Integrated Design and Manufacturing Analysis for Automated Fiber Placement Structures

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ABSTRACT

Automated fiber placement provides many advancements beyond traditional hand layups in terms of efficiency and reliability. However, there are also a variety of unique challenges that arise with automated fiber placement technology. In particular, steering of tows over doubly-curved tool surfaces can result in material overlaps and gaps due to path convergence/divergence, fiber angle deviation, as well defects in the tows themselves such as puckers and wrinkles. Minimization of these defects is traditionally considered a task for the manufacturing discipline. Manufacturing specifications are often created for these defects based on laminate testing and can be inflexible to avoid more tests. Recent efforts have been made under the National Aeronautics and Space Administration (NASA) Advanced Composites Project (ACP) to develop software tools and processes that provide automated coupling between design and manufacturing disciplines. The objective of this coupling is to provide information to the design discipline on the manufacturability of a laminate while the laminate is being designed. A variety of software tools, both existing commercial tools and research tools under development, will be used to achieve this objective: HyperSizer for laminate optimization, the Computer Aided Process Planning module for selection of manufacturing process parameters, Vericut Composite Programming for tow path simulation, and COMPRO for deposition and cure defects. The newly developed "Central Optimizer" tool will be used to tie the modules together and drive the design for manufacturing process.

1. INTRODUCTION

The objective of the current work is to create a design tool that incorporates Automated Fiber Placement (AFP) manufacturing constraints into traditional composite analysis and optimization process. This approach is known as Design for Manufacturing (DFM). The DFM process is depicted in the flow chart in Figure 1.

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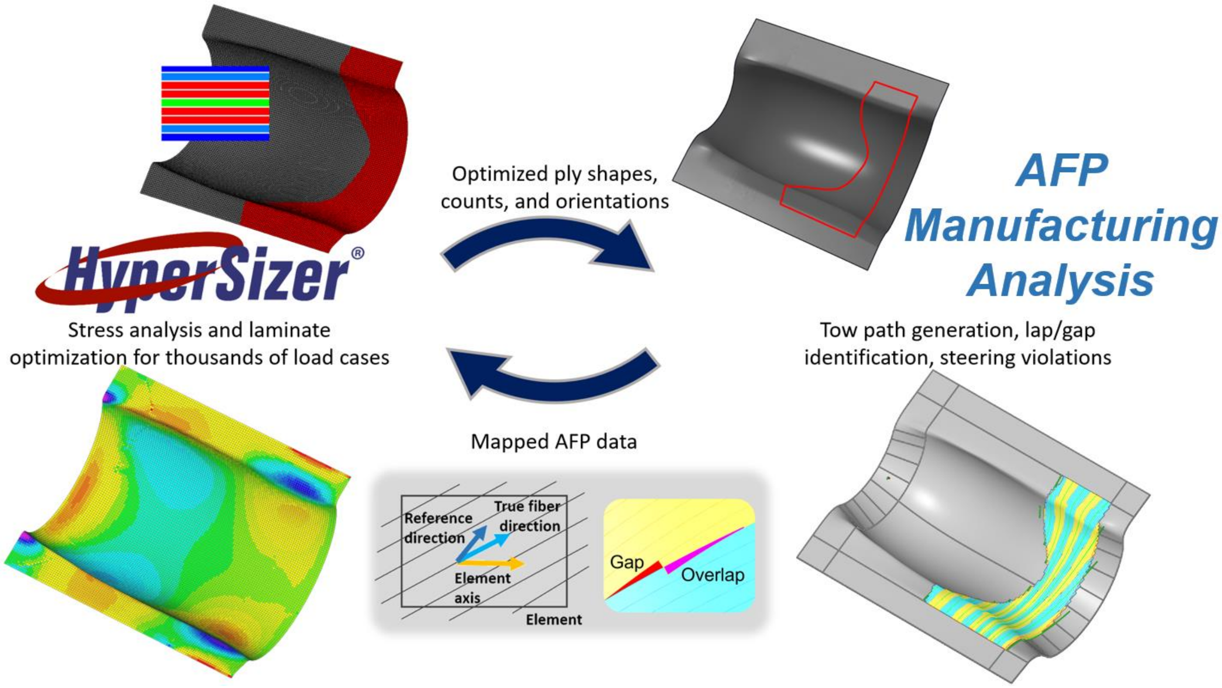

Figure 1. DFM approach for AFP. [1]

1.1 Background

Use of AFP manufacturing has become increasingly popular over the last decade. For large structures such as fuselages [2], wings [3], and space launch fairings [4], this manufacturing technique is often considered to be faster and more capable of producing consistent structural properties than traditional hand layup [5]. In AFP manufacturing, a composite tape deposition head, placed at the end of a robotic arm, is used to place tows on the tool surface. Use of a robotic arm allows material to be placed more consistently than a hand layup.

However, AFP manufacturing has its own set of unique challenges, both in manufacturing and design. AFP tows are usually steered (meaning that they do not follow the natural curvature of the surface) to some extent to achieve desired fiber orientations. This can cause defects such as puckers and wrinkles in the tows, as well as a variety of more complex defects.

1.2 Overview

In previous work by Collier Research [6], a process was developed to map fiber directions and tow overlaps and gaps from CGTech's Vericut Composite Programming (VCP) software [7] to the Finite Element Model (FEM) mesh in HyperSizer [8] for inclusion in stress analysis. This mapping process helped close the loop in automated data transfer between AFP design and stress analysis software.

The current work is focused on mapping additional manufacturing data back to the laminate design process, as well as create a design environment capable of iterating with manufacturing constraints. The challenge is that stress analysis and laminate design, process planning, and defect evaluation are all done in separate software tools. A new tool, dubbed the Central Optimizer, is being developed to tie these separate analyses together in a way that allows for rapid iteration between the disciplines. This tool is being developed as a part of the HyperSizer software framework, which is already a central part of producing laminate designs that meet strength and buckling requirements. The following sections describe the workflow of the tool, the individual analysis components, as well as some example results.

2. AFP COMPOSITE DESIGN WORKFLOW

The Central Optimizer workflow is iterative and does not necessarily follow the same steps in each iteration. This allows for more flexibility; the user can repeat steps at a higher fidelity or skip steps at their discretion. The general workflow for the Central Optimizer is described below, starting out with the overall inputs and outputs of the process.

2.1 Overview of Workflow

The Central Optimizer requires inputs for all of the analyses performed in both the stress analysis and manufacturing discipline. This includes models of the part geometry, as well as rules and constraints for the composite manufacturing. The inputs are listed below [9].

- Part geometry (CAD and FEM).
- Internal loads (from Finite Element Analysis, FEA).
- Failure criteria (strength, stiffness, buckling).
- Laminate rules (balance, symmetry, minimum gage, angle deviation requirements).
- Gap/lap requirements (density, size).
- Other engineering requirements (boundary coverage, tow end placement, etc.).
- Material properties (allowables, stiffness, etc.).
- AFP and other manufacturing process parameter requirements (AFP machine parameters, cure parameters).

Upon completion of the optimization process, the Central Optimizer and contributing software tools produce the following output [9].

- Optimum ply boundaries and ply counts.
- Optimum fiber paths.
- Gap/Lap reports with material area data.
- All which satisfy:
    - Structural failure criteria (strength, stiffness, buckling).
    - Elimination/minimization of AFP defects.
    - Elimination/minimization of cure defects.

2.2 Workflow Details

The planned software workflow for the Central Optimizer is depicted in Figure 2. This section describes the primary functions performed in each step of the workflow. Details of the individual tools are described in the next section.

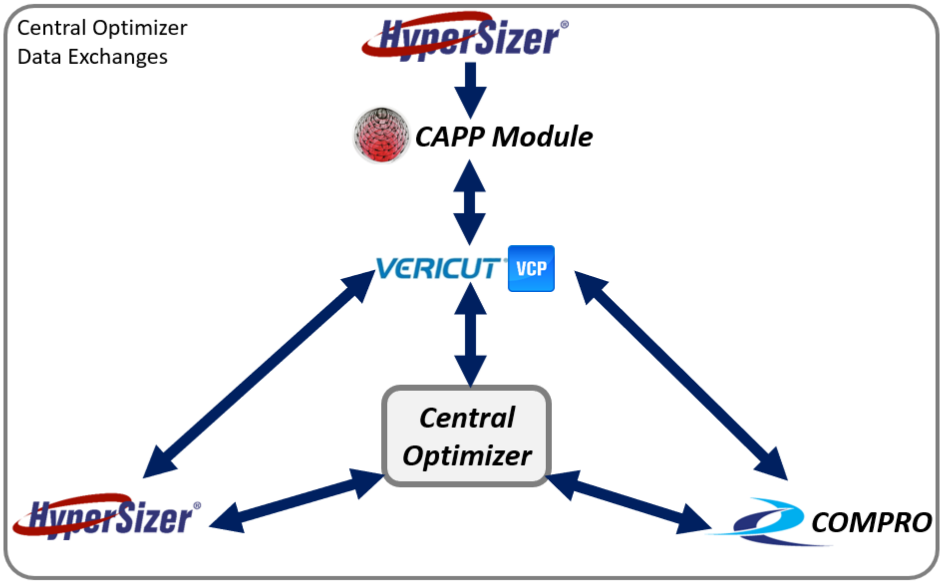

Figure 2. Central optimizer workflow. [9]

The process starts with optimization of ply shapes and ply counts in HyperSizer. The optimization uses loads from the FEM and evaluates strength and buckling requirements for the structure. Design requirements such as laminate balance and symmetry are also applied. At this point in the process, the strength analysis is based on assumed fiber directions, not the as-manufactured fiber directions.

The next step is to use the Computer Aided Process Planning (CAPP) Module to provide input on the start point and layup strategy for each ply. The start point provides the seed point for generating AFP paths over the tool geometry. Layup strategy describes how the paths propagate – steering versus natural path, etc. The CAPP iterates with VCP to check the quality of start points and layup strategies by monitoring laps and gaps, fiber angle deviation, and steering radii.

Once start point and layup strategy are selected by the CAPP for each ply, VCP is used to generate tow paths that initiate the first iteration of the Central Optimizer process. The resulting tow paths are used to extract data for subsequent analyses: fiber orientations, lap and gap geometry, tow steering radius, and fiber angle deviation. This data is used to update the laminate strength analysis and also to perform AFP manufacturing simulations.

The fiber orientations are imported to HyperSizer, where they are used to update the stiffness of the FEM as well as the strength analysis. Both laminate-based and ply-based strength analysis approaches are supported. Additionally, the geometry of tow overlaps and gaps is imported to HyperSizer for incorporation into the strength analysis. The lap and gap data are also used to evaluate deviation in the overall laminate thickness in locations where the laps and gaps from multiple plies are coincident.

The tow paths are also used to predict the likelihood of AFP defects at a given level of steering (and eventually tool surface curvature). The AFP tow deposition simulation under development by Convergent Manufacturing US (CMTUS) and NASA as a new subroutine for COMPRO is capable of predicting tow puckers and wrinkles during tow steering [12]. This capability will be used to determine the processing conditions which minimize the occurrence of these defects. Formation of AFP defects due to steering is an important consideration when generating tow paths because it often conflicts with the requirement to minimize fiber angle deviation. Steering tows over a doubly-curved surface to minimize angle deviation (from 0/45/90) can cause a significant build-up of stress in the tows, enough to overwhelm the tack force between tow and substrate, resulting in AFP defects.

The final assessment in the design process is to evaluate likelihood of defects that occur during cure. The COMPRO cure defects simulation is used for this purpose [13]. This physics-based process model is capable of predicting porosity that occurs during the cure cycle due to local changes in resin pressure. These porosity predictions inform the rest of the Central Optimizer process of changes that could be necessary to the laminate design or even the part geometry.

The steps described above are repeated until the laminate design reaches a point where all design and manufacturing constraints are met. In each iteration, the design is updated according to the current state of the design. The Central Optimizer helps the user evaluate all aspects of the design simultaneously, synthesize the data from all contributing analyses, and make an informed decision about how to modify the design in the next iteration to improve manufacturing and structural performance.

3. AFP DESIGN, MANUFACTURING, AND ANALYSIS TOOLS

3.1 HyperSizer Laminate Optimization

HyperSizer is used to determine the necessary thicknesses of laminates and ply orientations needed to meet failure criteria for strength and buckling. The primary input to HyperSizer is a FEM and FEA results, which provides the geometry of the structure and internal loads. An example is shown in Figure 3. Material properties are also required (stiffness and allowables).

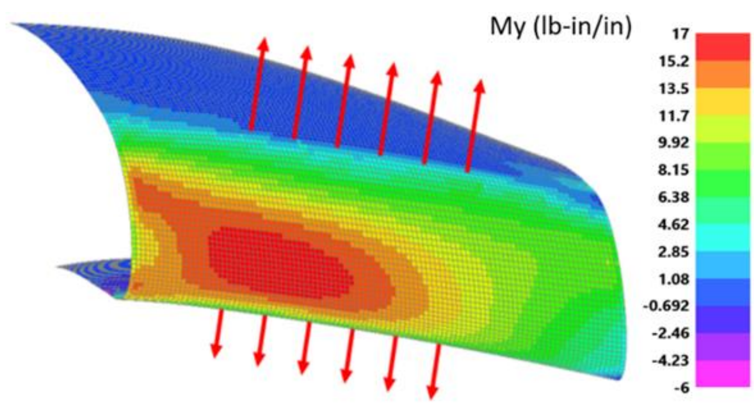

Figure 3. FEM with loads.

Additionally, HyperSizer is capable of optimizing zone shapes based on the internal loads of the structure. This is done with a per-element ply count optimization to meet strength criteria, as well as global buckling and frequency requirements (FEA-based). The results of the per-element optimization are used to group elements together based on similarity of ply counts and element proximity. Figure 4 shows an example of zone shape solutions.

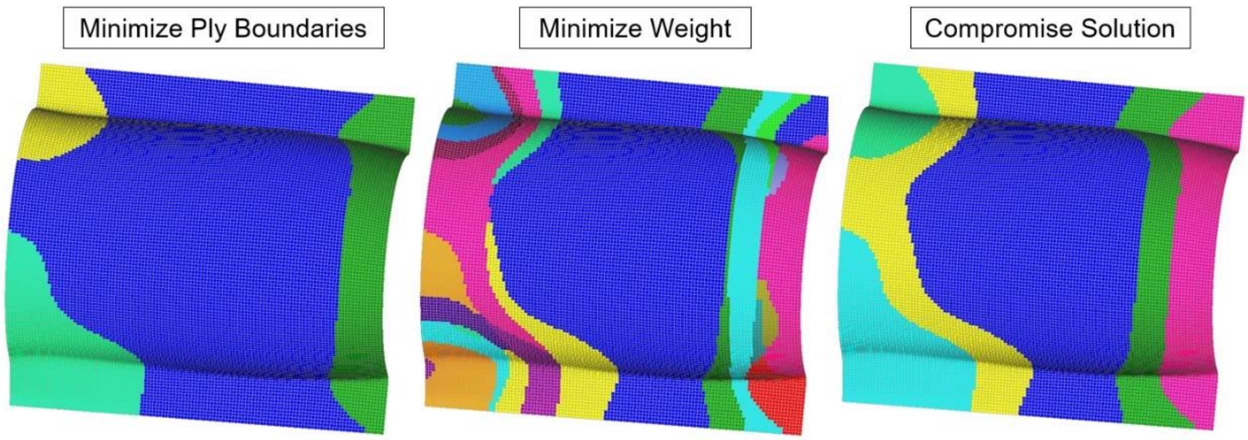

Figure 4. HyperSizer zone shapes for a turbofan Inner Fixed Structure (IFS). [1]

3.2 CAPP Module

The CAPP module enables rapid process planning for the investigated design. Process Planning is the act of matchmaking between Design considerations and Manufacturing constraints. It enables rapid manufacturing and certification of composite structures. A very complicated tasks that is often bound with trial and error, process planning has over 16 steps that are needed to ensure optimal consideration of the manufacturing requirements. Process Planning can be subdivided into three categories: Process Optimization, Toolpath Optimization and Miscellaneous. The proposed CAPP tool tackles the process optimization aspect of process planning which includes selection of layup strategy, identification of ideal starting point, and management of both ply-based functions and laminate-based ones. Figure 5 shows the current interface of the CAPP software.

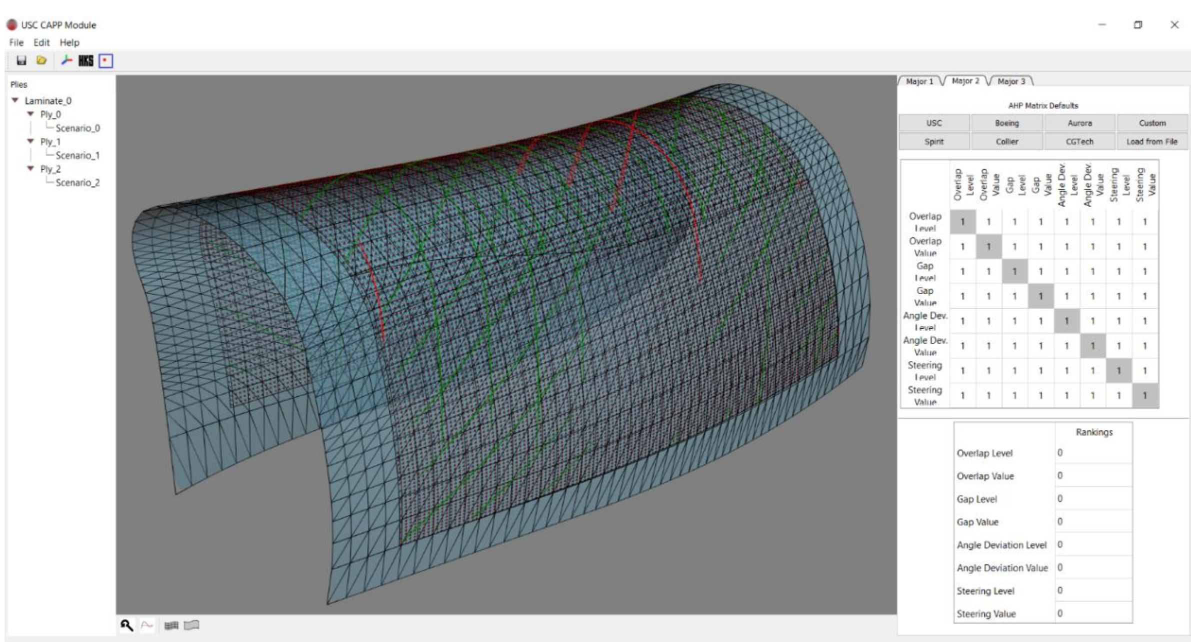

Figure 5. CAPP Module interface.

The proposed CAPP tool is semi-automated and includes knowledge justification for selections. It is composed of three major steps: (1) Computation of assessment parameters, (2) Ranking of assessment parameters that is subjective to everyone using the software, and (3) Ranking of the solution space based on the combination of (1) and (2). As such, the system considers the subject matter expert, and provides a solution oriented on his priorities. Figure 6 offers a closeup image to the defects visualization toolbar.

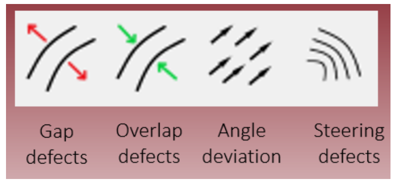

Figure 6. Sample of Toolbar for Defect Visualization

3.3 VCP Tow Path Generation

VCP is a Path Simulation Software (PSS) tool that generates tow paths to fill in specified ply boundaries. Figure 7 shows an example of VCP tow paths.

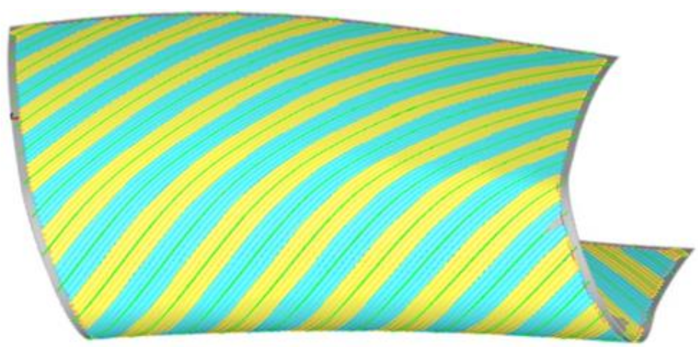

Figure 7. VCP tow paths for a 45° ply.

There are a variety of user inputs related to the AFP machine, tool geometry, path geometry, and material selection [9]. Those with relevance to the Central Optimizer process are:

- Ply boundaries and orientation from HyperSizer
- Tow width and number of tows in the course.
- Start point for each ply, as defined by the CAPP module.
- Layup strategy for each ply, as defined by the CAPP module.

VCP's primary function is to generate course paths that are ultimately used to program an AFP machine. However, data relevant to the Central Optimizer is extracted from the tow paths before they are post-processed for manufacturing. The extracted data includes:

- Fiber directions at every location on the tool surface for every ply (extracted with a grid of XYZ points).
- Fiber deviation from the rosette, at every location on the tool surface for every ply (extracted with a grid of XYZ points).
- Local steering radii at every location on the tool surface for every ply (extracted with a grid of points).
- Lap and gap geometry (profiles of the features).
- Lap and gap statistics (area, length, width).

3.4 COMPRO Process Models – AFP and Cure Defect Simulation [9]

The results generated by two physics-based models will be used by the Central Optimizer process to predict the likelihood of defect occurrence. Both use the Abaqus [10] FEA solver with the COMPRO plug-in [11].

3.4.1 AFP Defects Simulation

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 [12]. Once the simulation is run, defects must be identified in the deformed tow. This can be done manually, as would be done with a real tow placement trial. An Abaqus script is being developed to perform the post-processing in an automated and consistent way. Simulated defects are measured and counted, thus providing statistical information that out-of-spec defects will occur under the provided processing input parameters.

The initial model presented in Reference [12] performs simulations on flat tooling. In this mode of operation, the model will be 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.

3.4.2 Cure Defects Simulation

This process model can predict the level of porosity in a laminate that develops during cure [13]. This is done by simulating resin and gas flow that occurs due to local changes in resin pressure, as well as off-gassing of the resin during cure. Local variation of resin pressure is often caused by geometric features such as tight radii or placement of a caul sheet, as well the interaction of cure shrinkage with these features. Porosity is predicted from the gas volume fraction in each FEM element at the completion of the cure cycle simulation.

The cure defect simulation is run on a solid element mesh; this requires that laminate designs from HyperSizer be converted from a shell element mesh to solid elements. Once the simulation is complete, predicted porosity must be mapped from solid elements back to the shell elements in HyperSizer.

3.5 Central Optimizer Tools

The subsections below describe additional analysis tools that have been developed as a part of the Central Optimizer to perform supporting analyses and optimization to supplement the tools described above.

3.5.1 Minimization of Through-Thickness Fiber Angle Deviation

Through-thickness angle deviation is tracked separately from rosette deviation because it describes the fiber angle deviation *locally* in the laminate. Even if a ply has significant deviation from the global rosette, it is possible that the local laminate could still be close to a traditional 0/45/90 laminate (if all the plies had the same amount of rosette deviation at that location, for example). 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.

$$\theta_{new\,ref,i} = \frac{\theta_{dev,min,i} + \theta_{dev,max,i}}{2} \tag{1}$$

It is desirable to minimize the through-thickness deviation as much as possible, ideally to get 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^o), 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.

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. Three different forms of the objective function were implemented. The first is a weighted combination of maximum deviation (D_{max}) in the laminate and average deviation (D_{avg}). This is shown in Equation (2)

$$obj = D_{max} + D_{avg} \cdot W \tag{2}$$

The second objective function implemented calculates the 95th percentile deviation of all elements in the laminate (assuming a normal distribution of deviations), using the average (μ_{dev}) and standard deviation (σ_{dev}) of the fiber angle deviation. This is shown in Equation (3).

$$obj = \mu_{dev} + 1.645 \cdot \sigma_{dev} \tag{3}$$

The third objective function calculates the percentage of the laminate area that has through-thickness deviations that exceed a specified limit. This is shown in Equation (4).

$$obj = 100 \cdot \frac{count(D_{elem} > D_{limit})}{n_{elem}} \tag{4}$$

Each of these three objective functions can produce different results, and could be used for different purposes when reducing through-thickness deviation. An example application of this optimization is described in Section 4.

3.5.2 Impact on Laminate Strength from Tow Overlaps and Gaps

Laps and gaps are mapped to the FEM using the process described in Reference [6]. Lap and gap outlines from VCP are tessellated and mapped to the FEM based on proximity to the elements, and this is repeated for each ply. The thickness of plies on elements is scaled according to lap and gap coverage. An element that has 100% of its area covered by a gap would have the ply thickness reduced to zero. An element that is 100% covered by a lap would have its ply thickness doubled. Coverage of 50% would result in 50% ply thickness for a gap, and 150% ply thickness for a lap. The mapping process is shown in Figure 8.

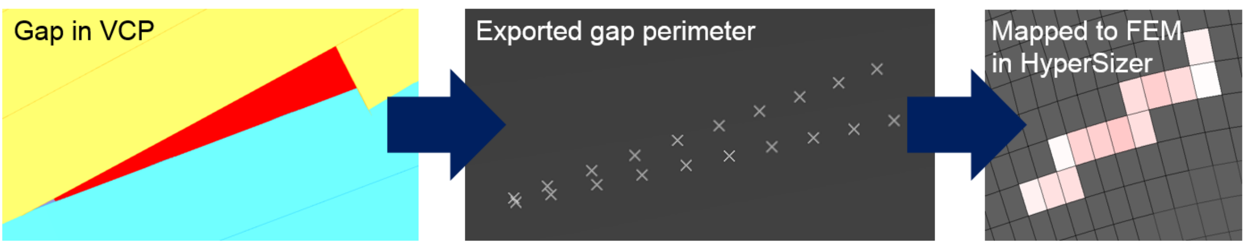

Figure 8. Lap and gap mapping approach [6].

3.5.3 FEM Update with AFP Data

Performing a FEM update with the AFP data is crucial because it can impact the stiffness of the FEM and thus change the load path through the structure. Modification of fiber orientation, as well as the presence of laps and gaps both have an influence on FEM stiffness. To capture the influence of these features per element, it is necessary to create individual FEM properties per element. Using Nastran PCOMPs, for example, it is possible to specify a unique fiber orientation per ply, per element. Additionally, the thickness of each ply in each element can be scaled according to the presence of laps and gaps. Figure 9 shows the effects of laps and gaps on the bending moment in a laminate.

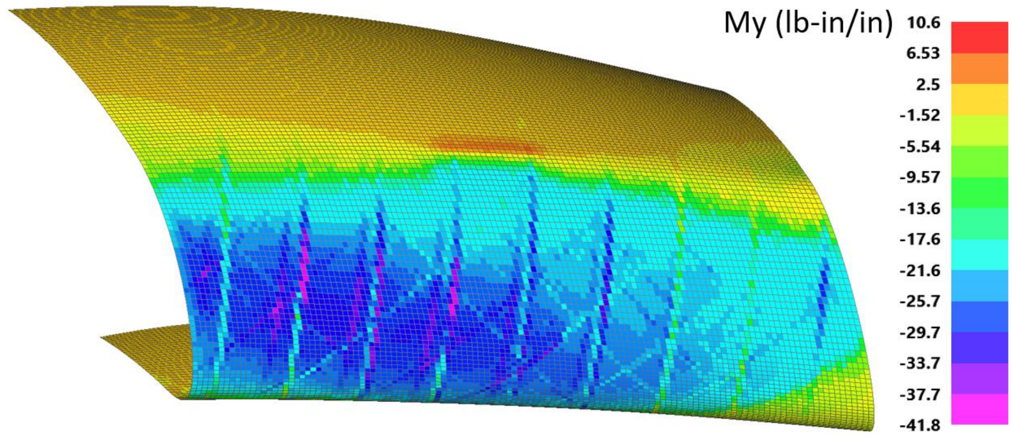

Figure 9. FEA loads with updated fiber directions and laps/gaps.

3.5.4 Laminate Thickness Deviation from Laps and Gaps

Laps and gaps cause doubled thickness and missing thickness, respectively, within each ply. If too many of these features are coincident in multiple plies, the overall laminate thickness can deviate significantly throughout the part. This effect can be approximated by using the scaled per-element ply thicknesses that were mapped for the strength analysis, as described in the previous section. The thickness of each element (t_{elem}) is calculated with Equation 2.

$$t_{elem} = \sum_{i=1}^{n_{ply,elem}} t_{ply\ i,elem} \tag{5}$$

The calculation is performed by looping through each ply on each element, looking up the scaled ply thickness ($t_{ply\ i,elem}$) according to the lap and gap mapping, and repeating until the number of plies on that element ($n_{ply,elem}$) has been reached (this number can vary per element).

Figure 10 shows an example of the accumulated thickness of laps and gaps. The blue and green areas have a nominal ply count of seven and nine plies, respectively. The plot shows that the calculated laminate thickness varies by as much as two plies in some locations.

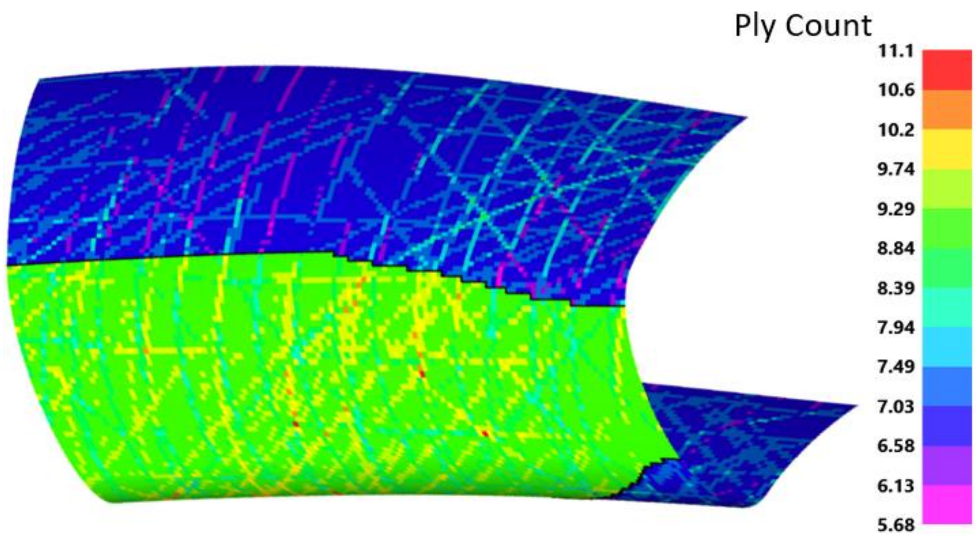

Figure 10. Accumulated thickness from laps and gaps.

4. RESULTS FOR OPTIMIZATION OF THROUGH-THICKNESS DEVIATION

This example solution for minimization of through-thickness deviation uses the methodology presented in Section 3.5.1. The model first shown in Figure 3 was used for the example. Tow paths were generated with VCP as shown in Figure 7.

Each of the three objective functions described in Section 3.5.1 were used to optimize ply orientations to minimize through-thickness deviation. The iteration history of each run is shown in Figure 11 through Figure 13. These three plots show that the optimization behaves differently for each approach. The metrics of the final solution of each approach are presented in Table 1. None of the approaches are necessarily superior to the others; selection depends on the user's objectives.

- Approach one (weighted combination of average and max deviation) can be useful for reducing the peak deviations in the laminate.
- Approach two (95th percentile deviation) helps bring down the overall deviation in the laminate while ignoring the peaks.
- Approach three minimizes the number of elements that violate an input deviation limit (2° was used for the example)

Table 1. Summary of optimization metrics for varying objective functions.

	Deviation at Percentile (deg)	**Average Deviation (deg)**	**Max Deviation (deg)**	**% Violations**
Approach 1	2.79	1.39	3.78	21.36
Approach 2	2.50	1.37	4.34	18.30
Approach 3	2.71	1.35	4.09	16.82

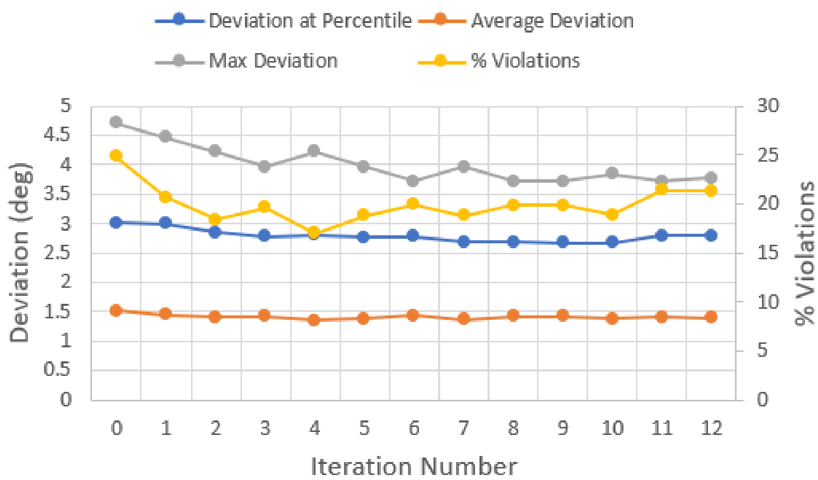

Figure 11. Iteration history for average+max deviation objective function (approach one).

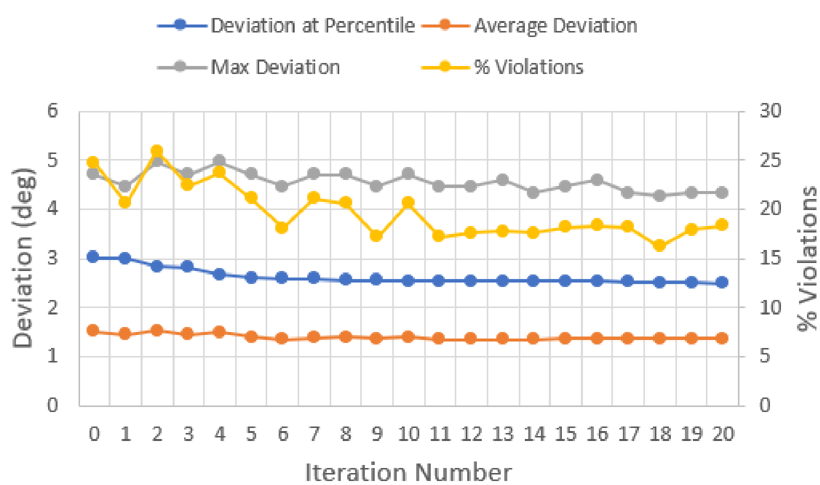

Figure 12. Iteration history for 95th percentile objective function (approach two).

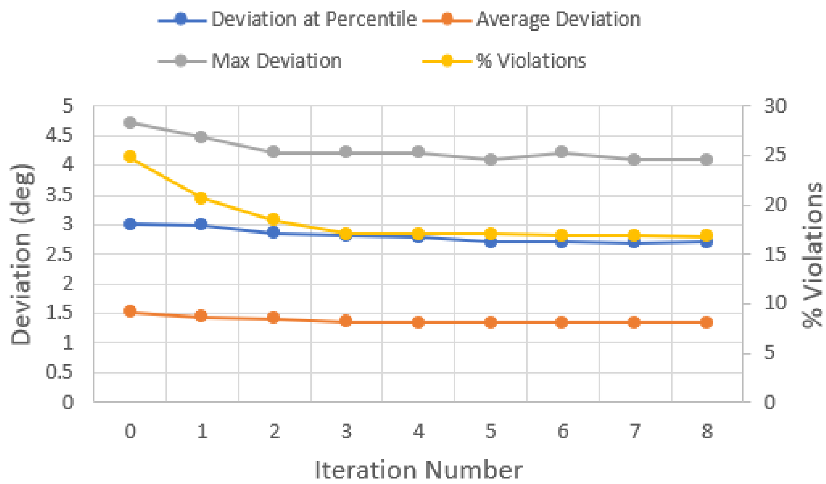

Figure 13. Iteration history for % violation objective function (approach three).

The histograms below show the distribution of through-thickness deviation in all the elements in the structure. After optimization, the distribution of deviations exhibits an obvious skew towards zero deviation. Additionally, the number of elements at the upper end of the distribution is significantly reduced.

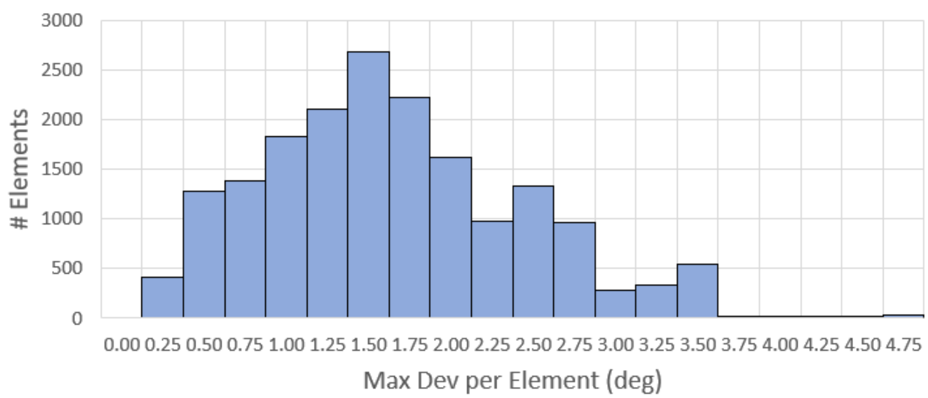

Figure 14. Histogram of deviation before optimization.

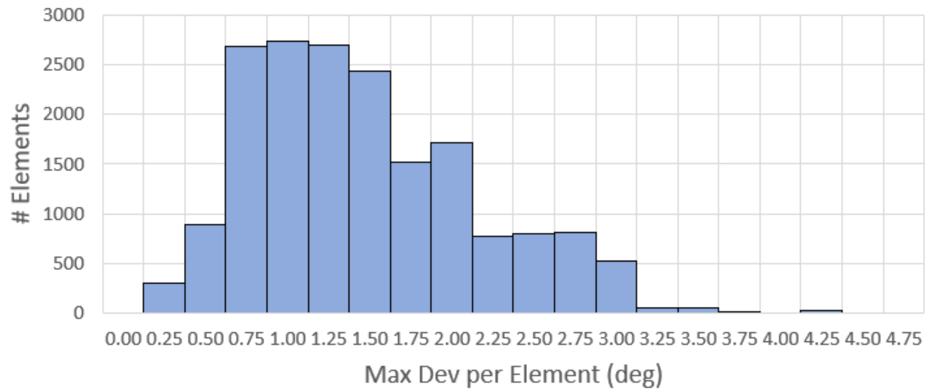

Figure 15. Histogram of deviation after optimization with approach three.

A visualization of the elements that meet or fail the 2° limit is shown in Figure 16. The area of the laminate covered by through-thickness deviations was reduced from 24.8% to 16.8%.

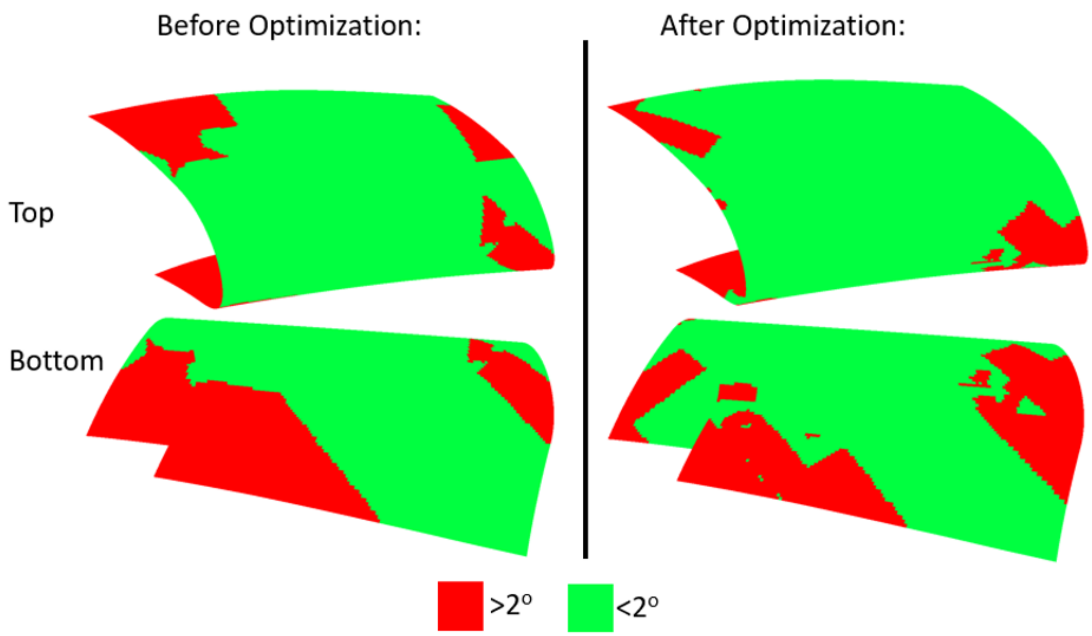

Figure 16. Elements that meet or fail specified through-thickness deviation limit.

5. CONCLUSIONS

A software tool and workflow has been proposed to provide a DFM solution for AFP structures. The workflow consists of a variety of analysis and design tools, including FEA, CAD, stress analysis, AFP path planning, AFP process planning, and manufacturing simulation. The Central Optimizer tool under development will connect the various disciplines by providing streamlined data exchanges between these tools. This will allow the user to quickly synthesize the various tool outputs and make informed decisions on updating the AFP laminate design to improve performance and meet design specifications.

Additional AFP analysis tools are being developed as a part of the Central Optimizer to supplement the existing tools. One of these new tools is the through-thickness angle deviation minimization routine. This routine has been demonstrated to successfully reduce the percentage of laminate area that violates angle deviation constraints.

6. ACKNOWLEDGEMENTS

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