Development of a Design for Manufacturing Tool for Automated Fiber Placement Structures

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Existing design processes for laminates constructed with automated fiber placement lack significant integration between the various software tools that compose the process. Tools for finite element analysis, computer aided drafting, stress analysis, tool path simulation, and manufacturing defect prediction are all critical parts of the design process. With traditional hand-layup laminates, the analysis performed with each of these tools could be fairly well decoupled from one another. However, for laminates generated by automated fiber placement, the disciplines can become significantly coupled, especially on structures with curvature. This gives rise to a need for integrated "design for manufacturing" software tools that are able to balance the competing objectives from each discipline. This paper describes the preliminary development of such a tool.

Nomenclature

C_i	=	Regression coefficient for ith regression term
E_i	=	Exponent for ith regression term
f	=	Regression function
P	=	Probability
R	=	Steering radius

Acronyms

AFP	Automated Fiber Placement
AHP	Analytical Hierarchy Process
CAPP	Computer Aided Process Planning
DFM	Design for Manufacturing
DoE	Design of Experiments
FEA	Finite Element Analysis
FEM	Finite Element Model
NTL	Non-traditional laminate
PSS	Path Simulation Software
VCP	Vericut Composite Programming

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I. Introduction

As design and analysis tools have become more accurate and powerful, the concept of Designing for Manufacturability (DFM) has become more and more achievable. In this paradigm, manufacturing constraints and considerations are evaluated during the design process, at the same time as the laminate is optimized for strength and buckling. This approach has the potential to significantly reduce design cycle time for composite structures, which have several unique manufacturing challenges. The enabling feature needed for a DFM environment is an approach to accurately simulate or predict aspects of the manufacturing process. This allows for automated and streamlined incorporation of manufacturing aspects in the design process.

For Automated Fiber Placement (AFP) structures in particular, there is a wealth of digital manufacturing data available due to the fact that the composite layup is done by a robot, not a human. Leveraging this data in the laminate design process is critical to the success of an AFP laminate design. Stress analysis and design of plies cannot be done in a vacuum and then passed off to manufacturing teams. Instead, it is important to simultaneously consider data from all disciplines, as a design change that may be favorable to one discipline can be detrimental to another. For example, a ply orientation selected from a strength analysis may not be suitable for AFP path deviation or AFP defects. Some of the competing objectives for an AFP laminate are:

- Minimize weight
- Maximize strength margins
- Meet laminate rules for balance and symmetry
- Minimize through thickness fiber deviation
- Minimize tow overlaps/gaps
- Minimize layup and cure defects

One of the ways these competing objectives can be handled is to enforce strict requirements on laminate design metrics (for example, only allowing a small number of laps and gaps). While this might simplify the analyses needed (by not having to evaluate impact on laminate strength), it inhibits interaction between design and manufacturing disciplines and drives the design away from the optimum laminate.

In previous work by Collier Research [1], a process was developed to map fiber directions and tow overlaps and gaps from CGTech's Vericut Composite Programming (VCP) software to the Finite Element Model (FEM) mesh in HyperSizer for inclusion in stress analysis. This mapping process helped close the loop in automated data transfer between AFP design and stress analysis software.

The challenge that remained is to provide a capability that facilitates iteration of the AFP laminate design to find a solution that meets stress, design, and manufacturing requirements. To address this challenge, a DFM tool is being developed in the HyperSizer software framework, using the existing graphics display and database, dubbed the "Central Optimizer." The objective of the Central Optimizer tool is to map the metrics listed above onto a single model (the FEM in HyperSizer) to provide the user with comprehensive insight to the quality of their current AFP laminate design. Additionally, the tool provides recommendations as to how the design can be improved by simultaneously overlaying all of these metrics and exploring design changes in an automated way.

The sections below describe some of the key functionalities that have been developed to enable this DFM software tool. The Central Optimizer itself is a software interface being developed in the HyperSizer framework. Additionally, there are several other tools that contribute to the Central Optimizer "process." These are existing tools, as well as new tools that are being developed in parallel for AFP process optimization, in addition to laminate design and analysis.

II. Software Workflow

The sections below describe the inputs and outputs of the Central Optimizer process and provide further details on the intended workflow between software.

A. Inputs to Central Optimizer

The inputs listed below come from a variety of sources, including modeling done before the optimization as well as design requirements.

- Part geometry (CAD and FEM).
- Internal loads (from Finite Element Analysis, FEA).

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- 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).

B. Outputs from the Central Optimizer

The outputs listed below correspond to the final laminate design selected with the help of the Central Optimizer. This design data is not produced directly by the Central Optimizer itself, but by the software tools in the presented workflow.

- 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.

C. General Description of Workflow

Figure 1 shows the overall workflow determined for the Central Optimizer, with a description below. The overall functionality of each software component is introduced to provide insight to the process as a whole. Note that the entire process is wrapped up by a data communication portion of the Central Optimizer. Some of the data exchanges between software will be fully automated, in cases where an Automated Programming Interface (API) exists, such as between HyperSizer and the Central Optimizer. More detailed descriptions of each component are provided in subsequent sections.
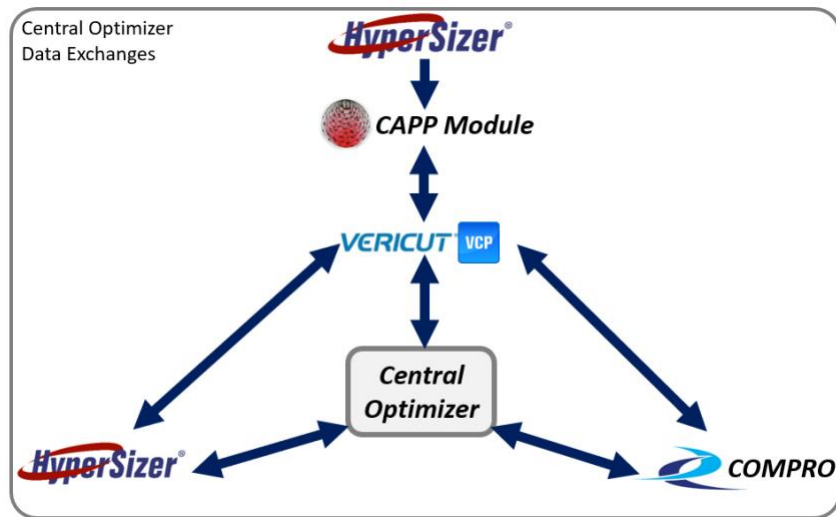

Figure 1. Overall software workflow for Central Optimizer.

1. Laminate Optimization

The Central Optimizer process starts with optimization of ply shapes and ply counts (of each orientation) in HyperSizer. This optimization is performed on the FEM. A laminate design is selected that meets strength and buckling requirements when evaluated with the loads from the FEA solution. Additionally, design requirements such as balance and symmetry are applied to the optimization. Note that at this point in the process, the optimization results are based on assumed fiber directions instead of the as-manufactured fiber directions.

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2. Start Point and Layup Strategy Selection

Once the initial ply definitions (boundary geometry and orientation) are formed by HyperSizer, the next step is to generate AFP tow paths that fill in the plies. However, this requires selection of a start point and layup strategy for each ply to be used by the Path Simulation Software (PSS) that generates tow paths. The majority of PSS tools use the start point to "seed" the tow paths with a "reference" course. The remainder of the courses are then generated outwards from the reference course, according to a selected layup strategy. On doubly-curved tool surfaces, selection of start point and layup strategy can have a significant impact on the quality of the layup [2]. This is where the Computer Aided Process Planning (CAPP) module is used to aid the selection process. The module iterates with VCP to check the quality of start points and layup strategies by monitoring laps and gaps, fiber angle deviation, and steering radii.

3. Update Fiber Directions in the FEM

The next step is to further asses the quality of the tow paths generated by VCP. The first part of this assessment is to update the FEM in HyperSizer with fiber directions that correspond to the tow paths generated by VCP. These fiber directions are used to generate updated strength and buckling margins. For a doubly-curved surface, the updated margins will usually be different than the original margins due to deviations from the original assumed fiber directions.

4. Evaluate Impact of Layup Quality

The quality of the tow paths is also assessed by estimating the likelihood of defect occurrence. During the CAPP-VCP iterations described previously, several layup quality metrics are checked, but the *impact* of those metrics was not assessed. The objective in this step is to evaluate the impact on the quality of the laminate as a whole. There are several parts of this evaluation, described below.

The impact of laps and gaps on laminate strength and stiffness is assessed by mapping the lap and gap geometry to the FEM. Ply thicknesses are scaled on the FEM elements to approximate the absence of material due to gaps or the presence of extra material due to overlaps. Additionally, the thickness deviation that results from the accumulation of laps and gaps is calculated.

Another important assessment to perform is the likelihood of AFP defects caused by steering the tows over a doubly-curved surface. 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 [3]. 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 [4]. 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.

5. Iterate to Achieve Satisfactory Design

The challenge of generating a satisfactory design is that significant coupling exists between the analyses discussed above. This requires iteration between the tools to produce a laminate that meets both manufacturing and structural performance requirements. For example, a set of tow paths that produces positive strength margins may require tow steering that creates an unacceptable number of defects. Conversely, another set of tow paths that has low steering could result in negative strength margins, a high number of laps and gaps, etc. It is necessary to evaluate every aspect of the laminate quality each time a change is made to the design (tow paths, ply boundaries, etc).

These competing objectives can make it challenging to choose a single design that perfectly satisfies every objective in each discipline. Thus, it is often necessary to choose a laminate design that is a compromise between the disciplines. The objective of iterating the laminate design is to find the best possible compromise. This solution will vary depending on program design requirements or manufacturer preferences.

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III. External Modules

The following sections describe modules that are external to the Central Optimizer software, but are still used as an integrated part of the Central Optimizer design process. Each section describes the inputs, outputs, and primary functionality that is relevant to the Central Optimizer process.

D. Computer Aided Process Planning Module

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.

The CAPP module has three main fragments:
- Major 1 where we identify and compute the eight parameters needed to select the optimal ply-level process planning strategies: Gap, Overlap, Steering and Angle Deviation. Each parameter has both a level and a value parameter.
- Major 2 where each parameter's influence is identified through the Analytical Hierarchy Process (AHP). This pair-wise comparison method ensures that the process planner context is taken into account.
- Major 3 where the solutions are propagated and ranked according to the identified metrics.

Below is a snapshot of the CAPP module, developed at the University of South Carolina, with major 2 highlighted where the AHP matrix of the eight deciding parameters is selected.
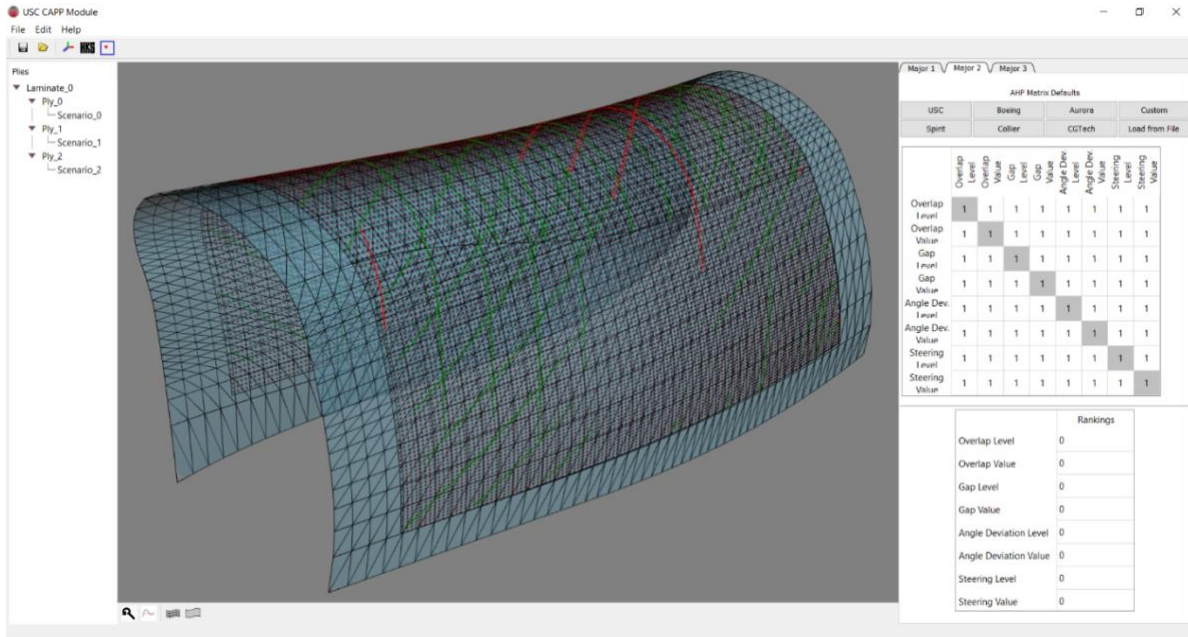

Figure 2. CAPP Module interface.

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E. Vericut Composite Programming – Tow Path Generation

VCP is a PSS tool that generates tow paths to fill in specified ply boundaries. There are a wide variety of user inputs related to the AFP machine, tool geometry, path geometry, and material selection. 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.
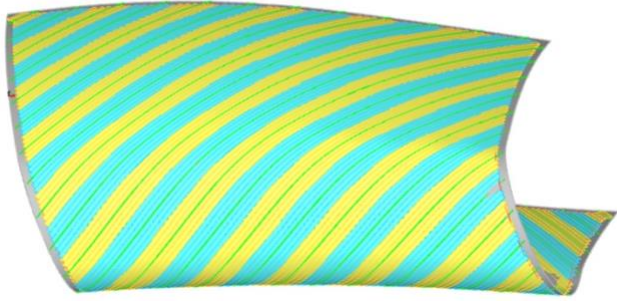
Figure 3. Tow paths for a 45° ply.

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).

F. COMPRO Process Models – AFP and Cure Defect Simulation

Two physics-based models will be used in the Central Optimizer process to predict the likelihood of defect occurrence. Both use the Abaqus [5] FEA solver with the COMPRO plug-in [6].

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 [3]. 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 Ref. [3] 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. This is described in greater detail in Section IV.E.

2. Cure Defects Simulation

This process model can predict the level of porosity in a laminate that develops during cure [4]. 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.

IV. Internal Modules

The following sections describe modules that are internal, or directly linked to the Central Optimizer software and therefore have an automated interface.

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A. HyperSizer Laminate Optimization

The HyperSizer laminate optimization is used to generate plies based on FEM loads (shown in Figure 4) and specified strength and buckling criteria, while minimizing the weight of the structure. Additionally, HyperSizer can evaluate the impact of AFP fiber directions as well as laps and gaps. The relevant inputs to HyperSizer are listed below:

- FEM and FEA results (element loads and grid displacements).
- Material selection and strength allowables.
- Failure criteria (ply strength, laminate strength, buckling requirements).
- Laminate rules (balance, symmetry, minimum ply counts, and any other stacking rules).
- Fiber directions from AFP tow path simulation (material vector per FEM element).
- Lap and gap geometry (outlines of each feature).
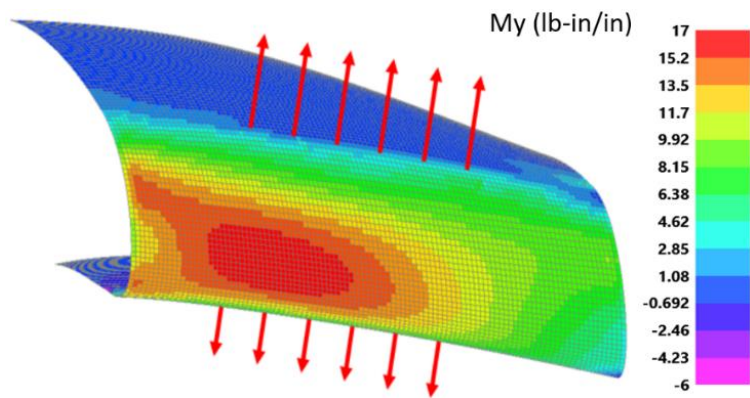
Figure 4. Bending moment in a FEM.

With these inputs, the optimization starts in the HyperSizer Express module 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. These element groupings form sizing zones. Next, optimization is performed within each of the zones. In this optimization, all elements in a zone are assumed to have the same ply stack. The final step is to perform ply sequencing, where plies are connected across zones to form "global" plies (shown in Figure 5). In this step, the user can chose between lower-weight sequences with more ply drops, or more manufacturable design with fewer ply drops but higher weight.

Once the laminate optimization is completed, there are several outputs that are relevant to the Central Optimizer:

- Ply boundaries (as a series of XYZ points).
- Ply orientations and number of each orientation.
- Per-element margins of each analysis.

The ply designs are passed back to VCP to generate updated tow paths, and also passed to the COMPRO process models to run updated defect simulations, as described in Section II.C.
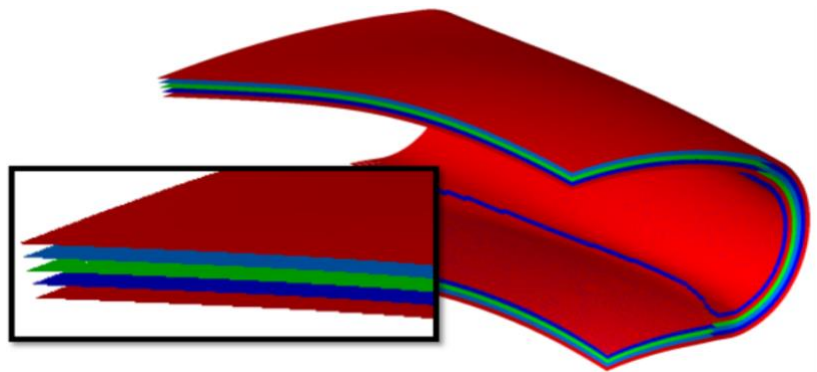

Figure 5. Laminate design output from HyperSizer.

B. Minimization of Through-Thickness Fiber Angle Deviation

In the interest of ease of certification, an optimization module was developed to minimize through-thickness fiber deviation over the entirety of a laminate. Laminates with traditional ply orientations ($0°$, $45°$, $90°$) are currently easier to certify than Non-Traditional Laminates (NTLs) due to the significant amount of existing test data and flight-worthy precedence. Thus, it is desirable to keep ply orientations as close to these angles as possible when generating AFP laminates. This is challenging on complex curvature because fiber paths can deviate significantly from a specified rosette. However, it is still possible to minimize deviation *locally*, through the thickness of the laminate, and keep the ply stack as close to a traditional 0/45/90 laminate as possible.

A deviation minimization routine was developed to modify the orientation of each ply at its start point to minimize though-thickness deviations. For a given layup strategy (natural paths, rosette paths, etc.), ply start point, and ply

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orientation, the fiber paths for the ply will cause varying amounts of deviation over the entire part. By adjusting the orientation of each ply by a small amount (less than 10º), 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. A "compass search" optimization routine was implemented to solve this minimization problem. The optimization is performed on the FEM, after the initial fiber directions have been mapped from VCP.

The inputs to the optimization are listed below:

- Initial fiber directions for each FEM element, for each ply.
- Requirements for symmetry and balance.
- Optimization bounds.

Figure 6 shows an example result of the minimization process. Before the deviation minimization, 24.8% of the laminate area has through-thickness deviations exceeding $2^°$. After minimization, that number drops to 17.8%.
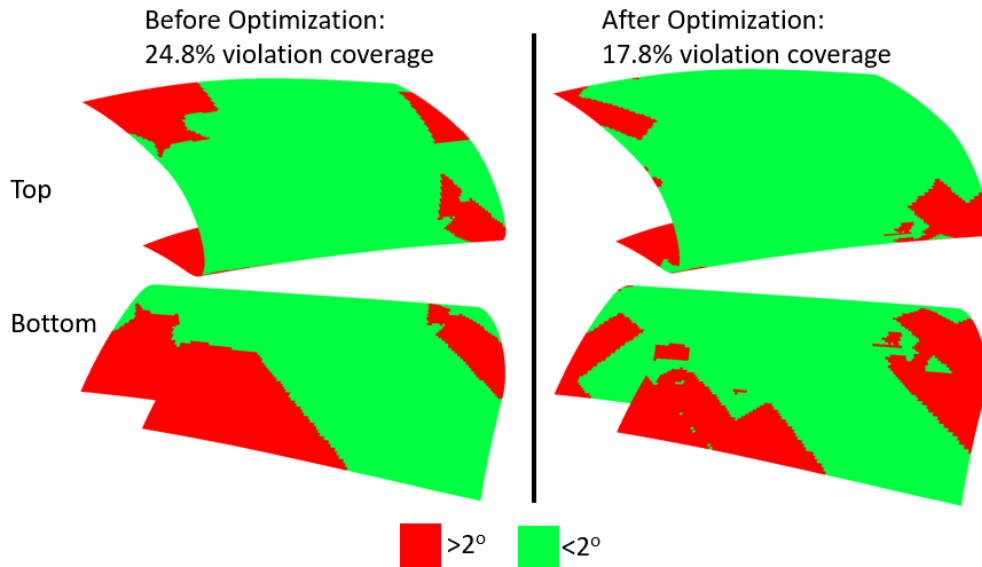

Figure 6. Example result of through-thickness deviation minimization on complex curvature part.

The output of the optimization is simply a list of rotations for each ply, along with the corresponding deviations on each element.

C. Lap and Gap Impact on Laminate Strength

Once laps and gaps have been mapped to the FEM in HyperSizer, the impact on laminate strength can be evaluated. The mapping and analysis approaches are similar to that described in Ref. [1]. 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 depicted in Figure 7.

Figure 7. Lap and gap mapping approach [1].

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The first step to evaluating impact on laminate strength is to re-run FEA to determine the redistribution of internal loads around the lap and gap features. The ply thickness scaling strategy described above is used to modify the thickness of plies in the layered shell composite property (Nastran PCOMP) in the FEM. Thicker regions of the laminate tend to carry more load and thinner regions shed load into surrounding elements. Capturing this redistribution is critical to calculating accurate strength margins. Without re-running FEA, areas with gaps will have unrealistically high loads, resulting in negative strength margins. Figure 8 shows a comparison of minimum strength margins without and with re-running FEA. After capturing load re-distribution, only a few negative margins remain in areas where there are several gaps stacked on the same element.
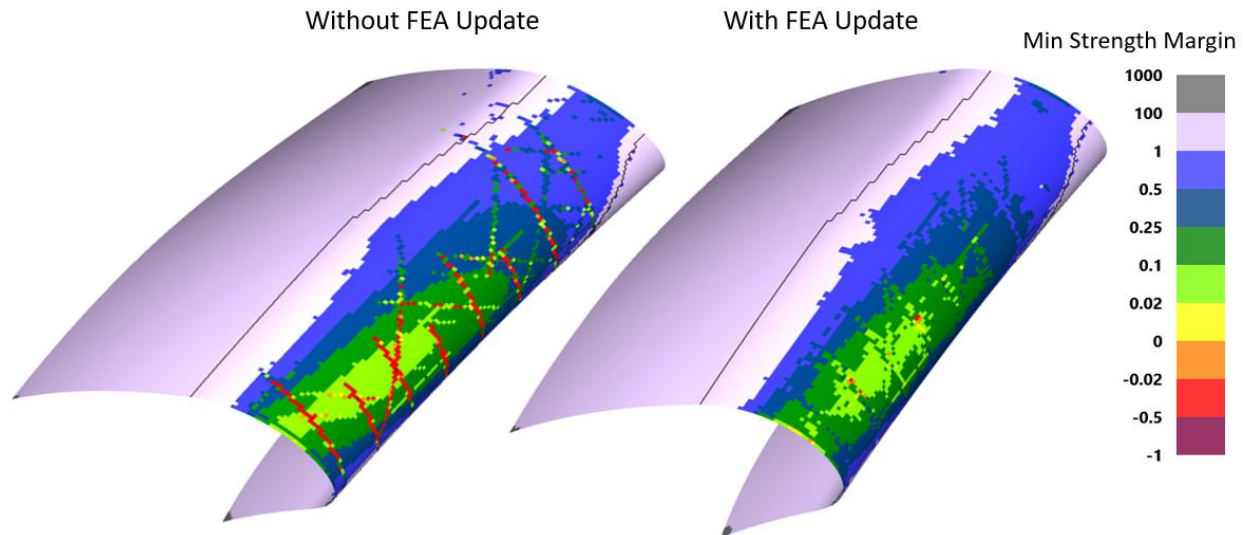

Figure 8. Ply-based strength margins without (left) and with (right) updated FEA loads.

D. Accumulated Thickness Deviation from Overlaps and Gaps

In addition to having an impact on the strength of a laminate, laps and gaps can accumulate and cause significant deviations in the thickness of the laminate. This can be detrimental depending on the location of thickness deviation in the part. For portions of the laminate that are bonded or bolted to another part, it is critical to have low thickness deviation to achieve good joint performance. Thus, it is important to track the accumulation of laps and gaps from each ply in each design iteration. The lap/gap thickness module is able to track the thickness deviations in user-specified portions of the part (via element sets). This allows the Central Optimizer to apply constraints to critical areas while ignoring thickness deviation in other areas.

The approach introduced previously to scale ply thickness for the strength analysis is

Figure 9. Ply count deviation due to lap and gap accumulation.

also used to determine the impact on laminate thickness. After the laps and gaps are mapped from VCP to the FEM, the ply thicknesses are summed up on each element, including the scaling due to laps and gaps. Figure 9 shows an example of ply count deviations due to the presence of laps and gaps.
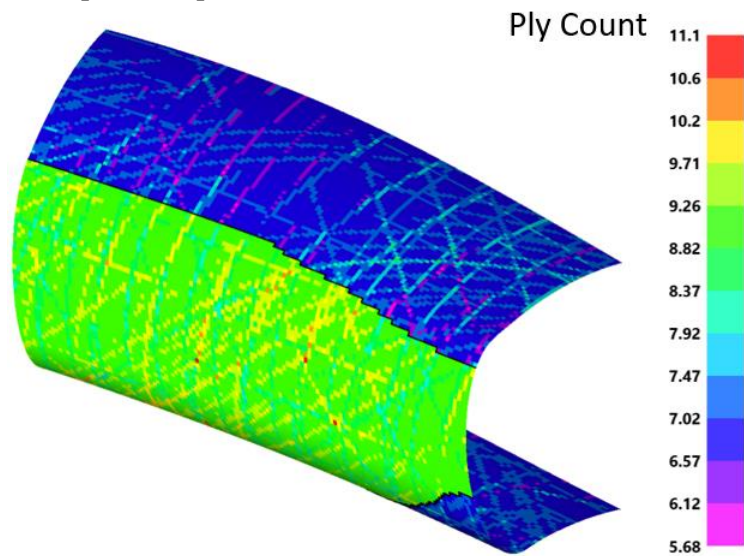
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E. AFP Defect Probability via Surrogate Model

The early version of the AFP defect simulation described previously is currently functional for flat tool surfaces. Thus, it is not possible to directly simulate defects for doubly-curved tool surfaces. This capability is currently under development by Convergent Manufacturing Technologies US (CMTUS) and NASA. However, 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 (1) is the regression polynomial whose form is chosen by the user. Equation (2) is a logistic function that has been adapted to produce defect probabilities varying from 0 to 100%.

$$f(R) = C_0 + C_1 \cdot R^{E_1} + C_2 \cdot R^{E_2} + C_i \cdot R^{E_i} \tag{1}$$

$$P(R) = 100 - \frac{100}{1 + e^{-f(R)}} \tag{2}$$

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. An example of the regression is shown in Figure 10. The regression data in this example is idealized, based on trends observed for AFP tow steering, but did not come from the COMPRO simulation.
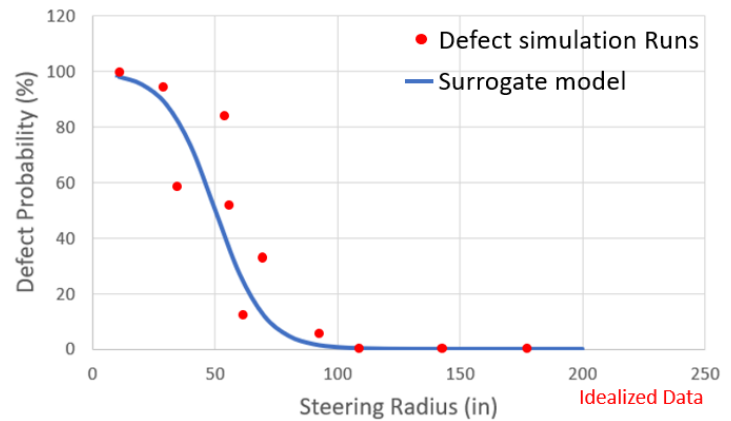
The surrogate model is utilized in the Central Optimizer process to evaluate steering radii predicted by VCP. VCP can export steering radii for each ply across the entirety of the tool surface. Each radius is evaluated with the surrogate model to produce a probability map of defect likelihood across the entire tool surface, for each ply. An example of this probability map is shown in Figure 11.
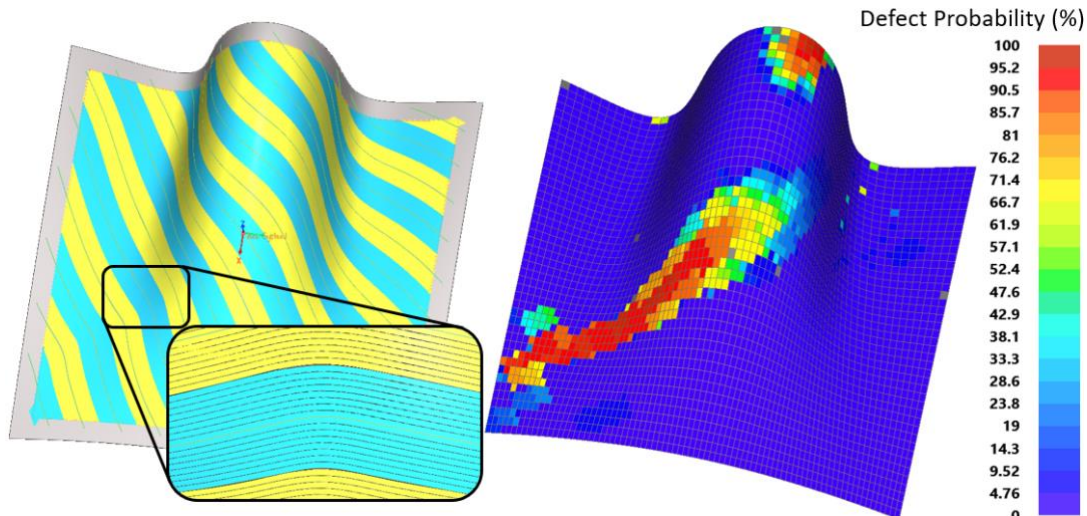

Figure 10. Idealized AFP defects surrogate model.

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

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V. Future Work

Sections below describe planned tool development and evaluation.

F. Central Optimizer Enhancements

The analysis approaches and software data exchanges described above are the first step to achieving an overall DFM optimization process for AFP. The next major capability to be added is an approach to provide automated guidance on how to modify the laminate design based on feedback from the individual analyses. This requires overlaying the results of each analysis, determining the design changes that are best for each discipline, and then finding a solution that is a compromise between disciplines. Automating this approach allows for faster and more consistent design iterations.

G. Planned Software Evaluation

Once completed, the entire Central Optimizer design process will be evaluated on several different structures, including a wing skin, fuselage panel, as well as some smaller composite parts. The intent of this evaluation will be to determine improvements to design cycle time and overall quality of the laminate. For each structure, two designs a will be generated; a "baseline" and "optimized" design. The baseline design will use legacy tools and approaches for AFP laminate design, and the optimized design will use the described Central Optimizer process.

VI. Conclusions

The proposed "Central Optimizer" software and processes will provide a tool to enable a DFM approach for AFP laminates. This will be achieved by streamlining data transfer between key AFP analysis and stress analysis software. The final tool will be capable of reading and assessing data related to fiber angle deviation, laps and gaps, impact on laminate strength, as well as likelihood of AFP defects. By simultaneously overlaying this data and weighing the objectives of the optimization, the tool will be able to recommend iterative changes to the laminate design that converge towards a satisfactory design for both stress analysis, design, and manufacturing disciplines.

Acknowledgments

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