Design for Manufacturing of Structures with Automated Fiber Placement via Integration of Analysis and Process Planning

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Abstract. Under the Design for Manufacturing (DFM) task in the NASA HiCAM program, significant process has been made towards establishing a fully automated optimization process that spans the structural analysis, design, and manufacturing process planning for Automated Fiber Placement (AFP) structures. Previous efforts in this area established the data formats and mapping processes needed to exchange data between disciplines. The software tools used in the framework are HyperX (structural optimization), CAPP (process planning), and VCP (AFP path generation). The work has culminated with automation of data exchanges and an optimization process that drives the three software toward convergence. Within this framework, HyperX is used to generate mass-optimum composite designs which are iterated with VCP and CAPP to improve manufacturability of the designs. As the ply manufacturing process is adjusted by CAPP and VCP, HyperX continually re-assesses the structural integrity of the part and adjusts the laminate as needed. For example, the position of fiber steering and tow overlaps/gaps can necessitate changes to the laminate design. Once the design converges, the end result is a stack of plies that meets both structural and manufacturing requirements. This paper presents the details of the framework and demonstrations the automated process on several parts with significant double-curvature.

Keywords: Design for Manufacturing, Composite Optimization, Digital Thread

1 Introduction

There is an ongoing effort in the Aerospace industry to evolve engineering tools and processes into a “digital thread” ecosystem, where all design, analysis, and manufacturing data is shared on common digital model and data is passed between disciplines in a seamless manner [1]. The work described in this paper is in pursuit of this goal as well. In particular, the work focuses on an area referred to as Design for Manufacturing (DFM). The goal of DFM is to assess manufacturing objectives and constraints in parallel to the analysis and design of a part. This results in a superior (weight and performance) design than if the design was passed back and forth between disciplines manually. The DFM tool described in this paper has been developed for composite structures manufactured with Automated Fiber Placement (AFP).

The DFM tool is being developed under the NASA High-Rate Composite Aircraft Manufacturing (HiCAM) program. HiCAM's goal is to develop new manufacturing technology to accelerate the production rate of composite aircraft by up to 6X. The DFM tool is being developed in parallel with these new manufacturing approaches to ensure compatibility. Although the DFM tool does not directly target manufacturing rate as an optimization objective, it enables a wider breadth of configurations to be studied during the design process, which can assist with finding a solution that is more manufacturable than the baseline.

The "tool" itself is the integrated result of three separate engineering software tools: HyperX [2], Vericut Composites Programming (VCP) [3], and the Computer Aided Process Planning module (CAPP). HyperX and VCP are COTS tools, and CAPP has been in development by University of South Carolina for several years [4][5][6][7][8][9]. The tools used are summarized below [10].

HyperX is a stress analysis and optimization tool for metal and composite structures. It uses FEA loads to determine the mass-optimum design while achieving positive margins of safety for strength and buckling. The Computer Aided Process Planning (CAPP) module is used to streamline the process planning portion of implementing an AFP design. It is primarily focused on selecting a ply start point and layup strategy to minimize AFP defects. Vericut Composites Programming (VCP) provides a suite of path planning tools to generate machine motion for multiple composites processes. VCP also contains tools to analyze these processes as well as pass data for analysis to other software. As it pertains to this effort, VCP determines all the paths needed to completely fill in a ply with material and then outputs the gcode needed to run the machine.

The linking and automation between these tools is described in Ref. [10]. An overview of the optimization process is shown in Fig. 1. The process starts with inputs typical of aerospace design, and analysis. The first step is to generate a baseline laminate design in HyperX. Next, the DFM optimization is performed, where the tools iterate with each other in an automated fashion. Once optimization is complete, some manual cleanup is needed to prepare the plies for manufacturing. The end result is a weight-optimized and manufacturing-optimized laminate stack, ready to be run on an AFP machine.

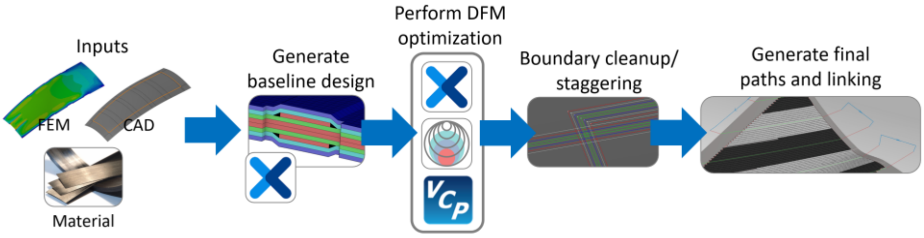


Fig. 1. Workflow for optimization with DFM tool.

2 Overview of Optimization Tool

Prior work on the DFM tool has been focused on establishing formats and processes to pass data back and forth between the three software. This work was done under the Advanced Composites Program (ACP) prior to HiCAM [11][12][13]. In the early stages of HiCAM, these processes were automated by utilizing the Application Programming Interface (API) in each of the three software. Additionally, a new User Interface (UI) was created to facilitate the tool's operation. The sections below describe the latest work done on the DFM tool in the pursuit of automated optimization.

2.1 Inputs and Outputs

Since the DFM tool encompasses the stress analysis, design, and manufacturing disciplines, the required inputs to the tool are essentially the combined core inputs of each of those disciplines. The inputs are listed below.

- Finite Element Model (FEM) and Finite Element Analysis (FEA) results
- Computer Aided Drafting (CAD) model of the manufacturing tool surface
- Material information
  - For stress analysis: lamina stiffness, lamina stress and strain allowables, etc
  - For manufacturing: tape width, #tows per course, etc

The output of the DFM tool is an optimized laminate stack. Each ply has the following features:

- Orientation (0°, 45°, etc).
- Shape, defined with a ply boundary. The boundary is defined on the FEM and does not contain any staggering or offsets between plies.
- Start point for AFP paths.
- Layup strategy for AFP paths.

Note that some manual work is needed at the end of the process to prepare the plies for manufacturing. This includes creating the final ply boundaries with staggering and offsets, and generating course linking for the AFP program.

2.2 Optimization Approach

The DFM tool uses a bi-level approach [14] to drive the optimization of the structure. In a general optimization problem, the goal is to minimize the value of an objective function (such as total mass) while also satisfying constraints imposed on the problem (e.g. analysis constraints such as meeting failure criteria and manufacturing constraints such as minimum gauge thickness). Many optimization approaches, such as a generic gradient-based method or genetic algorithm method require both the objective and constraints to be simultaneously evaluated with each iteration of the optimization [14]. However, this was not possible in the DFM framework considering that each of the three tools perform their own optimization (therein evaluating their own objective and constraint functions).

Use of a bi-level optimization approach allows for some decoupling of the optimization performed within each of the tools, while still enabling them to converge towards an optimum solution that satisfies the constraints within each tool. Fig. 2 provides an overview of the DFM optimization approach.

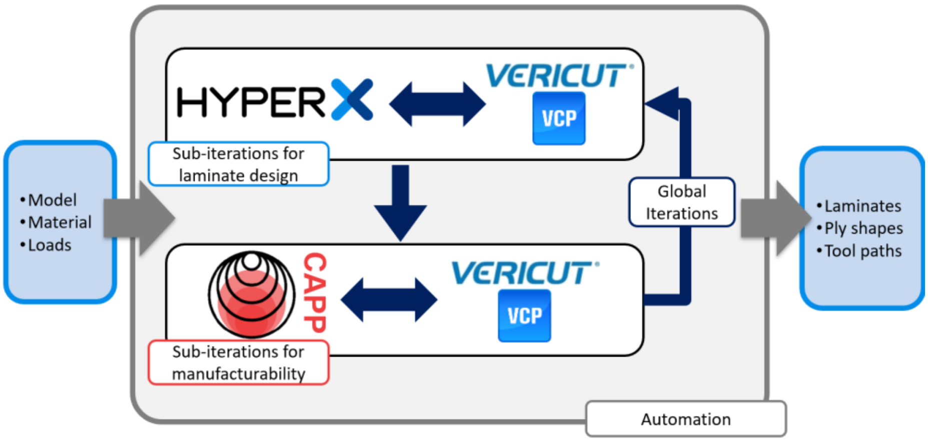


Fig. 2. Bi-level DFM optimization approach.

The bi-level optimization proceeds as described in the following sections.

Generate Baseline Laminate in HyperX.

The objective of this step is to generate the initial laminate used in the optimization. At this stage, HyperX knows nothing about the manufacturability of the structure. The initial optimization is done with off-the-shelf HyperX functions; no new DFM tools are used in this step. An example of optimized plies in HyperX is shown in Fig. 3. The sub-steps are:

1. Import FEM and FEA results file.
2. Set up model.
   - Define optimization parameters – material, layup rules, etc.
   - Define failure criteria to be considered.
3. Run optimization and generate FEM-based plies that are defined by element coverage.

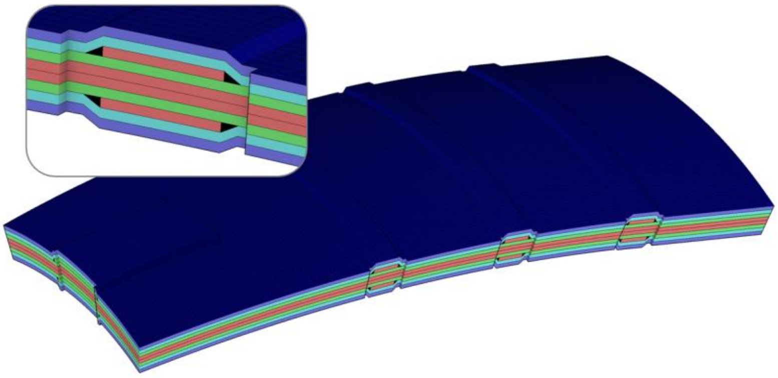


Fig. 3. Example of optimized plies on a FEM in HyperX.

Run HyperX-VCP Iteration.

This iteration loop is the final part of the DFM process to be implemented. For the demonstration described later in the paper, the design data was handed off manually between HyperX and CAPP. The objective of this step is to get the HyperX analysis in sync with manufacturing approach. HyperX calls VCP (automated) to generate paths for the current HyperX plies. Fiber directions (and eventually laps and gaps) are imported back to HyperX to update the analysis. At this stage, the start points and layup strategies are not optimized; the tool approximates the area centroid of each ply for the starting point and the layup strategy is selected by the user.

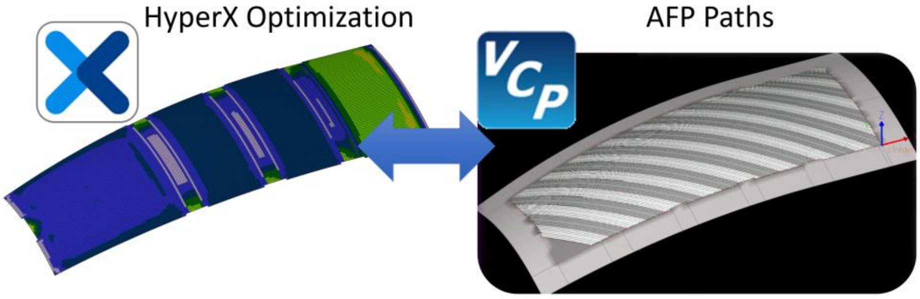


Fig. 4. HyperX iteration with VCP.

Run CAPP-VCP Iteration.

The objective of this step is to optimize the start point and layup strategy for each ply to maximize manufacturability while also respecting the HyperX strength margins. CAPP calls VCP (automated) to generate paths for a large number of different start points and layup strategies for each ply, as shown in Fig. 5.

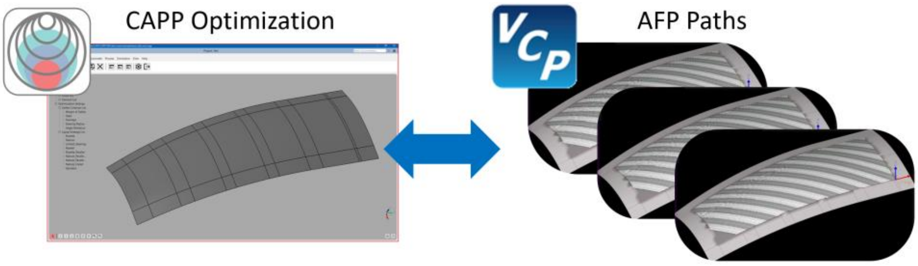


Fig. 5. CAPP iteration with VCP.

Re-run HyperX Analysis and Optimization.

The objective of this step is to get HyperX in sync with the optimized start point and layup strategy. Now that the start points and layup strategies have been modified, the fiber paths (and laps/gaps) are different than the previous step and need to be re-checked. If needed, HyperX can add new plies to resolve negative margins of safety that were caused by the new plies, as shown in Fig. 6.

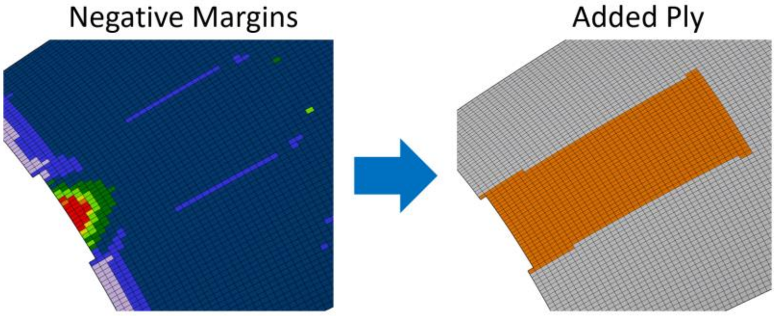
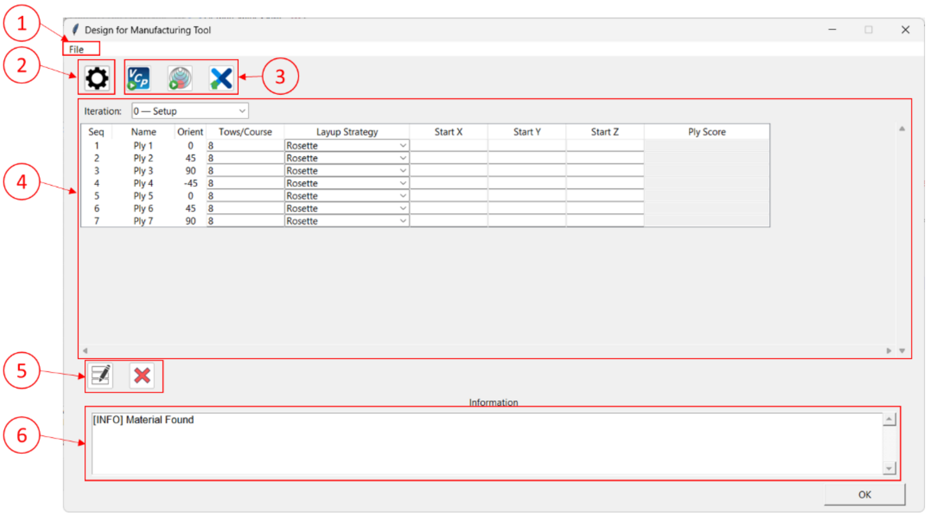


Fig. 6. Ply added to resolve negative margins from laminate changes for manufacturability.

2.3 User Interface

The UI for the DFM tool is used to drive the optimization process. Based on feedback from potential users in the HiCAM project, the intent was to avoid creating a 'black box' tool that would execute every step of the optimization on its own without user feedback. The selected UI layout enables users to run each step of the optimization at their own pace, review the state of the design after each step, and modify the model setup if needed. The main user interface is shown in Fig. 7 below.



Iteration: 0 — Setup

Seq	Name	Orient	Tows/Course	Layup Strategy	Start X	Start Y	Start Z	Ply Score
1	Ply 1	0	8	Rosette				
2	Ply 2	45	8	Rosette				
3	Ply 3	90	8	Rosette				
4	Ply 4	-45	8	Rosette				
5	Ply 5	0	8	Rosette				
6	Ply 6	45	8	Rosette				
7	Ply 7	90	8	Rosette				

```
[INFO] Material Found
```

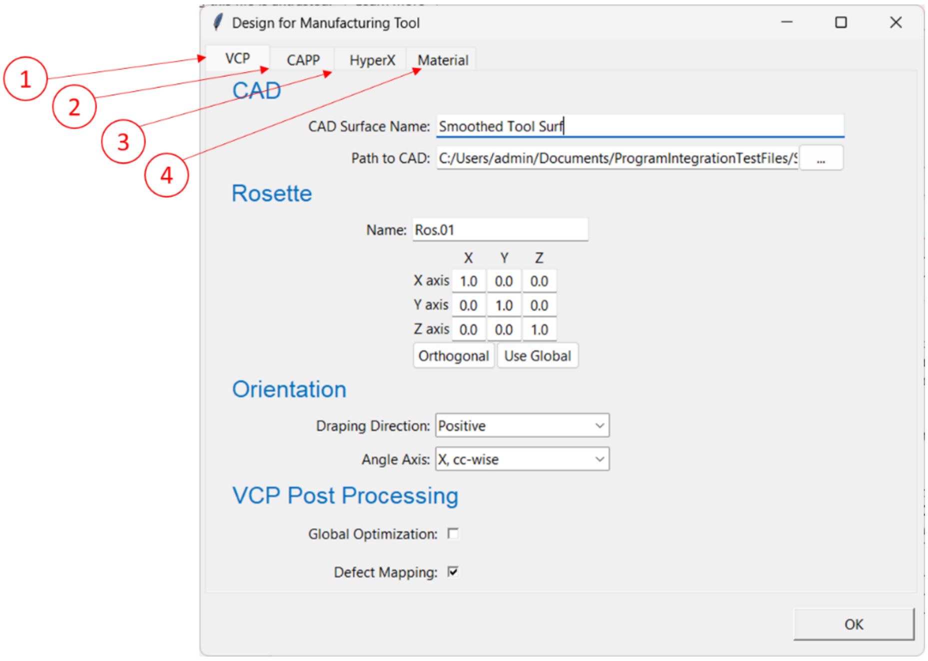
Fig. 7. The main UI of the DFM Tool.

The main UI of the DFM Tool consists of various components, including **1)** a file menu that offers options for saving and loading settings. Saving as XML allows for the settings to be stored and retrieved.

A selection of buttons on the top of the UI includes **2)** The settings button that opens another window containing settings particular to each of the software tools in the DFM process. These settings are divided into tabs: VCP, CAPP, HyperX, and Material. Each tab includes settings required for both VCP and CAPP runs, as shown in Fig. 8. The settings are organized into tabs, which will be explained below.

3) This group of buttons runs each stage of the optimization process. The buttons are laid out in the order in which they are typically used: VCP iteration, CAPP iteration, upload to HyperX once the optimization is completed.

The VCP run and the CAPP runs update the iteration dropdown shown in **4)**. It also includes the laminate table that contains the resulting data for each ply. The active iteration (selected in the drop-down) contains ply data and settings that are sent to VCP or CAPP. It includes the result data from CAPP. This table will be automatically filled when a compatible laminate is found in HyperX. The table changes based on the iteration chosen. The plies can be highlighted for selection in the override window. **6)** The information window displays the current progress of the VCP fiber mapping process or the CAPP optimization process. It also shows warnings and errors for the UI.



CAD Surface Name: Smoothed Tool Surf

Path to CAD: C:/Users/admin/Documents/ProgramIntegrationTestFiles/

Name: Ros.01

	X	Y	Z
X axis	1.0	0.0	0.0
Y axis	0.0	1.0	0.0
Z axis	0.0	0.0	1.0

Draping Direction: Positive

Angle Axis: X, cc-wise

Global Optimization: ☐

Defect Mapping: ☑

Fig. 8. The settings window of the DFM script which shows the VCP run settings

The settings window for the DFM script features settings for: **1)** The VCP run, including the CAD file path, the rosette used for VCP, the orientation of the draping and the angle axis, and the toggle for global optimization and defect mapping.

2) The CAPP tab sets the weighting for manufacturability versus defect criteria for laminate-level optimization. The defect criteria include the percentage allowance of gaps, overlaps, angle deviations and the steering. Thresholds can be set for each of these variables. The advanced mode allows setting the severity and the instances of these settings. It also contains the threshold for the margin of safety. Furthermore, four default defect criterion strategies can be selected. It may also control the allowed tow layup strategies that CAPP may change for its optimization.

3) The third tab is the HyperX tab, which includes data fields for HyperX related to FEA loads, the reference plane, the failure criteria, and enables the layup rules for global optimization. It also contains settings for the next feature in development: defect mapping.

4) The fourth tab contains details of the material. The fields auto-fill when detecting a homogeneous laminate in HyperX. It also includes fields to define the tow width and the reference temperature for use in VCP run and global optimization, respectively.

3 Application to Medium Contour Tool

The DFM software was run on a HiCAM part, dubbed the “medium contour tool” which is representative of a panel on the forward fuselage section of a commercial aircraft. The tool has both single and double curvature, making it a suitable challenge for the DFM tools.

3.1 Model Setup

As described previously, the primary input to the process are FEM and CAD models which are shown in Fig. 9 for the medium contour tool. Note that the boundary of the CAD model extends beyond the FEM boundary, which is needed to represent the manufacturing tool surface. The colored regions on the FEM represent optimization zones – each of which can choose a unique laminate thickness and stacking sequence.

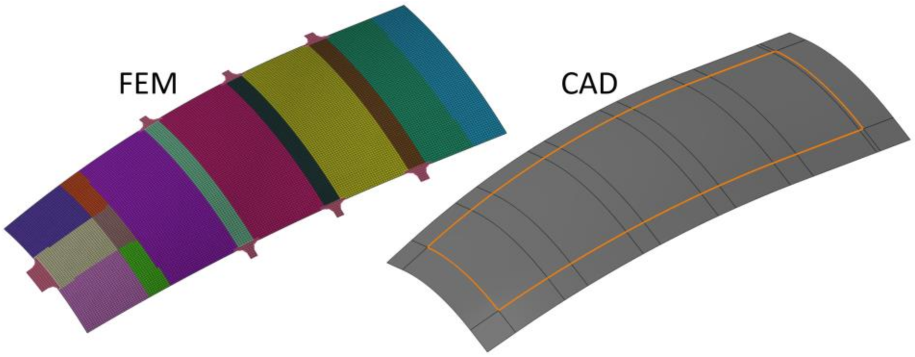


Fig. 9. FEM and CAD models for the medium contour tool.

The FEA loads fed into the optimization are shown in Fig. 10. A total of five load cases were applied; these cases generate a mixture of acreage loading as well as concentrated loading. An example of the internal loads for each of these five cases is shown in Fig. 10.

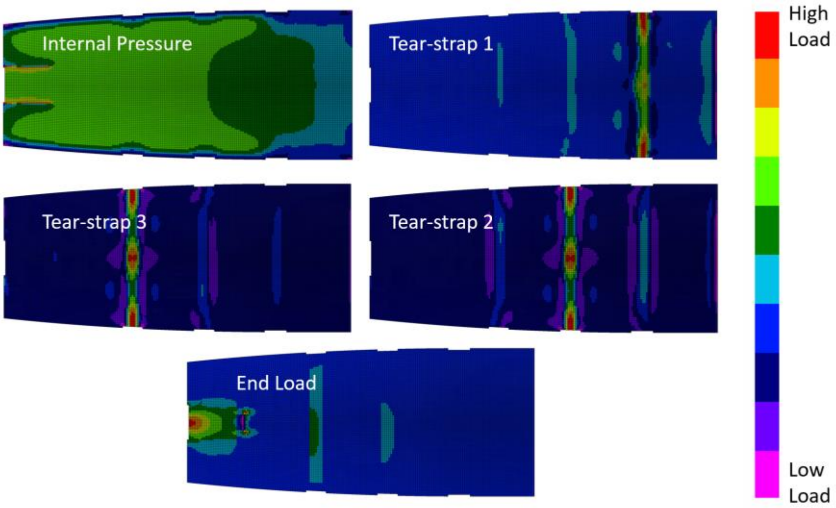


Fig. 10. Example of internal loads for the five load cases on the model.

The material properties used in the optimization are similar to the IM7/8552 material [15].

3.2 Optimization Results

As described previously, the first step of the optimization process is to generate a baseline laminate design in HyperX, as shown in Fig. 11. This baseline design has an 8-ply quasi-isotropic on much of the structure with 10-ply pad-ups in regions with concentrated load.

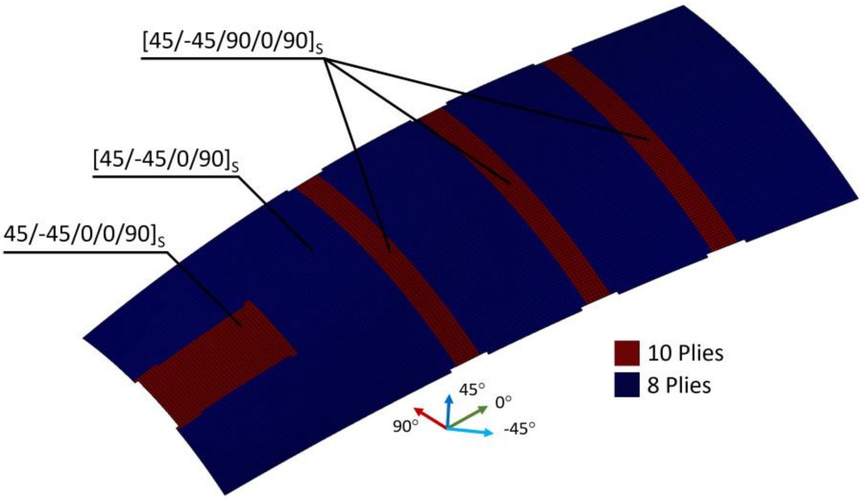


Fig. 11. Baseline laminate design from HyperX.

The minimum margins of safety of all load cases and all composite failure modes considered are shown per-element in Fig. 12. At this stage, no information about manufacturing has been included in the analysis. Note that a positive margin of safety indicates that the part meets the failure criteria. The majority of the structure has a margin between 1.0 and 0; some areas are very close to the threshold due to the part being optimized for minimum weight.

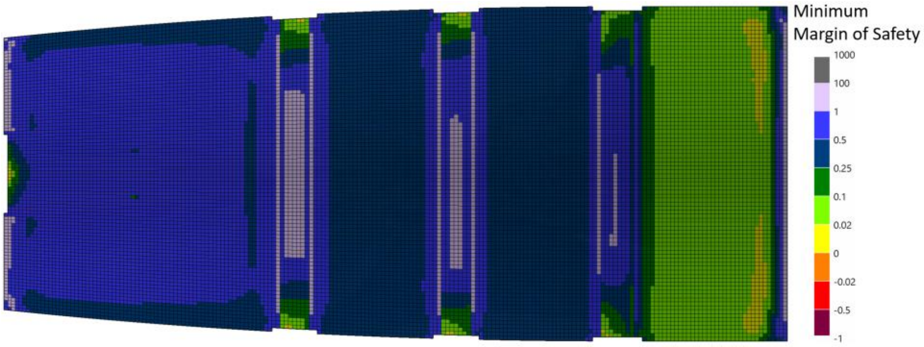


Fig. 12. Margin of safety for baseline design prior to manufacturability iterations.

Next, the HyperX-VCP iterations were performed. In this step, VCP was used to generate fiber paths for each ply, and the resulting as-manufactured fiber directions were passed back to HyperX for inclusion in the analysis. The margin of safety after this update is shown in Fig. 13. Note that this update cycle results in areas of negative margins at the end of the tapered region and at the edge of the tearstrap locations. These negative margins are due to differences between the original baseline fiber directions and the as-manufactured fiber directions. As the fiber angles change, the stiffness and strength of the laminate also change. This change happens on a localized basis and can have a different impact in different areas of the part.

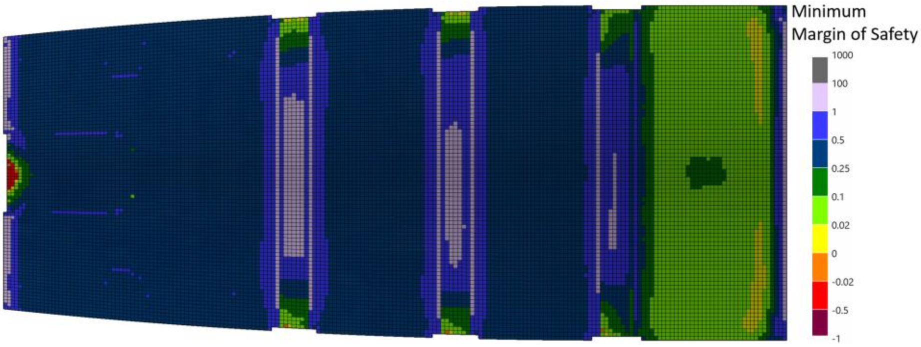


Fig. 13. Margin of safety after updating the part with as-manufactured fiber directions.

Once the DFM framework is fully completed, the next step in the process would be to automatically send the plies to the CAPP module for optimization of the start point and AFP layup strategy of each ply to minimize stacking of overlaps and gaps. However, that automatic process is not completed as of the writing of this paper. Instead, the design was transferred manually to CAPP, which then ran its optimization outside of the main automation loop. The results of the CAPP optimization will be published in a future paper.

The final step of the DFM optimization process is to converge the design by performing any updates needed to achieve positive margins of safety after the manufacturing. This part of the tool automatically determines if any changes made by VCP or CAPP will cause issues with the strength of the part, and adds plies where necessary. In this case, as shown above, the iteration with VCP resulted in some negative margins in the pad-up regions of the part. The plies added by the optimizer are shown in Fig. 14.

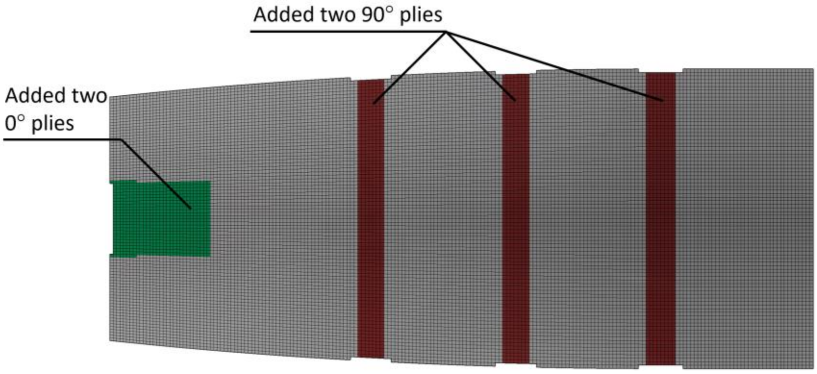


Fig. 14. Plies added by the DFM optimizer.

The plies added by the optimizer target only the areas of negative margin and choose the most mass-efficient plies (shape and orientation) that will bring the structure back to positive margins in all areas. Note that the optimizer did not add any material in regions where the structure already had positive margins. The final margins of safety for the part are shown in Fig. 15. This final design meets structural analysis criteria and contains manufacturable plies.

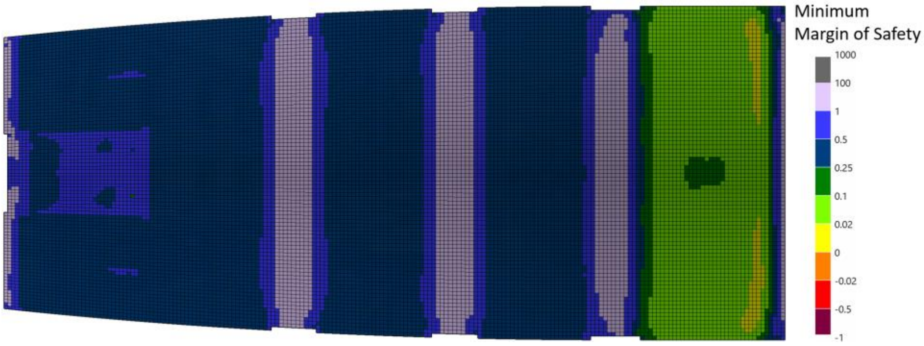


Fig. 15. Final margins of safety for the part after optimization.

4 Conclusions

A DFM tool has been developed under the HiCAM program which can perform optimization of AFP composites that simultaneously considers design, stress analysis, and manufacturability of the laminate. This tool is near completion, with one final piece needed to connect the CAPP manufacturability optimization to the rest of the framework. The portions of the framework that have been connected were demonstrated on a fuselage panel structure, and were shown to effectively optimize the part while meeting all constraints.

5 Acknowledgements

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