Verification and Validation of Integrated Design and Manufacturing Analysis Tool for AFP Structures

August Noevere, Craig Collier
Collier Research Corporation
Newport News, VA 23606

ABSTRACT

The design of structures for Automated Fiber Placement (AFP) can be a challenging problem for structures that have significant double curvature, such as the forward nose of a fuselage. A software tool has been developed under the National Aeronautics and Space Administration (NASA) Advanced Composites Project (ACP) to address many of the challenges of designing AFP structures. The tool, dubbed the "Central Optimizer" is able to incorporate manufacturing data in the early stages of the design process to reduce the number and severity of design changes needed downstream to accommodate manufacturing requirements. This data includes material overlaps and gaps due to path convergence/divergence, fiber angle deviation, as well defects in the tows themselves such as puckers and wrinkles. The Central Optimizer is used to extract this data from other tools associated with the AFP manufacturing process and map it to the structural analysis Finite Element Model (FEM) in HyperSizer, where laminate optimization takes place. The present work describes the application of the Central Optimizer to several examples, including a saddle tool, wing skin, and fuselage skin. For the fuselage skin, validation was also performed with two builds comparing the resulting manufactured panels with and without the use of the Central Optimizer and HyperSizer.

Keywords: Automated Fiber Placement, Design for Manufacturing, Stress Analysis
Corresponding author: August Noevere (August.Noevere@HyperSizer.com)
DOI: (will be filled by SAMPE)

1. INTRODUCTION

Existing software capabilities for design of AFP structures are limited to manufacturing similations that are not directly connected to stress analysis tools. The developments described in this paper are aimed at closing the gap between manufacturing and stress analysis disciplines to provide software tools that automatically exchange AFP data and provide optimization capaiblities that were not previously possible without this connection.

1.1 Challenges and Motivation

Manufacturing structures with double curvature using AFP presents several unique challenges. The first challenge is to achieve traditional laminates (containing only 0/45/90-degree ply orientations) over the entirety of the structure. This is desirable to ensure that the structure is compatible with the laminate-based failure analyses used widely for aerospace structures [1]. If traditional laminates cannon be achieved, a much larger material test campaign is needed to derive material allowables for a Non-Traditional Laminate (NTL).

SAMPE Conference Proceedings. Seattle, WA, May 4-7, 2020. Society for the Advancement of Material and Process Engineering – North America.

DOI: (Will be added by SAMPE)

Another challenge that arises with AFP on doubly-curved surfaces is the creation of overlaps ("laps") and gaps where adjacent courses (passes of the machine head) converge due to the curvature of the tool surface. When adjacent courses converge, it is necessary to cut tows on either course so that the tows do not cross over each other. However, it is impossible to cut the tow such that it perfectly butts up against the adjacent tow in the adjacent course; this usually results in a triangular-shaped overlap with the adjacent tow and a corresponding area of missing material. These two features are depicted in Figure 1.

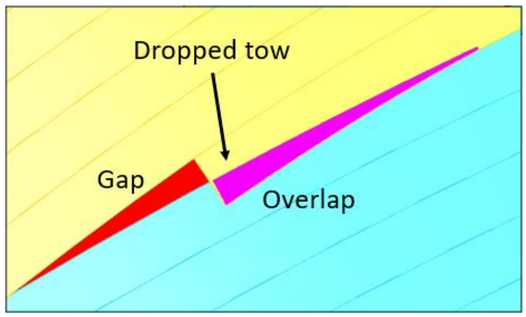

Figure 1. Depiction of a Gap and Overlap.

The third primary challenge faced with AFP structures is the occurrence of AFP defects. There are some defects that occur unexpectedly and randomly during the manufacturing process, such as Foreign Object Debris (FOD), shredded or split tows, etc. However, the defects of interest are those that occur due to steering of the tows. Tow steering is used to avoid having NTL fiber orientations. If it were possible to steer tows to a very tight radius of curvature, NTLs could be avoided entirely. Unfortunately, there is a limit to minimum radius of curvature for steering which is dependent on the width of the tow as well as a variety of AFP process parameters such as compaction force, heating, tow tension, and roller speed.

This paper describes the development, verification, and validation of software tools intended to merge the constraints described above into a single design environment. These tools were developed under the Design for Manufacturing (DFM) task of the NASA ACP in collaboration with industry partners who helped guide the objectives of the tool and verify and validate tool performance.

1.2 Summary of Commercial Off-The-Shelf (COTS) Software

Three existing software tools were incorporated into the DFM analysis and design environment. The figure below summarizes the three COTS software that were used in the DFM project.

DOI: (Will be added by SAMPE)

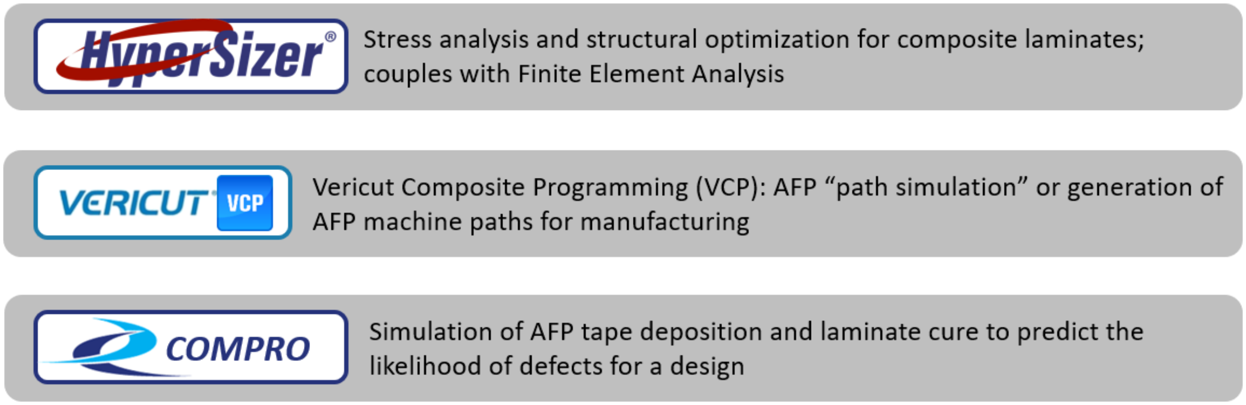

Figure 2.COTS software used on DFM project.

1.3 Summary of Developed/Modified Software

Two entirely new software packages were developed under the DFM project. The figure below summarizes the two new products.

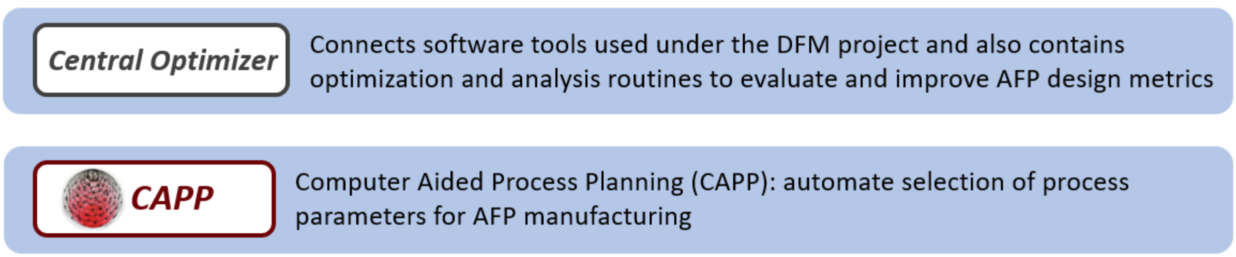

Figure 3.New software developed under the DFM project.

It is also important to note that the three COTS software listed in the previous section were also modified to function better in the DFM environment.

- **HyperSizer** was modified to import and analyze AFP data from Vericut Composite Programming (VCP) and COMPRO.
- **VCP** was modified to export more useful data in a format that could be read in by HyperSizer and the Central Optimizer, including:
  - Lap and gap statistics data per ply
  - Tow steering radius per element, per ply
  - Fiber angle deviation per element, per ply
- **COMPRO** was modified (on a contract outside of the ACC) to include an AFP defects simulation model and cure defects simulation model that are described later in the report.

1.4 Software Integration Goals

The overarching goal of the software developed under the DFM task is to provide as much of the manufacturing data described above as possible to the stress analysis and design disciplines. Doing so allows for localized analyses to determine the true impact of AFP features, in turn allowing for a more optimum AFP structure to be produced.

DOI: (Will be added by SAMPE)

The above goal was achieved by developing and enhancing software tools to provide an integrated design and analysis environment for AFP structures. Although there are several existing software tools dedicated to AFP manufacturing and also existing approaches for analyzing the strength of AFP structures, there is very little automation in the data exchanges between these two disciplines. Additionally, there was very little standardization in data formats in the data exchange between the two disciplines. This is primarily due to the fact that manufacturing data is usually in a CAD-based format whereas structural analysis data is usually in a FEM-based format. The DFM project was focused on addressing these shortcomings to streamline the design process for AFP structures.

One of the initial goals of the DFM project was simply to automate the data transfer between the software tools involved. Each of these is summarized in the subsections below.

1.4.1 Exchange Between HyperSizer and VCP

The primary data exchange is mapping optimized plies (weight and strength optimum) from HyperSizer to VCP. The transfer was accomplished through CATIA to convert the plies from a FEM-based format to a CAD-based format for CATIA. Once the VCP simulation is complete, fiber directions per FEM element for each ply can be mapped from VCP to HyperSizer for inclusion in strength analysis and FEM update. Additionally, lap and gap geometry for each ply can be mapped from VCP to HyperSizer for inclusion in strength analysis and FEM update.

1.4.2 Exchange Between CAPP and VCP

CAPP can read the following data from VCP for each ply: lap and gap location, lap and gap geometry, fiber angle deviation, tow steering. After processing this data, CAPP can send selections for ply start points and layup strategies to VCP via a batch spreadsheet input.

1.4.3 Exchange Between COMPRO and Central Optimizer

<u>COMPRO AFP Defects Model</u>
This defect model can be used to generate a surrogate model that predicts defect probability as a function of AFP process parameters (such as steering, compaction, heating, etc). A Python script is used automatically identify and measure defects generated by the AFP defects simulation. The extracted defects are used to generate a surrogate model of the simulation.

<u>COMPRO Cure Defects Model</u>
Laminates optimized by HyperSizer can be mapped to Abaqus and used to set up a solid element FEM (homogenized material properties) for the COMPRO cure simulation. Porosity predicted by the cure defects model can be mapped from the cure simulation to the stress analysis FEM.

1.4.4 Exchange Between Central Optimizer and HyperSizer

The Central Optimizer connects to HyperSizer via the HyperSizer Automated Programming Interface (API) and can read the following data from HyperSizer:

- Optimum laminates
- Structural weight
- Strength margins
- Analysis details

  - Critical ply
  - Critical failure mode
  - Critical element
  - % of area with negative margins

The Central Optimizer also outputs plot files that can be imported to HyperSizer to view AFP data on the FEM in HyperSizer.

1.4.5 Exchange Between Central Optimizer and VCP

The data read by the Central Optimizer is similar to that read by HyperSizer:

- Lap and gap geometry and frequency
- Tow steering radii
- Fiber angle deviation

Beyond simply automating data transfer, the next major goal of the DFM project was to create optimization capability with the developed software tools. These optimization capabilities are summarized below.

- **Central Optimizer**
  - The Central Optimizer is responsible for driving the overall optimization of the composite AFP laminate.
  - Metrics from both stress analysis and manufacturing disciplines are simultaneously tracked
  - The user iterates the design to produce an overall improvement in all metrics
- **CAPP**
  - The CAPP module is responsible for selecting an optimum start point and layup strategy for each ply.
  - Optimization is performed by selecting an initial start point and layup strategy and iterating with VCP to evolve the selection to minimize AFP defects.
  - In each iteration, the CAPP reads in lap and gap information, fiber deviation, and tow steering to determine how changes in ply start point and layup strategy help or hurt these various metrics.
- **HyperSizer**
  - Optimizes laminates to minimize weight while meeting strength and stability requirements as well as design rules such as symmetry, balance, etc.
  - Effect of AFP features on strength margins are included in the optimization.
  - HyperSizer explores different materials, ply counts, and even structural concepts (i.e. sandwich vs solid laminate) to find an optimum solution.

2. RELATED WORK

2.1 Computer Aided Process Planning Module (CAPP)

As discussed in the previous section, the CAPP module is intended to be used in the optimization process to determine start points and layup strategies for each ply. However, the CAPP was developed with broader goals in mind. Future versions of the CAPP will consider many process parameters beyond start point and layup strategy, including settings such as roller compaction, substrate heating, AFP machine type, etc. Future versions of the CAPP will also consider more AFP defects beyond laps/gaps, deviation, and steering radii, as identified in Reference [2] and ranked in Reference [3]. The ultimate goal of CAPP is to provide users with an automated process to select the best combination of process parameters to minimize these AFP defects.

2.2 Enhancements to Vericut Composite Programming (VCP)

The VCP software was enhanced in parallel to the development of the DFM software [4]. The objective of this enhancement was to add capability to interface better with the DFM environment. This included the output of data such as fiber directions, deviations, steering, and laps and gaps per ply. Additionally, enhancements were added to make VCP a better AFP design tool in general. This included a "laminate manger" that allows the NC programmer to make wholescale changes to programming settings for an entire laminate, as opposed to manually modifying each ply individually (as was the case for previous versions of VCP).

2.3 AFP Defects Process Model

An AFP defects model was developed in parallel to the other DFM software by Convergent Manufacturing Technologies (CMT) to simulate defects that occur during manufacturing. This simulation started out as a tack model to predict the adhesion between AFP tows and the substrate [5]. Eventually the tack model was migrated to explicit FEA simulations in ANSYS [8] and Abaqus [9]. This allowed for the tow and substrate to be modeled to simulate the tow deposition process. This process simulation includes a physics-based tack model to represent tow interaction with the substrate. Also modeled are the roller, tow guide, compaction force, tow tension, and substrate temperature. These features together are able to simulate the buildup of forces in a tow that potentially overwhelm the tack force and ultimately cause defects during deposition. Simulated defects are measured and counted, thus providing statistical information that out-of-spec defects will occur under the provided processing input parameters. The resulting model is able to predict locations where AFP defects may occur [9][10].

2.4 Cure Defects Process Model

Similar to the AFP defects model, the cure defects process model was developed by Convergent Manufacturing Technologies in parallel to the other DFM software. This process model was focused on prediction of defects that form during the laminate cure, such as porosity and wrinkling. Unlike the AFP defects model, the cure model was FEA-based from the beginning [11]. The porosity prediction aspect of the model was thoroughly validated against experimental results [12] and eventually expanded to include the influence of entrapped air and off-gassed volatiles during cure [13]. While these porosity predictions can be made with a simple homogenized solid model of a laminate, the wrinkling predictions require a much more advanced FEM. This wrinkling model is still in work.

3. SUMMARY OF DESIGN AND ANALYSIS TOOLS DEVELOPED

This section focuses on the design and analysis tools developed within the Central Optimizer. In addition to having capabilities to analyze and optimize AFP data, the Central Optimizer is responsible for managing the outputs from all the contributing software (described previously), displaying data related to AFP manufacturing and stress analysis, and tracking the overall progress of the design.

3.1 Central Optimizer Workflow

The intent of establishing the software workflow for the Central Optimizer is to define the order of operations for each individual AFP design/analysis software tool used to achieve a satisfactory laminate design. This section defines the order of operations and the data exchanged between each AFP design/analysis software tool.

In each step of the process, the "data communication" portion of the Central Optimizer passes data between the various modules. The general workflow is:

1. The process starts with HyperSizer optimization of ply shapes and counts (of each orientation) to meet strength and buckling requirements (Item 1 in Figure 4)
2. The CAPP module assesses the ply shapes and surface geometry to determine good layup strategies and start points for the layup (Item 2 in Figure 4).
3. Enter iteration loop to generate tow paths and improve the design to meet specified requirements (listed above).
   - VCP generates tow paths that fill the plies from HyperSizer (Item 3 in Figure 4).
   - COMPRO process models analyze tow paths for defects (Item 4 in Figure 4).
   - HyperSizer assesses laminate strength due to fiber deviation and gaps (Item 6 in Figure 4).
   - The Central Optimizer tracks relevant AFP design metrics for each design iteration (Item 7 and 8 in Figure 4), and proposes changes in both HyperSizer and VCP to resolve design issues (Item 9 in Figure 4).
   - Note: for each design iteration, VCP, HyperSizer, and COMPRO must be kept in sync. For example, a change to tow paths in VCP would require a new analysis in COMPRO for defects and in HyperSizer for strength margins.
4. The iteration loop completes when a design is found that satisfies all of the constraints for the AFP laminate design, or when the design cannot be improved any further.
   - An objective function will be used to track the overall "goodness" of each design. This objective function will depend upon weighting factors defined by the user.
   - Additionally, a history of all the laminate designs will be stored in a tabular format and updated during the optimization to allow the user to track trends among common defects, failure modes, etc.

DOI: (Will be added by SAMPE)

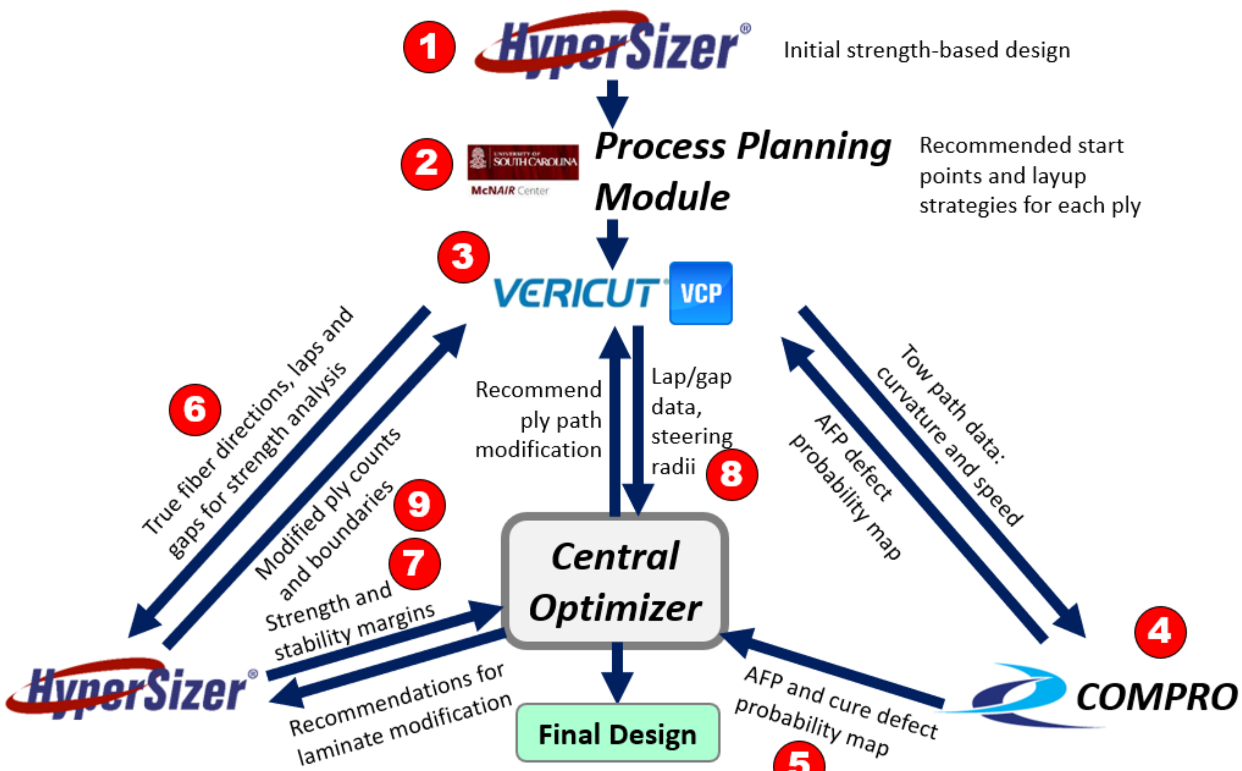

Figure 4. Central Optimizer workflow.

3.2 AFP Data Mapping

The Central Optimizer (and HyperSizer) are able to map a variety of AFP data from VCP. As summarized previously, this includes AFP fiber directions, fiber angle deviation, lap and gap geometry, and tow steering radius.

Fiber directions, deviations, and steering radius are simple to map to the stress analysis FEM because VCP provides the data per element, per ply. This provides a simple one-to-one mapping of the data. Figure 5 shows an example of fiber directions mapped to the FEM in HyperSizer.

DOI: (Will be added by SAMPE)

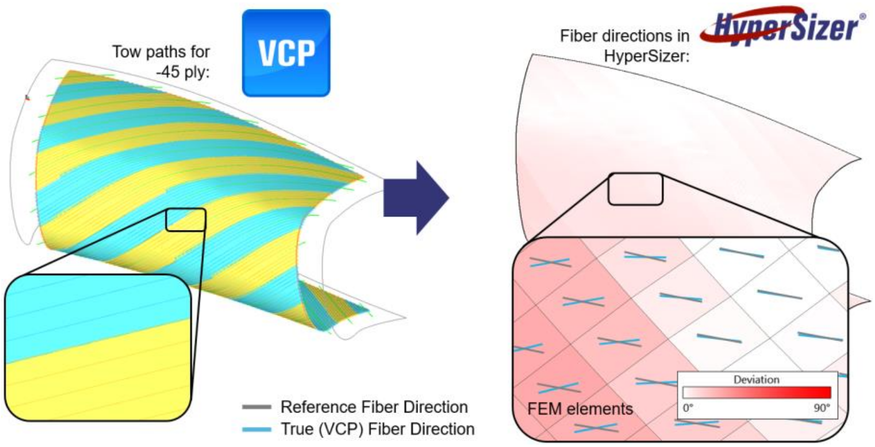

Figure 5. Example mapping of AFP fiber directions from VCP. [14]

Mapping of laps and gaps from VCP to HyperSizer is more complex. This mapping requires translating CAD-based entities from VCP to FEM-based entities in HyperSizer. This mapping is depicted in the figure below.

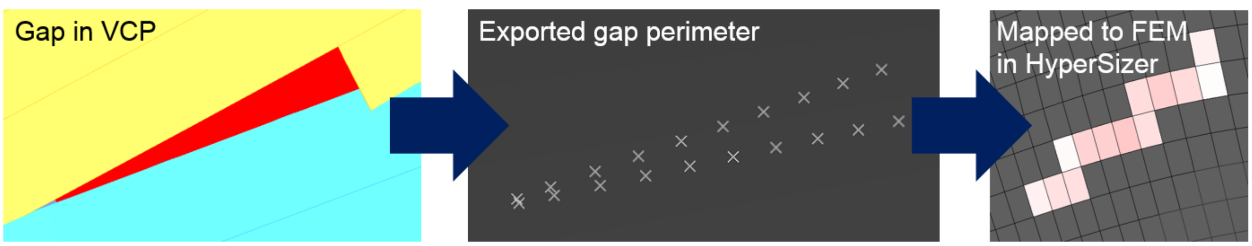

Figure 6. Lap and gap mapping process. [14]

3.3 Stress Analysis with AFP Data

This section describes the stress analysis performed by HyperSizer and the Central Optimizer with AFP data imported from VCP.

3.3.1 Analysis with AFP Fiber Directions

The stress analysis approach is a ply-based analysis using Classical Lamination Theory (CLT). For each element, the specified laminate design is used to build an ABD stiffness matrix for the laminate. This stiffness matrix includes the impact of fiber angle deviation. Using the membrane and bending loads from the element, local laminate deformation is then calculated and resolved into ply strains and stresses. Strain and stress output are used to write margins for each ply, considering a variety of failure criteria. These include max strain and max stress for the 1, 2, and 12 directions, as well as several interaction criteria including Tsai-Hill, Tsai-Hahn, Tsai-Wu, and Hoffman criteria.

3.3.2 Ply-Based Analysis with Laps and Gaps

Gaps are analyzed with a simple thickness scaling approach in the ply-based analysis. For elements that are covered by a gap for a particular ply, the thickness of that ply is scaled down by the amount of gap coverage. For example, an element that has 50% of its area covered by a gap in a given ply will have a 50% reduction of thickness in that ply in the CLT analysis. This is depicted in Figure 7.

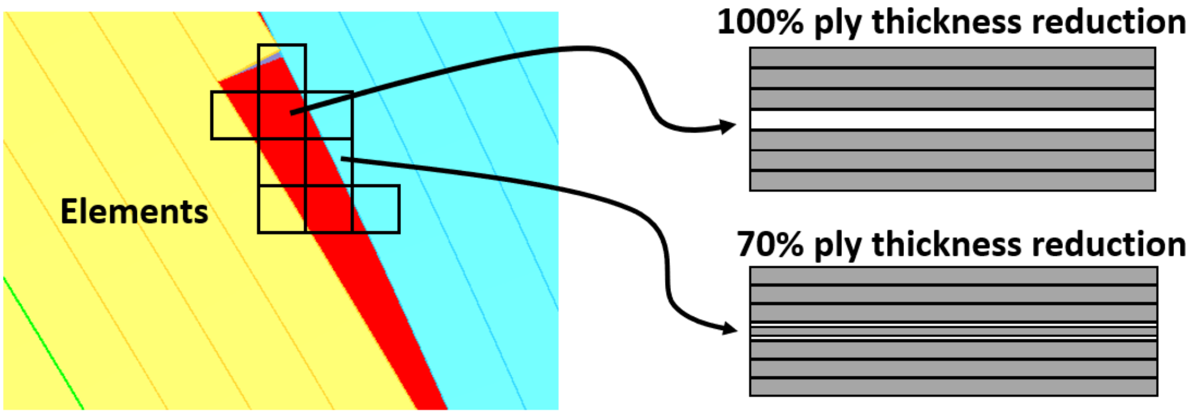

Figure 7. Thickness reduction scheme to account for gaps in CLT analysis.

Overlaps were not analyzed this way because the thickness scaling would actually increase the strength of the laminate in the location of the overlap. Because laps are often classified as a defect, this analysis was not implemented to avoid a knock-up to the laminate strength.

3.3.3 Laminate-Based Analysis with Laps and Gaps

A tool was added to the Central Optimizer to reduce the laminate strength margin based on the presence of gaps (laps could also be included, but were left out for the time being). The laps and gaps are still mapped to HyperSizer as described in previous sections. Once the features are mapped to the FEM, the Central Optimizer extracts geometry information about the gaps and modifies the strength margins accordingly. The Central Optimizer is currently configured to knock the margin down based on gap width, but could be modified to use other dimensions.

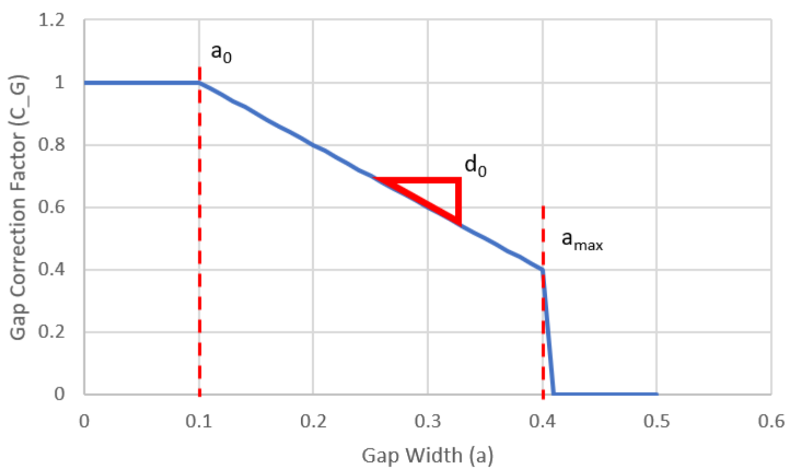

Figure 8. Correction factor (knockdown) curve based on gap width.

Figure 8 shows an example of the correction factor (C_G) curve used to generate the material strength knockdowns. The parameters a_0, d_0, and a_{max} are used to control the shape of the curve and can be modified by the user. Once calculated, the correction factor is applied to the element strength margin as shown in the equation below.

$$MS_G = (MS + 1) \cdot C_G - 1 \tag{1}$$

3.4 Optimization with AFP Data

This section describes two optimization routines developed in the Central Optimizer. The first is focused on laminate optimization *with* AFP data. HyperSizer traditionally performs laminate optimization with laminates containing 0/45/90 fiber orientations. A process was developed within the Central Optimizer to extend the laminate optimization to handle laminates with deviation from traditional fiber orientations.

The second optimization routine described in this section focused on simply minimizing deviation from a traditional laminate, instead of considering the laminate strength analysis. This optimization adjusts the ply orientations to minimize the overall deviation throughout the laminate.

3.4.1 Laminate Strength Optimization

The Central Optimizer and HyperSizer combined have the ability to resize the composite laminate to resolve negative margins that appear due to fiber angle deviation and the presence of laps/gaps. This is a multi-step process, as described in the user manual. The user first maps the VCP fiber directions and laps/gaps onto the HyperSizer model. A separate analysis is performed for the two data sets to establish the margins due to fiber deviation (MS_{Dev}) and those due to the presence of laps/gaps (MS_{Dev+LG}).

Once the user has generated the two sets of updated strength margins, the margins are used to calculate two sets of per-element knockdown factors. Equation (2) below is for the knockdown associated with the fiber deviation and Equation (3) is for the knockdown associated with the laps and gaps.

$$KD_{Dev} = \frac{MS_{Dev} + 1}{MS_{Ref} + 1} \tag{2}$$

$$KD_{LG} = \frac{MS_{Dev+LG} + 1}{MS_{Dev} + 1} \tag{3}$$

Two rules are also applied to the generation of these knockdowns. First, the knockdown is always required to be less than or equal to 1.0. This means that the resizing process will not be allowed to size the laminates *down* due to the presence of AFP data (however, the user can modify this value). Additionally, the knockdowns are only generated for elements with a *negative* margin (the user can modify this value as well). The figure below shows an example of the KD_{Dev} values on the CCT model.

DOI: (Will be added by SAMPE)

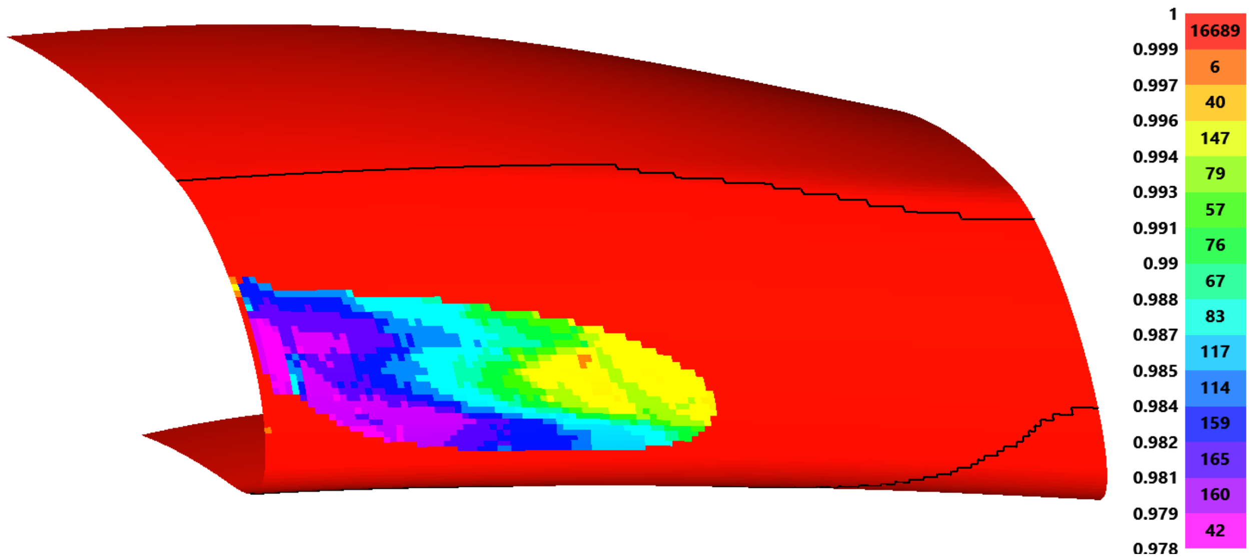

Figure 9. Knockdowns for Fiber Deviation

3.4.2 Fiber Angle Deviation Optimization (Through-Thickness Deviation)

Calculating through-thickness deviation requires determining a new reference direction for each element (instead of referencing the rosette). The new reference direction is determined by the average of the min and max deviation of any ply in that element, as shown in Equation 1. Deviations for each ply are then calculated relative to this new reference direction.

$$\theta_{new\ ref,i} = \frac{\theta_{dev,min,i} + \theta_{dev,max,i}}{2} \tag{4}$$

It is desirable to minimize the through-thickness deviation as much as possible, ideally enough to push the deviation below the threshold required by material allowable specifications. The challenge is that rotating a ply to improve through-thickness deviation in one area may make it worse in another area. Additionally, it is not immediately obvious which ply to rotate to improve through-thickness deviation overall. A "compass search" optimization routine (a gradient descent method) was implemented to solve the deviation minimization problem. The optimization is performed on the FEM, after the initial fiber directions have been mapped from VCP. By adjusting the orientation of each ply by a small amount (less than 10°), the overall through-thickness deviation can be minimized without significantly changing other characteristics of the layup, such as tow overlaps and gaps or steering radii. The optimization routine is described in Figure 10.

DOI: (Will be added by SAMPE)

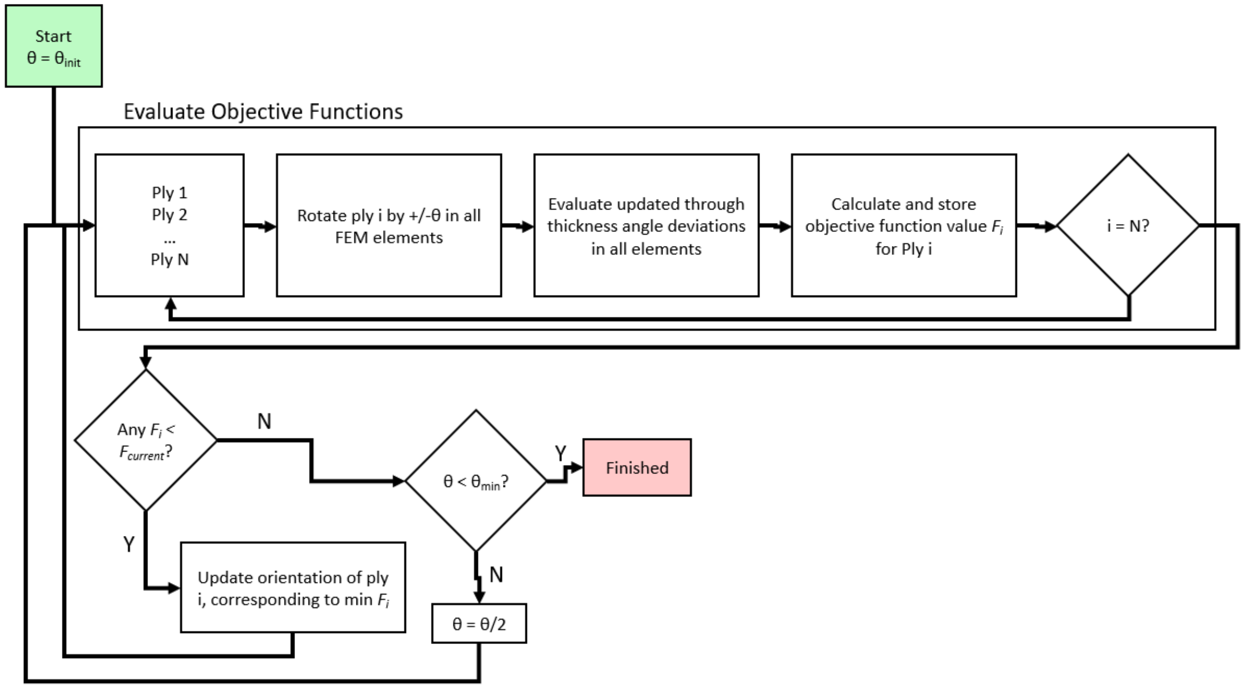

Figure 10.Optimization Routine for Through-Thickness Fiber Angle Deviations.

In each step of the optimization, a small rotation of each ply is attempted. The objective function value for each ply rotation is evaluated and the ply rotation that results in the lowest objective function then becomes the “current” orientation for that ply. The process repeats until no more improvement in the objective function can be found.

3.5 Mapping Simulated AFP and Cure Defects

An AFP defects process model was developed by Convergent Manufacturing Technologies US (CMTUS) and NASA to predict the occurrence of AFP defects during tow deposition. The initial model performs simulations on flat tooling. In this mode of operation, the model was used to generate a surrogate model (via polynomial regression) that estimates the probability of AFP defects as a function of steering radius and other process parameters. The simulation has also been enhanced to function on complex curvature. However, due to long run times, the complex curvature simulation was not used. Regardless, the flat surface simulation can still be used to develop a surrogate model for AFP defect probability. The surrogate model is limited to defects that are caused by excessive tow steering, such as puckers and wrinkles.

Surrogate models are often used to represent time-consuming higher fidelity analyses (also known as response surface models). Polynomial regression was used to generate the surrogate model for the flat surface AFP defect simulation. The form of the regression is shown in the equations below. Equation (5) is the regression polynomial whose form is chosen by the user. Equation (6) is a logistic function that has been adapted to produce defect probabilities varying from 0 to 100%.

$$f(R) = C_0 + C_1 \cdot R^{E_1} + C_2 \cdot R^{E_2} + \ C_i \cdot R^{E_i} \tag{5}$$

DOI: (Will be added by SAMPE)

$$P(R) = 100 - \frac{100}{1 + e^{-f(R)}} \tag{6}$$

The exponents E_i are defined by the selected form of the polynomial. The coefficients C_i are generated when regression is performed against a sensitivity analysis of AFP process parameters. After the sensitivity analysis of process parameters has been run through the AFP defects simulation described previously, the probability of AFP defects is extracted from the simulation results. These datapoints are used in least squares regression to produce the coefficients described above.

The surrogate model is utilized in the Central Optimizer process to evaluate steering radii predicted by VCP. VCP can export steering radii for each ply across the entirety of the tool surface. Each radius is evaluated with the surrogate model to produce a probability map of defect likelihood across the entire tool surface, for each ply. An example of this probability map is shown in Figure 11.

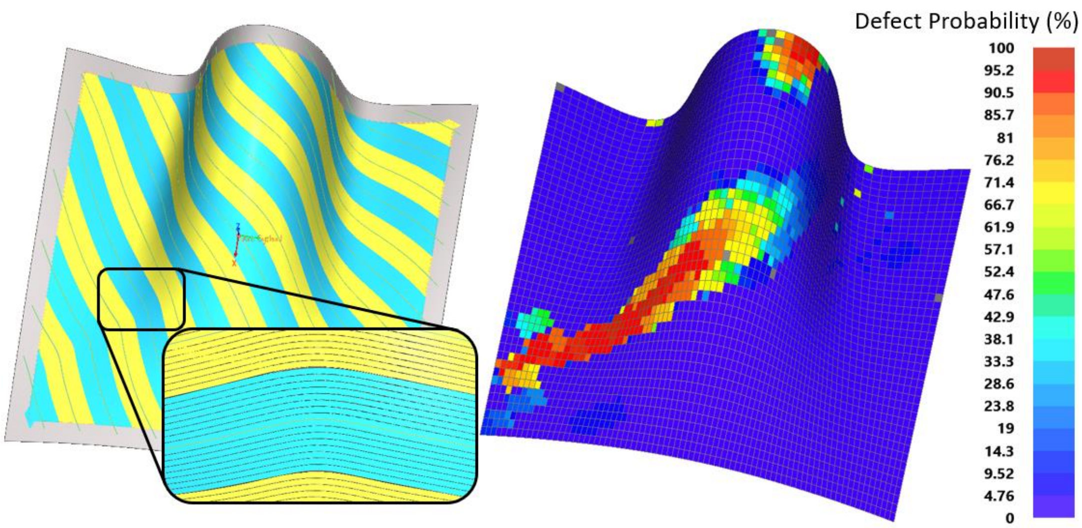

Figure 11. Map of AFP defect probability due to local tow steering radius.

Capability was also developed in the Central Optimizer to map porosity data from the COMPRO cure simulation. This was more straightforward than the AFP defects mapping because of the efficiency of the cure simulation and lower volume of data. The cure simulation outputs gas volume fraction (V_g), which is representative of porosity. This type of cure model typically has 10-15 solid elements through the thickness of the part. A filter can be applied to the V_g values to only extract those above a target threshold. Those values are then mapped from the solid elements to the shell element FEM in HyperSizer. This allows the stress analyst to determine if the porosity is in a highly loaded part of the structure, or if a material strength knockdown is needed to account for the presence of porosity. Figure 12 below shows an example of the cure model output and Figure 13 show the V_g data mapped to a FEM in HyperSizer.

DOI: (Will be added by SAMPE)

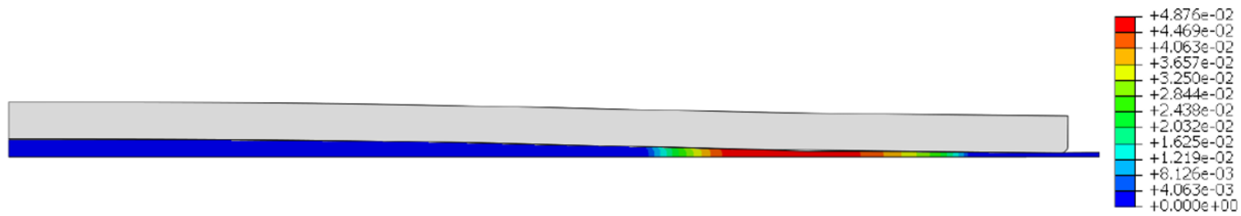

Figure 12. Example of gas volume fraction from cure simulation.[12]

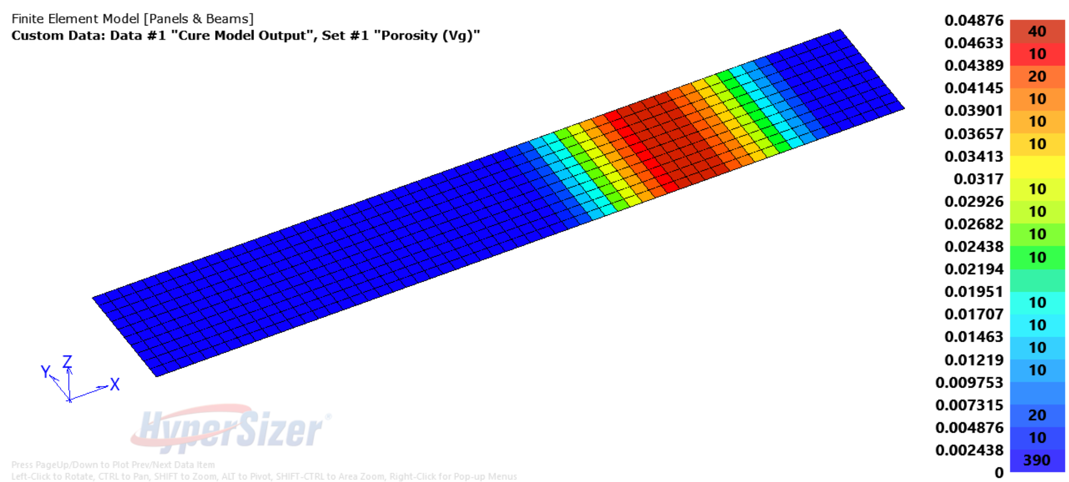

Figure 13. Gas volume fraction mapped to FEM in HyperSizer. [15]

4. VERIFICATION AND VALIDATION OF TOOLS

The verification and validation of the tools described above was performed on three separate models by three industry partners. A summary of the verification and validation with model is described below. Two designs were generated for each model, a baseline and optimized design. The baseline designs were generated using existing legacy design tools (with a specific process created by each industry partner). The optimized design was generated using the Central Optimizer and other tools described in Section 3.

4.1 Verification with Saddle Tool

A verification was performed previously with a saddle tool geometry similar to that shown in Figure 14. This verification is descried in Reference [15].

DOI: (Will be added by SAMPE)

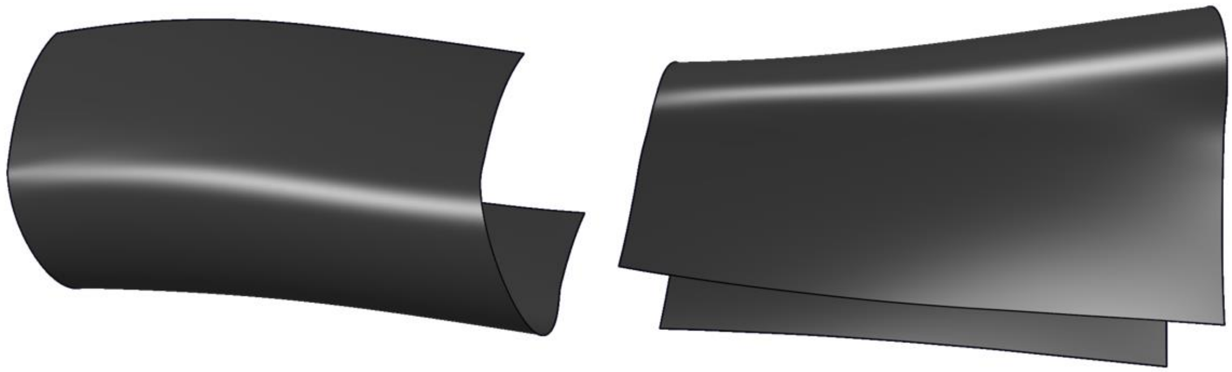

Figure 14. Example of saddle tool geometry.

4.2 Verification with Wing Skin and Spar

The second verification performed was with a partial wing skin and spar model. The verification model is a subset of a full wing box model from the NASA Common Research Model (CRM). The model is shown in Figure 15 [16].

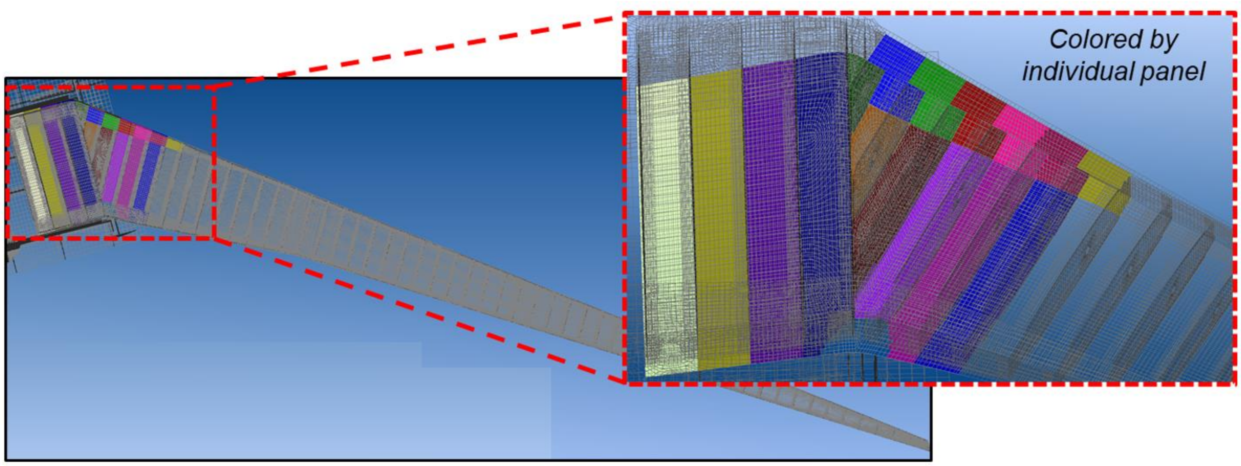

Figure 15.Wing model used in verification.

The objective of this verification was to compare the optimized solution generated by HyperSizer and the Central Optimizer to a baseline design developed by legacy design tools. In the verification, the model was run through the HyperSizer optimization process and the Central Optimizer AFP evaluation tools. The design produced by HyperSizer showed improvement in weight and labor savings.

Many of the capabilities demonstrated on the saddle tool were also demonstrated on this model, but are not included here for brevity. One capability not discussed previously is the transfer of optimized laminates from HyperSizer to CAD (in CATIA). This is a critical intermediate step for being able to run the tow path simulation in VCP. The HyperSizer plies are output in a FEM-based format, which is incompatible with VCP. However, a translation process was developed to convert the plies from a FEM-based format to a CAD-based format in CATIA, and can then be output to VCP for simulation. The HyperSizer-CATIA mapping is depicted in Figure 16.

DOI: (Will be added by SAMPE)

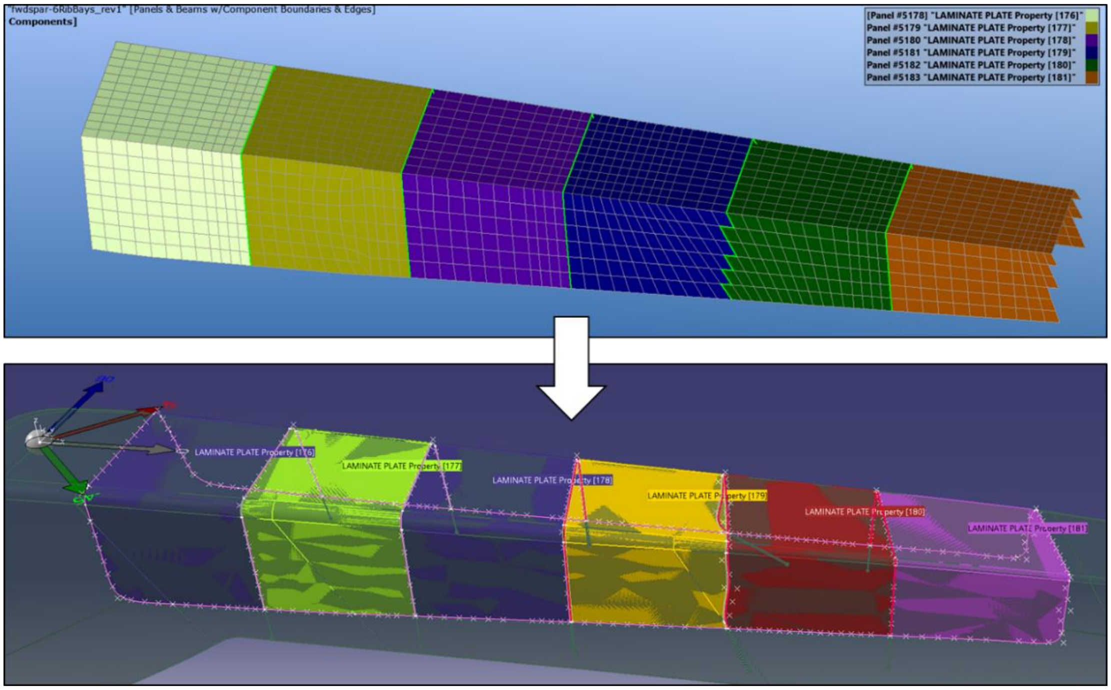

Figure 16. Transfer of HyperSizer plies to CATIA.

The CAPP module was also run on the spar module. As discussed previously, the CAPP module helps the user determine optimum starting/seed points and layup strategies for the tow paths in each ply. The start/seed point algorithm uses the Heat Kernel Signature (HKS) of a surface to determine appropriate points for further examination. An example of the HKS plot for the wing spar is shown in Figure 17.

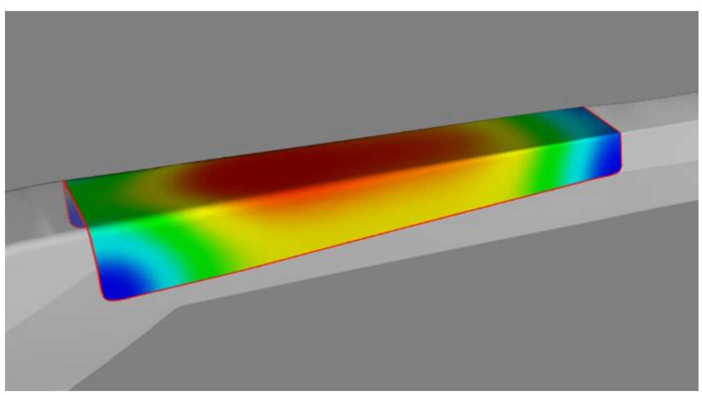

Figure 17. Plot of HKS values on wing spar.

4.3 Verification and Validation with Fuselage Nose

Verification and validation were performed with a section of a forward fuselage nose that is representative of a commercial airliner. This model is shown in Figure 18. The model is representative of a typical detailed FEM for this type of structure, including discretely meshed stiffeners and many elements per skin bay.

DOI: (Will be added by SAMPE)

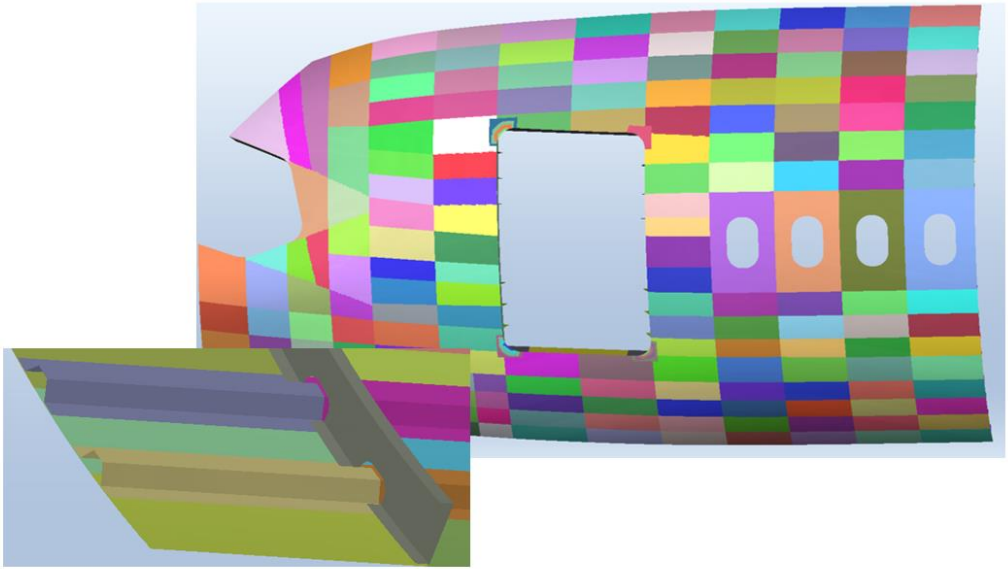

Figure 18. Fuselage model used for verification and validation.[15]

Due to the model size (number of elements and number of plies), not all of the Central Optimizer capabilities could be demonstrated on this model. However, the verification did include mapping and analysis of fiber directions, laps and gaps, and steering radii. Figure 1 shows the rosette fiber angle deviations for a 0° ply mapped to the FEM in HyperSizer from VCP. The greatest deviation occurs in the areas of greatest curvature, which is above and below the cockpit window cutout.

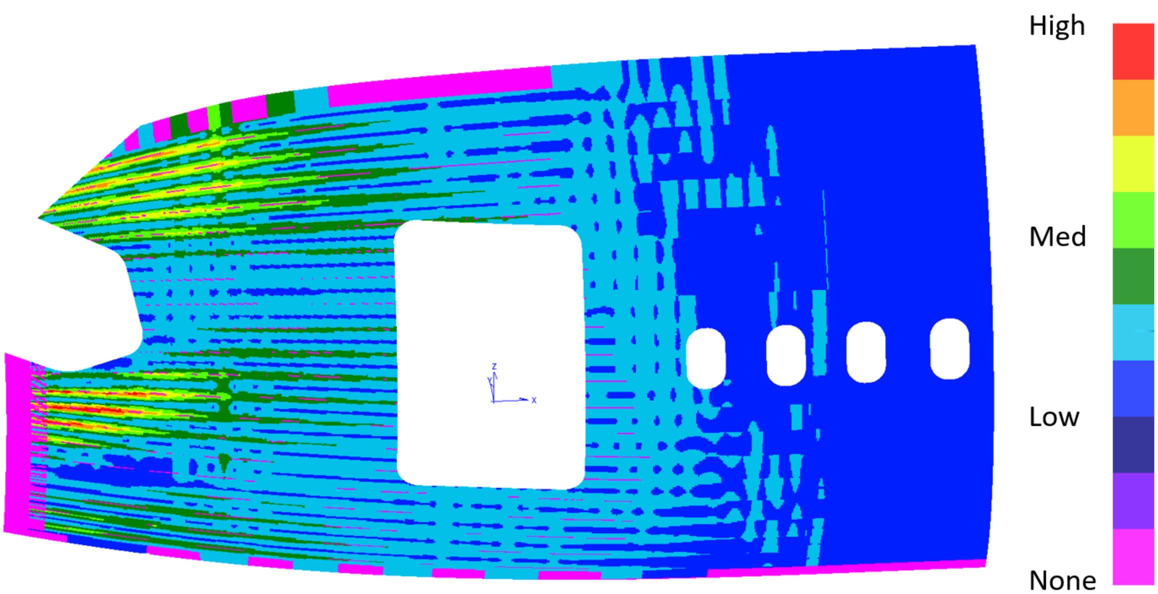

Figure 19. Rosette fiber angle deviations for 0° ply mapped to FEM.

The mapped gap data was used to generate strength knockdowns for the laminate. This was done by overlaying ply thickness reductions (as described in Section 3.3.2) for all plies to determine the total thickness reduction to the laminate. The result is shown in Figure 20. The areas with the most severe knockdowns are where gaps from multiple plies coincide. It is useful for a stress analyst to understand if this happens in a highly loaded area. HyperSizer can write an updated strength margin of safety that includes the gap knockdown to determine if the coincident gaps are problematic.

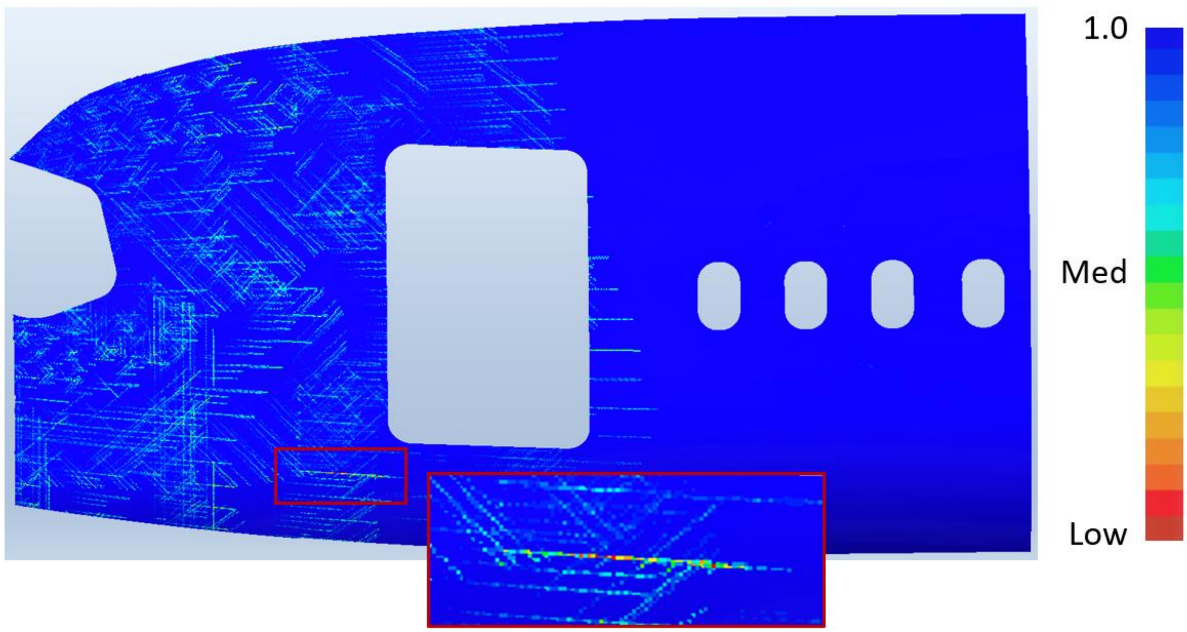

Figure 20. Laminate strength knockdowns from tow gaps.

The mapped steering radii were used to determine areas with a high probability of AFP defects. This calculation used the surrogate model methodology for AFP defects described in Section 13. Figure 21 shows that the areas with the lowest steering radii are directly above and below the cockpit window cutout. As observed previously, these areas have the most curvature on the tool. Rosette paths were used during programming of the tow paths for the tool; this type of path geometry uses steering to stay as close as possible to the rosette coordinate system defined for the ply. The result is that the lowest steering radii usually occur in the areas with highest curvature. These areas of low steering radii are also where AFP defects are most likely to occur as the tow is steered.

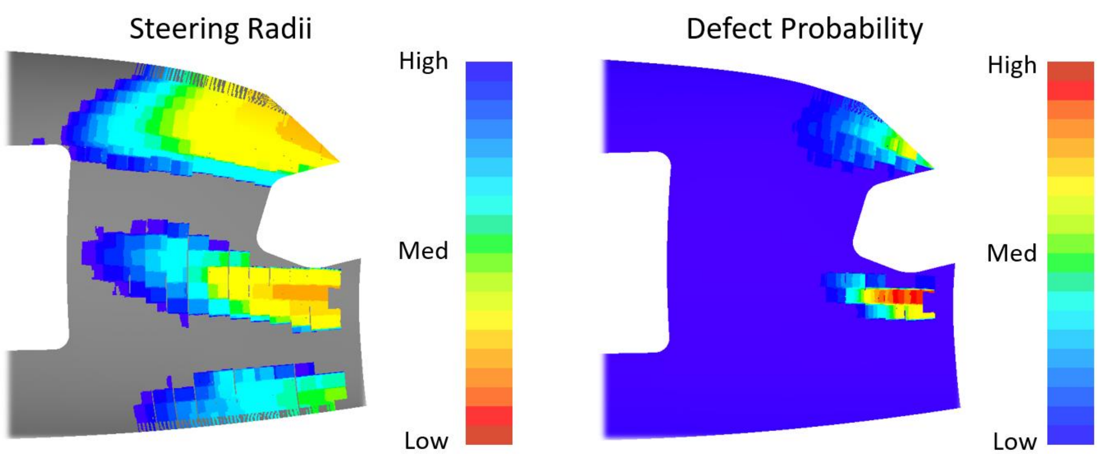

Figure 21. Steering radii and resulting predicted AFP defect probability for 90° ply.

Two validation builds were also performed with the fuselage model in additional to the verification described above. The baseline build was done with the baseline design generated with existing legacy design tools. Likewise, the optimized build was done with the optimized design generated from software tools discussed in this document. Both builds were performed on AFP equipment representative of a production environment. The objective was to compare the manufacturability of the two designs. Figure 22 shows the AFP defects recoded during the baseline (left) and optimized (right) builds. This comparison clearly shows that the number of AFP defects were reduced in the optimized build, from 97 to 34 defects, a 65% reduction. It is also notable that recorded defects from the optimized build are all clustered in the "hotspots" predicted in Figure 21.

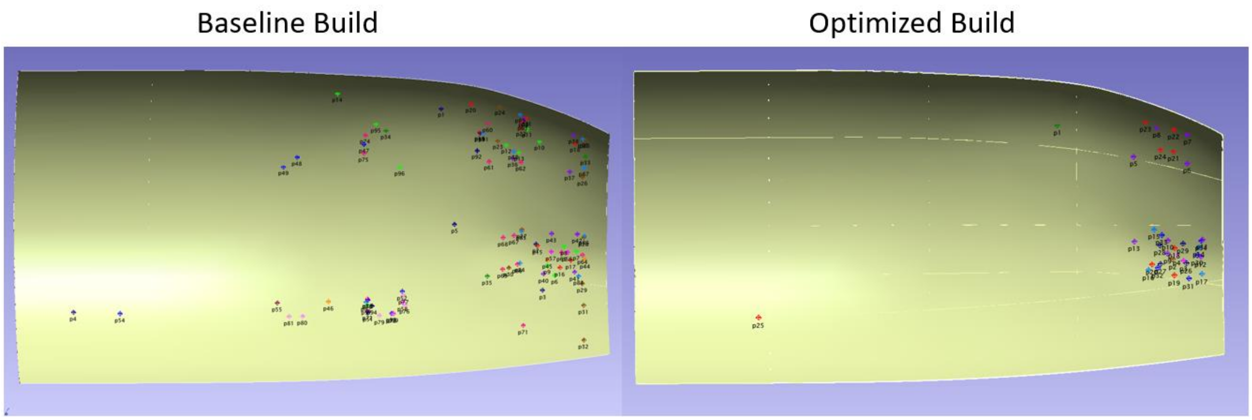

Figure 22. Comparison of recorded AFP defects from baseline and optimized builds.

5. CONCLUSIONS

The "Design for Manufacturing Software Development" task under the NASA ACP was focused on developing new software and modifying existing COTS software to achieve an improved design environment for AFP structures. These tools provide an approach to optimize a composite structure while considering features from AFP manufacturing such as fiber angle deviation, laps and gaps, and steering radii (and resulting AFP defects). This capability was successfully demonstrated on three different verification models representing a variety of typical aerospace structures. Additionally, two validation builds were performed with the fuselage model to demonstrate an improvement to manufacturability.

6. ACKNOWLEDGEMENTS

This work was heavily supported by fellow team members of the 2C22 Design for Manufacturing task in the NASA Advanced Composites Consortium. The team included Gary Wolfe of Aurora Flight Sciences; Jeron Moore, Sayata Ghose, Bill Avery, and Brice Johnson of the Boeing Company; Brian Grimsley of NASA Langley Research Center (task lead); Trevor Angell, Jared Ross, Ruth Ross, Ben Ferrell, and Steve Oyarzabal of Spirit AeroSystems; and Ramy Harik and Joshua Halbritter of the University of South Carolina.

Special thanks to Jeron, Gary, Ben, and Jared, whose work directly contributed to this paper.

DOI: (Will be added by SAMPE)

The material is based upon work supported by NASA under Award Nos. NNL09AA00A and 80LARC17C0004. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Aeronautics and Space Administration.

7. REFERENCES

[1]ASTM D5766 / D5766M-11(2018), Standard Test Method for Open-Hole Tensile Strength of Polymer Matrix Composite Laminates, ASTM International, West Conshohocken, PA, 2018

[2]Harik, R., Saidy, C., Williams, S., Gural, Z., Grimsley, B., Automated fiber placement defect identity cards: cause, anticipation, existence, significance, and progression, *SAMPE 2018 Technical Conference and Exhibition*, Long Beach, CA, 2018

[3]Halbritter, J., Harik, R., Saidy, C., Noevere, A., Grimsley, B., Automation of AFP Process Planning Functions: Importance and Ranking, *SAMPE 2019 Technical Conference and Exhibition*, Charlotte, NC, 2019

[4]Moore, J., Colvin, A., Ghose, S., Johnson, B., Design for Manufacturing: Laminate Focused Design and Analysis Tools for Automated Composites Manufacturing, *SAMPE 2019 Technical Conference and Exhibition*, Charlotte, NC, 2019

[5]Forghani, A., Hickmott, C., Bedayat, H., Wohl, C., Grimsley, B., Coxon, B., Poursartip, A., A Physics-Based Modelling Framework for Simulation of Prepreg Tack in AFP Process, *SAMPE 2017 Technical Conference and Exhibition*, Seattle, WA, 2017

[6]Forghani, A., Hickmott, C., Hutten, V., Bedayat, H., Wohl, C., Grimsley, B., Coxon, B., Poursartip, A., Experimental Calibration of a Numerical Model of Prepreg Tack for Predicting

[7]ANSYS Simulation Software, Software Package, ANSYS, Canonsburg, PA, 2020

[8]Abaqus, Software Package, Dassault Simulia, Vélizy-Villacoublay, France, 2018

[9]AFP Process Related Defects, *SAMPE 2018 Technical Conference and Exhibition*, Long Beach, CA, 2018

[10]Hutten, V., Forghani, A., Silva, P., Hickmott, C., Sreekantamurthy, T., Wohl, C., Grimsley, B., Coxon, B., Poursartip, A., A Validation Study of a Physics-based Tack Model for an Automated Fiber Placement Process Simulation, *SAMPE 2019 Technical Conference and Exhibition*, Charlotte, NC, 2019

[11]Bedayat, H., Roy, M., Forghani, A., Hickmott, C., Palmieri, F., Grimsley, B., Coxon, B., Fernlund, G., Poursartip, A., An Efficient Modelling Approach for Prediction of Porosity Severity in Composite Structures, *SAMPE 2017 Technical Conference and Exhibition,* Seattle, WA, 2017

[12]Bedayat, H., Forghani, A., Hickmott, C., Palmieri, F., Grimsley, B., Coxon, B., Fernlund, G., Poursartip, A., Numerical and Experimental Study of Local Resin Pressure for the

DOI: (Will be added by SAMPE)

Manufacturing of Composite Structures and their Effect on Porosity, *SAMPE 2018 Technical Conference and Exhibition*, Long Beach, CA, 2018

[13]Hickmott, C., Forghani, A., Hutten, V., Lorbiecki, E., Palmieri, F., Grimsley, B., Coxon, B., Fernlund, G., Poursartip, A., A Numerical and Experimental Approach for Modeling Porosity Due to Entrapped Air and Volatiles Off-gassing During Manufacturing of Composite Structures, *SAMPE 2019 Technical Conference and Exhibition*, Charlotte, NC, 2019

[14]Noevere, A., Collier, C., Mapping Manufacturing Data for Stress Analysis of Automated Fiber Placement Structures, *2018 AIAA/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference*, Kissimmee, FL, 2018, https://doi.org/10.2514/6.2018-0228

[15]Noevere, A., Collier, C., Design for Manufacturing Tool for Automated Fiber Placement Structures – Verification and Validation, *2020 AIAA/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference*, Orlando, FL

[16]Brooks, T. R., Kenway, G. K. W., Martins, J. R. R. A., Benchmark Aerostructural Models for the Study of Transonic Aircraft Wings, *AIAA Journal*, Vol. 56, No. 7, June 2018, pp. 2840-2855