types. The results are presented as identity cards for each defect type, intended to provide researchers and the manufacturing industry a clear understanding of the (1) cause, (2) anticipation, (3) existence, (4) significance, and (5) progression of the defined AFP defects. The link between AFP defects and process planning, layup strategies, and machining was also investigated. Categorization of all important automated fiber placement defects is presented.

1. INTRODUCTION AND LITERATURE REVIEW

Composite materials are one of the most widely used materials in the world today (Yan et al., 2014). Automated Fiber Placement (AFP) is increasingly utilized for manufacturing these composite materials into useful parts [8]. An AFP machine is typically comprised of a robotic arm/gantry and a fiber placement head that can layup multiple strips of carbon fiber material, which are usually resin-infused. These strips of carbon fiber material, known as tows, are often laid up in differently oriented layers, known as plies, to increase the strength of the part [3]. To secure adhesion of these tows to the tool or the plies that are laid up in prior layers, the fiber placement head must have a method of heating the resin and compacting it down to the surface. This is done by having a controlled amount of heat coming from a heater within the head and a compaction roller going over the tows after they have been placed [4]. After compacting the first ply to the tool, subsequent plies can be added until the desired shape and strength for the part has been reached.

Automated fiber placement brings a more efficient and productive method of composite manufacturing; however, the automated manufacturing process is far from refined, and defects can

be found throughout products of AFP manufacturing. The defects found in the layup portion of the AFP process are often an unintended part of the layup process. Therefore, a full understanding of what these defects are and how they interact with the part being made is critical. On this front, many papers have been published. Some of the most common defects in a part have been determined to be tow gaps/overlaps and wrinkles. These defects have been investigated in previous work. For example, tow gaps/overlaps, have been found to result in reduction in laminate strength in the work by Fayazbakhsh et al. (2013). Lopes et al. (2007) showed that gap/overlap defects lead to a decrease in strength at the site of the defect, whereas an overlap is shown to increase the strength at that site in a constant stiffness laminate [5] [7]. Sawicki et al. (1998) detailed the geometric consequence of these defects and their potential consequence, such as strength reduction [11]. Lan et al. (2016) determined that gaps and overlaps can lead to resin-rich and fiber-rich areas in the part if left untreated [6]. The wrinkle defect has also been investigated. Details of the effects of minimum turning radius on wrinkling were presented by Nik et al. (2014) [9]. Another paper detailed the reduction in strength that resulted from wrinkling and identified it to be as high as 36% [10]. Finally, the expected effects of the defects on the laminate structural properties are included. [1], [2].

Based on the literature reviewed, combined with the experience of the researchers at the University of South Carolina McNAIR Center, a more complete understanding of these defects is presented. This understanding is utilized to define each defect from different viewpoints. Viewpoint modelling is the investigation of a certain model from multiple and different perspectives. The easiest example is design of structural parts: some see the design from its functional point of view, others from the part's structural behavior … assemblers look at mating surfaces and care less about other portions as long as they do not obstruct the assembly process. Following this introduction, section 2 presents the different viewpoints of interest that will be investigated to understand AFP defects. Section 3 presents the most prominent AFP defects based on the researchers' industrial practice and manufacturing. The article concludes with future elements to be considered in AFP defects investigations.

2. VIEWPOINT MODELLING

In order to fully understand AFP defects, a complete understanding of the source and how the part geometry might influence the defect formation must be reached. The current work begins with a thorough categorization of AFP defects to develop understanding of the importance of defects from five different perspectives: the cause, anticipation, existence, significance, and progression. Each of these categories have a specific perspective of defining what is considered a defect. The cause category investigates the core cause or causes of a defect. The anticipation category comes from the view of the process planner and investigates whether a defect can be expected with certain parameters in place. This category will show some possible parameter changes to avoid the defect. The existence category defines the defect from an inspection point of view and what the defect visually looks like. This category will show whether a defect is better suited for either a visual inspection or an automated or semi-automated inspection system. The significance category investigates the level of significance a particular defect can have on a part if it occurs. In addition, this section investigates what the defects can lead to if left unresolved. The progression category fully investigates if the defect will progress in the part under service loads if nothing is done to fix the affected site.

3. DEFECT IDENTITY CARDS

We provide a definition of 14 different defect types, along with a graphical representation that we are adopting, and discuss the relevance of the defect to the four different points of views depicted in Figure 1. For each defect we propose a schematic, a CAD representation and a picture from the actual manufacturing of a defect.

3.1 Gap/Overlap

A gap is when two adjacent tows are not perfectly laid up next to each other and there is a gap between the two. An overlap is when the two adjacent tows are overlapping onto each other. The most common cause of gaps and overlaps is steering during layup since, the tows in a course will not fit together perfectly, especially when adopting a parallel coverage strategy. However, gaps and overlaps can naturally occur outside of steering if laying up over a complex 3D tool surface.

Table 1: Gap/Overlap –Characteristics

|	
Anticipation	Purposeful steering creates well-anticipated gaps or overlaps. Doubly curved parts will produce either gaps or overlaps since roller courses will not have perfect coverage of the surface. Based on the exact surface geometry and the path of the machine head, the amount of gap/overlap can be computed.
Existence	Gaps and overlaps are easy to detect since they will be visible by the lack of or addition of material when compared to a regular course. As successive plies are laid up over overlaps, consistently at the same location at each layer, significant thickness buildup will be visible.
Significance	A gap and/or overlap may become a site for failure initiation under loads. Gaps would create resin rich regions for crack growth. Overlaps create undulation in the fiber that can lead to compressive failures. They may also become a site for wrinkling in the layers placed over them in the succeeding layer.
Progression	Progressive failure events under static and fatigue loads are a current topic of research by the authors. It may be too speculative to describe micromechanics of failures at this time.
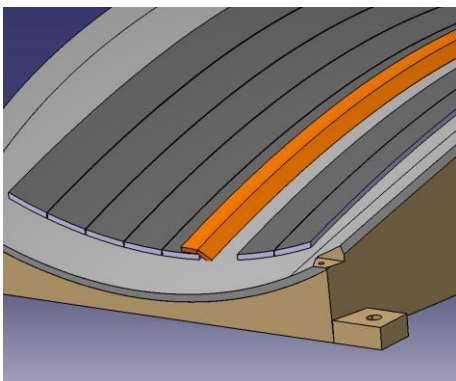
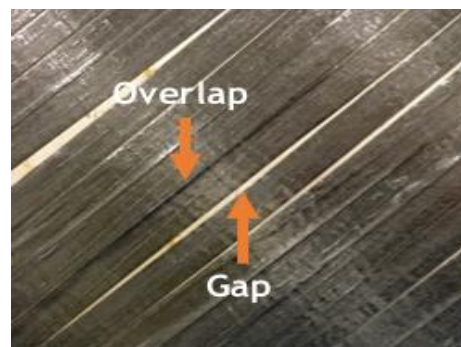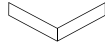
Figure 1: Gap/Overlap CAD Representation.

Figure 2: Gap/Overlap Actual Representation.

3.2 Pucker

Initiating at the inside radius of a steered tow, resulting in the tow lifted from the tool surface either partially or across the entire tow width forming an arch of excess material that is not adhered to the underlying substrate material. Puckered tows are caused by excess feeding of a tow that gradually accumulates ahead of the compaction roller and at some point emerges in the part surface. If placement is over a compliant surface, with the force of the compaction roller, longer tows may be deposited that can form the pucker after the surface spring backs to its original shape.

Table 2: Pucker - Characteristics

| Anticipation	Can be prevented through appropriate towpath planning. Thickness buildup in concave shapes may cause shortening of the surface length, and the tow length paid-out by the machine head may need to be shortened to compensate for the reduced length.
Existence	Small puckers may be difficult to detect visually. A profilometery-based sensor detection system can be utilized to identify the puckered tow.
Significance	A puckered tow is typically flattened by successive layers placed over them and by debulking. However, if the puckers are not properly compacted, it may result in a significant loss of strength.
Progression	Like most defect types, the progressive failure of puckers is not investigated. However, if the pucker is not flattened by placement of the next layer, delamination growth should be expected between the folds under cyclic loads that can propagate to become delamination between the layers.
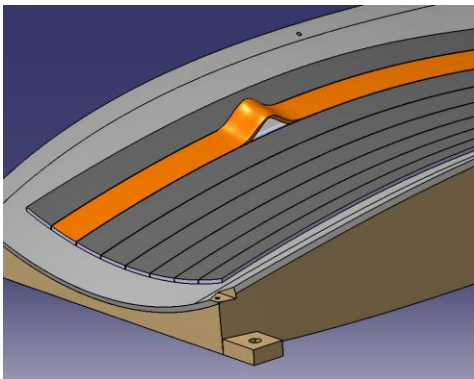
Figure 3: Pucker CAD Representation.

Figure 4: Pucker Actual Representation.

3.3 Wrinkle

A wrinkle is typically indicated by a wavy pattern of puckering along the edge of a tow when it is steered through a non-geodesic path over a complex (potentially doubly-curved) surface or following a steered path on a flat surface. These types of defects occur on the inner radius and remains out-out-plane after compaction and curing. Wrinkles are often caused by placing tows at small steering radii, which can lead to excessive differential length between the two edges of the projection of the tow on the part surface. The two edges of a tow delivered from the machine head are equal length, hence part of the excessive differential length presents as puckers and/or wrinkles.

Table 3: Wrinkle - Characteristics

|	
Anticipation	The steering radius definition and the complexity of the tool surface being laid up on are the main ways to anticipate a wrinkle. Tow path definition during design phase can have a strong influence on wrinkling behavior. Process parameters and tow material properties are also influential.
Existence	Can be detected either visually or using automated inspection systems. Can be difficult to distinguish from puckers as the tow is overhanging along its orientation.
Significance	Wrinkled tows covered by layers that are laid on top, forcing them to flatten during which in-plane fiber waviness or folded fibers may be caused. Can cause gaps and folded tows which can result in a loss of strength.
Progression	Progressive damage of in-plane waviness, as well as the folding are the subject of ongoing research.
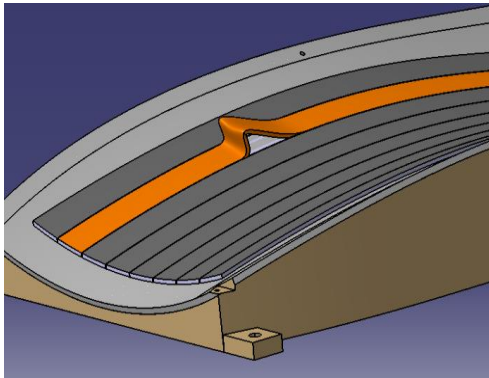
Figure 5: Wrinkle CAD Representation.
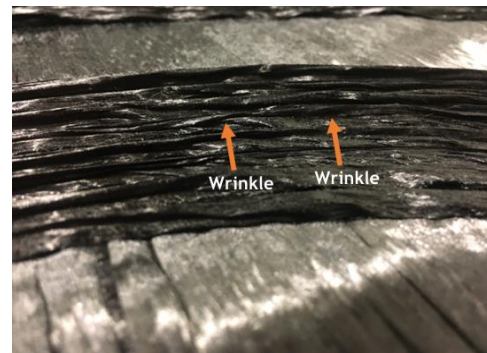
Figure 6: Wrinkle Actual Representation.

A tow-path based model of wrinkling during the automated fiber placement process was developed at USC McNAIR and presented in *The Composites and Advanced Materials Expo CAMX2017* [13]. An investigation of wrinkling within an arbitrary path for a composite tow constructed using the automated fiber placement process was presented. Governing equations and assumptions for a basic zeroth-order model were derived based on geometric considerations only, neglecting the viscoelastic properties of the material, and formulated for an arbitrary curve on a general three-dimensional surface.

3.4 Bridging

A bridged tow does not fully adhere to the concave surface (female tool portion) or a re-entrant corner or ramp-up area over which the tows are being laid up on, leaving a gap between the radius of the concave tool surface and the tow. The main causes of a bridged tow are too much tension on the tow, which will force the tow to lift up, or insufficient tack adhesion to the surface being laid up on due to the roller not providing full contact with the substrate material.

Table 4: Bridging - Characteristics

| Anticipation	The main ways to anticipate this defect are to ensure that the roller has the best contact coverage possible when going over a complex tool surfaces, especially concave portions. Overfeeding of tow may eliminate bridging in re-entrant corners and ramps.
Existence	Bridging is often readily identified visually and by automated inspection systems since the tow in question will be raised about the concave portion of the tool being laid up on.
Significance	Successive passes of the roller to place additional layers with different orientations or de-bulking step with vacuum may push the bridged tow to re-adhere to the substrate. However, the bridging could leave resin rich areas at best, or delamination at worst.
Progression	Significant consideration should be given to these sites as potential progressive growth of delamination.
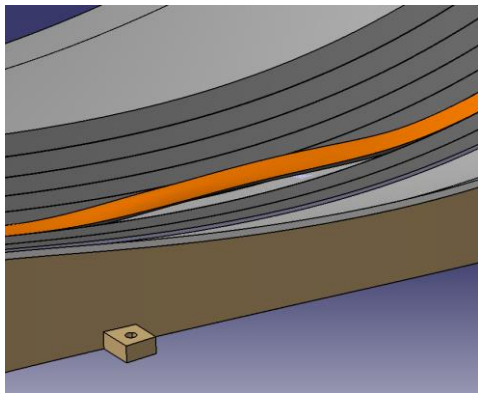
Figure 7: Bridging CAD Representation.

Figure 8: Bridging Actual Representation.

3.5 Boundary Coverage

A boundary gap/overlap occurs when the material cannot perfectly meet up with the edge of a part when laying up at off-axis orientation such as ±45° in rectangular parts. Since the tows do not meet up perfectly with the edge, this will result in either an excess of material along that edge or a shortage between the tow-end and the boundary edge. This can be at the boundary of any coverage zone, be it internal to the part inducing ply drop-offs, or at the external boundary.

Table 5: Boundary Coverage - characteristics

| Anticipation	The ways to anticipate this defect are in defining the percentage of boundary gap and overlap and observing the part's geometry in relation to the ply angles.
Existence	These defects are clearly visible on the edges of any variable angle laminates and will be visible post-cure.
Significance	A boundary gap and/or overlap can have an effect on the shape of the part since the course will not line up with the desired geometry. If the edges are trimmed to ensure accuracy the part may also become more likely to fail in those spots.
Progression	Not investigated by the authors currently.
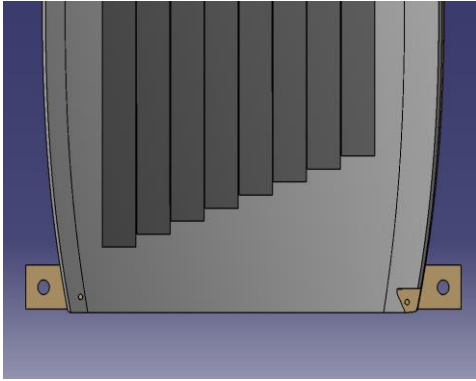
Figure 9: Boundary Coverage CAD
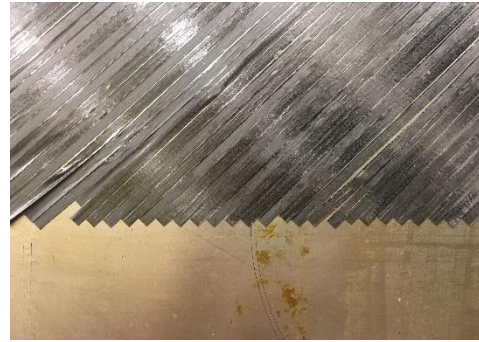Representation.

Figure 10: Boundary Coverage Actual
Representation.

3.6 Angle Deviation

Angle Deviation is when the angle of the as-manufactured layup deviates from the as-designed one. Angle deviation can be caused by incorrect roller coverage or small radius steering as the tow may move after being steered.

Table 6: Angle Deviation - characteristics

| Anticipation	The main way to anticipate angle deviation is through defining the steering radius for any required steering throughout the layup, since a smaller radius can cause angle deviation.
Existence	Angle deviation is observed by visual inspection, but it requires further processing and comparison with the as-designed angles. Inspection systems alone cannot confirm the angle deviation without a benchmark for comparison.
Significance	Angle deviation can cause overlap on portions of the ply when a course will be laid up on top of the deviated tows. This can lead to an undesired shape in the laminate and can be a cause of failure due to resin rich areas on the counter side. This is a similar effect to overlap and gaps.
Progression	Can lead to delamination in the resin rich areas due to improper course coverage.
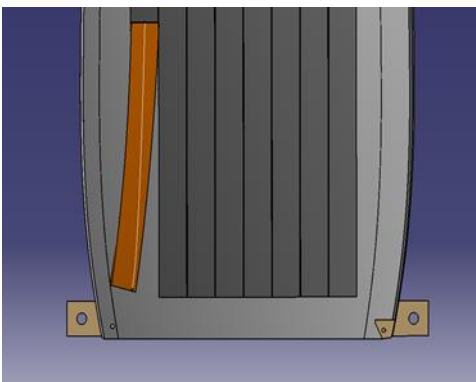
Figure 11: Angle Deviation CAD Representation.

3.7 Fold ▬

This defect occurs when the tow folds in the transverse direction onto itself, creating a gap in the surface coverage and doubling the tow thickness over the folded part. An extension (and probably the worst-case scenario) of the folding could be rolling (or completely twisting) of the tow to become "rope" like. Tensioner errors, lack or too much tension, could increase the propensity of the tow to fold. Long unsupported/complex towpaths from the spools to the head can also result in folding. In a steered/curved towpath, the outer segment of the tow may fold towards the inner side after the compaction roller nip point due to tension on the outer edge of the tow and improper tack adhesion.

Table 7: Fold - Characteristics

| Anticipation	Quality of the slit-tape or tow would have large influence on folding defect. Machine type and machine calibration (health) would have an impact. Design has some influence if the tow-path is steered. Process parameters (speed and temp) influence the tack adhesion.
Existence	Can be detected either visually or via automated inspection systems.
Significance	One of the more serious defect types for cured laminates due to increased thickness right next to a reduced thickness region. Substantial influence on local fiber volume fraction variation, and creation of resin rich areas for failure initiation.
Progression	Sites for delamination initiation following the crack growth from the resign rich defect sites.
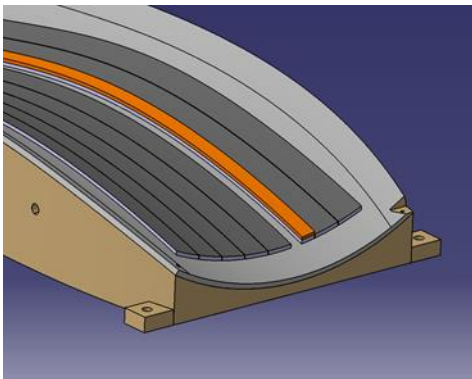
Figure 12: Fold CAD Representation.

Figure 13: Fold Actual Representation.

3.8 Twist ◄►

For this type of AFP defect, the tow is rolled axially 180º onto itself and then flattened by the compaction roller. Depending on the length over which the twisting occurs, the shape may be like a bow-tie with bunching of the fibers and increased thickness at the center. For long twists, $L>5t_w$, the sides are simply folded. Twisted tow could be initiated by folding, in which the fold grows and completes a full turn rather than unfold (folded tow could be considered incomplete twist). Friction between guide holes along a long/complex tow path and a tacky tow may cause twisting due to head rotation during bi-directional layups.

Table 8: Twist - Characteristics

| Anticipation	The rotation of the machine head, the geometry of the part, and the tows not being properly fed into the machine can all contribute to having a twisted tow during layup. The geometry of the part contributes since a head rotation may be necessary on some portions of the part surface.
Existence	Can be detected either visually or via automated inspection systems. Machine learning algorithms can be useful in classifying the defect as twist.
Significance	Like folded tows, twisting roots a portion of the part surface not covered with fiber, especially for long twists, and parts with increased thickness. A Twist may be considered to be more damaging than a fold, as structural load may cause scissoring deformation.
Progression	Besides being a source for cracking and delamination, severe deviation of the fiber paths within the tow from being straight will cause kinking failure of tows under compressive loads.
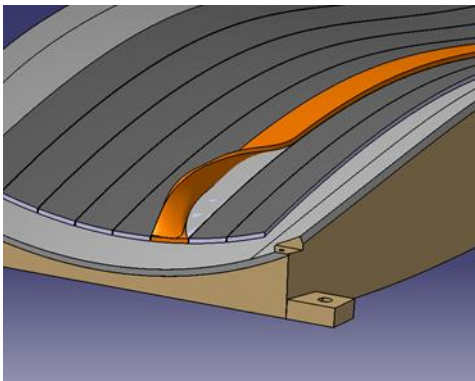
Figure 14: Twist CAD Representation.

Figure 15: Twist Actual Representation.

3.9 Wandering Tow

A wandering tow is when the portion of the tow between the roller and the cutter wanders from the original fiber path after being cut. Similar to tow "angle deviation", wandering tows are more attributable to having an unsupported portion of the tow between the compaction roller and the tow cutter and therefore the angle deviation will only be of the dimension of this un-supported tow length.

Table 9: Wandering tow - Characteristics

| Anticipation	The main approach to anticipate, and thereby prevent, a wandering tow would be in ensuring that any steering does not have too small of a radius or that the roller coverage is maximum to ensure proper adhesion.
Existence	Wandering tows can be visually observed since they are typically located at the ends of a course.
Significance	Wandering tows can lead to a gap/overlap between tows which can result in a resin rich area and ultimately a higher chance of failure.
Progression	Can lead to failure within the laminate due to any gaps created in the ply.
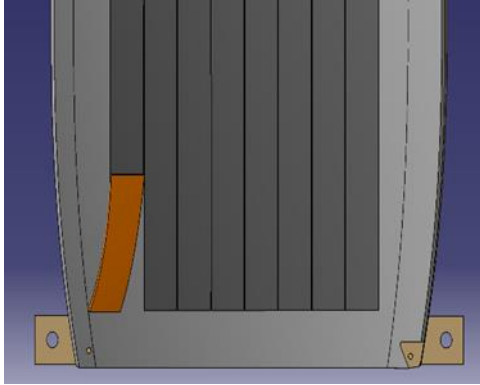
Figure 16: Wandering Tow CAD Representation.

3.10 Loose Tow

A loose tow generally refers to a section of a tow (or tows) that the machine head attempts to place on a part without having complete and precise control over where it is actually placed, causing the tow to meander. A tow is completely loose when the length of a tow is shorter than the length between the cutters and the compaction roller that controls tow's final position. In this case, the tow is free to land on an arbitrary position. If at the end of a course the fiber path is still steered, the section of the tow before the compaction roller may not follow the defined steered path.

Table 10: Loose tow - Characteristics

|	
Anticipation	Angle plies at rectangular corners or other geometric features that require short tows will need to be forced to have longer tow placement, resulting in features called "dog-ears", or "bat-wings". Tow paths for parts that need steering near edges can also be extended beyond their boundaries to eliminate meandering of tows.
Existence	If the loose tow results in significant gap in the laminate, or a completely missing tow, then it can be detected visually or by automated vision systems. For steered tows, it will not be obvious if the tow is floating because of precision or because of course steering.
Significance	Missing tow is already discussed with its own identity card. If the loose tows are because of steering, then its consequences have to be accounted for by using tools appropriate for it (if/when they exist). If it causes unanticipated gap or overlap, refer to appropriate ID card.
Progression	Described in missing tow, and tows with gaps and overlaps.
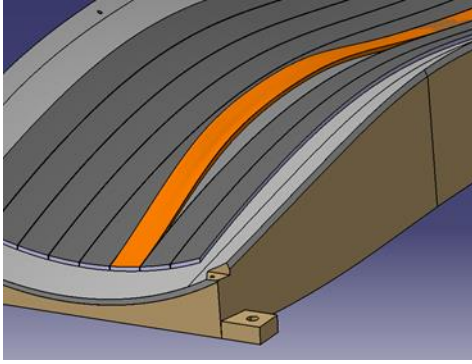
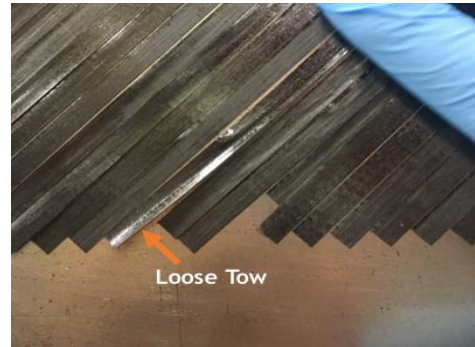Figure 17: Loose Tow CAD Representation.

Figure 18: Loose Tow Actual Representation.

3.11 Missing Tow

This defect typically occurs when an entire tow does not correctly adhere and falls off the surface or is not successfully fed onto a surface from the spools. The resulting missing tow is very similar to a gap, and in fact can be considered as a gap with a size equal to a tow width. Missing tows are caused by either discontinued material feeding into the machine head or layup of a tow with insufficient tack adhesion.

Table 11: Missing tow - Characteristics

|	
Anticipation	This type of defect is not related to any designed features. Ensuring proper splices, and full material spools will eliminate accidental missing tow. On complex surfaces, providing sufficient compaction pressure, and ensuring sufficient material tack with proper temperature will preclude long bridged tows that may fall off the surface.
Existence	The gaps created by missing tows are easy to detect either visually or through automated hardware.
Significance	Like a gap, missing tow will cause local thickness variation, and potential resin rich pockets in the layup that can serve as a failure initiation point.
Progression	This defect is a potential site for progressive delamination failure with the adjacent layers.
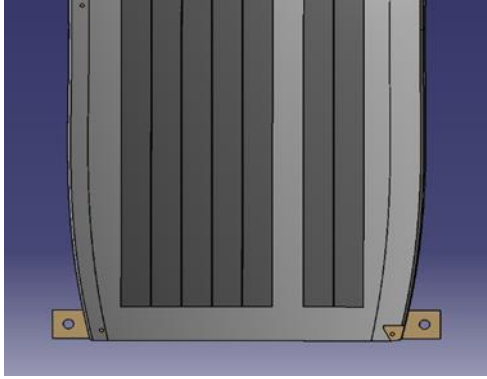
Figure 19: Missing Tow CAD Representation.   Figure 20: Missing Tow Actual Representation.

3.12 Splice

When two tows are joined together by the material or slitting supplier end-to-end in a spool by overlapping 1 to 3 inches over each other and tacking them together. This results in a portion of the spool that is thicker than the rest and is usually marked by white dashes for detection. Theoretically, carbon fibers can be drawn infinitely long. However, most AFP pre-impregnated tows are slit-tape that are cut from a roll of finite length unidirectional tape. These slit tapes are spliced and spooled based on customer specifications.

Table 12: Splice - Characteristics

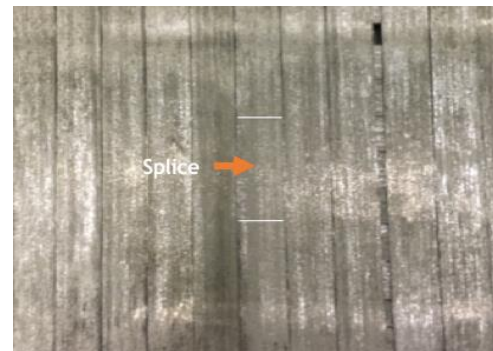| Anticipation	Monitoring and keeping track of spool length for the splice locations with respect to the part size may completely eliminate the spliced tow from the part.
Existence	Splices are difficult to detect visually if not marked. The thickness increase over the splice allows detection with a detection system.
Significance	Thickness change over a small area may be insignificant for stiffness change. This site may become a location for failure initiation especially under compressive loads.
Progression	Splices are possible sites for fiber kinking progression under compressive loads.
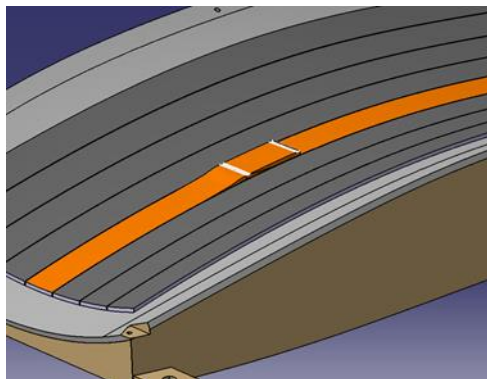
Figure 21: Splice CAD Representation.   Figure 22: Splice Actual Representation.

3.13 Position Error

A position error is when a tow is placed in a wrong location in reference to the end or beginning of a course. This results in a tow that is misaligned with the rest of the tows in the boundary. Main causes of this defect are either obstruction of the tow during feeding (such as building up of fuzz in one of the guide chutes of the machine head), or incorrect machine reference points with respect to the part for a particular course. Sometimes they are due to machine control issues and auto tuning requirements.

Table 13: Position Error - AESP characteristics

| Anticipation	Position errors are arbitrary, and there is no way to anticipate. However, ensuring that there is no material build up in the head of the machine that can cause resistance during layup, and monitoring the accuracy of the layup simulation will reduce the possibility of occurrence.
Existence	Detected visually or by automated techniques.
Significance	Similar to tow gap close to the part boundary, hence their influence compared to the regular defects are expected to be more pronounced due to edge-effect failures observed in multi-layered composites.
Progression	Unknown, but can be expected to be like missing tows or gaps.
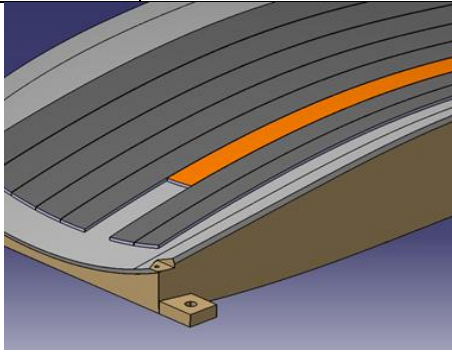
Figure 23: Position Error CAD Representation.   Figure 24: Position Error Actual Representation.

3.14 Foreign Object Detection

A foreign object debris (FOD) defect is when a small piece of composite material, either carbon fiber "fuzz-ball" or "resin ball" that has collected on surfaces of the head or other debris from the production area fall onto the part during layup. This results in a small excess volume of material on the ply if laid up over.

Table 14: FOD - AESP characteristics

| Anticipation	Monitoring the head of the machine and the production area for FOD and routine cleaning of surfaces are the appropriate ways to anticipate this defect.
Existence	Visually detect as it will be an irregular shape out of thickness along the same layer.
Significance	A FOD defect in layup can cause the portion of the next ply above the defect to improperly adhere to the defect's ply. This will lead to an undesired shape and strength of the part being made.
Progression	Unknowable as it will depend on the "Foreign Object".
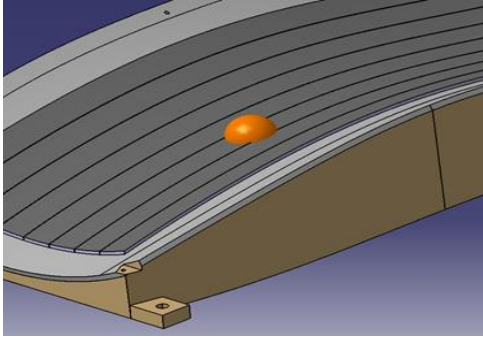
Figure 25: FOD CAD Representation.

Figure 26: FOD Actual Representation.

4. CONCLUSION

This paper described a new way to categorize AFP defects, and does so with a number of the major defects that have been identified through the McNAIR Center's experience and through review of the available literature on AFP defects. In categorizing the defects in this way, the defects can be defined from the viewpoint of the designer, the process planner, the machine operator, and even the inspector. This allows for a rich understanding of each individual defect which can help to fully answer the following questions:

- Can the formation of a certain defect be <u>anticipated</u> based on knowledge of the part geometry, machine parameters, and process planner decisions?
- Can the <u>existence</u> of a certain defect be confirmed based on available inspection systems such as profilometry, heat, ultrasounds or other technologies?
- Can the significance of the existence of the defect be <u>understood</u>, in a certain size/shape, on the overall integrity of my structure?
- Can defect progression be <u>explained</u> to the point of the performance effect and how it can initiate failure?
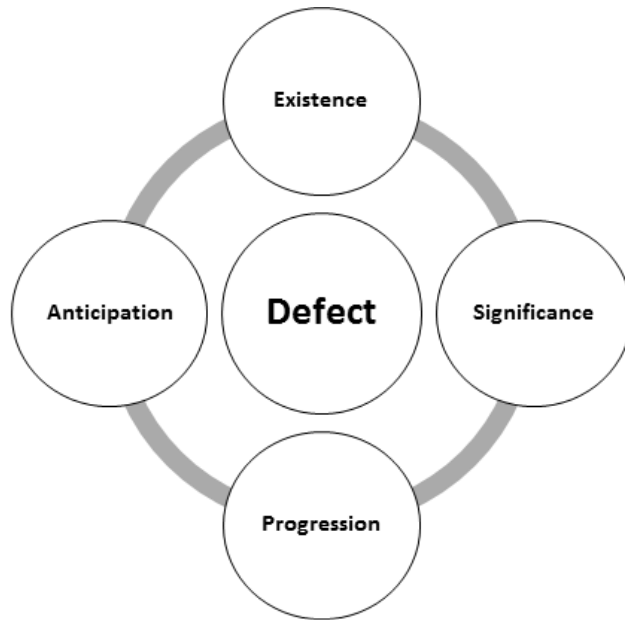
Figure 27. Understanding defects from 4 point of views

5. ACKNOWLEDGMENTS

6. REFERENCES

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