HOLISTIC DESIGN ANALYSIS APPROACH FOR ADDITIVE TAPE PLACEMENT PROCESS

Anthony Cheruet, Pierre-Yves Lavertu
e-Xstream Engineering
ZAE Robert Steichen – 5 rue Bommel, Hautcharage, L-4940, Luxembourg

Yvan Blanchard
Coriolis Composites
Am Technologiezentrum 5, D-86159 Augsburg, Germany

ABSTRACT

This paper is focused on the design optimization of complex 3D composites structures made by additive manufacturing processes. There are commercial CAD-CAM software solutions for detailed offline path programming, but there is a growing need for innovative tools and methodologies for doing trade off studies very early at design stage. Most of the technology available on the market are not really suited to easily check and compare various design proposals, with an efficient compromise between accuracy and performances, especially for thick and large laminates. A new innovative solution has been developed, allowing both designers and stress engineers to quickly analyze complex double-curved geometries, including variable stiffness approach and structural analysis of manufacturing defects. Automatic Fiber Placement (AFP) is a fast and efficient deposition process of carbon prepreg for large component applications. To accommodate the composite strips onto a double curved surface, the tows can be cut, restarted and slightly mis-oriented resulting in the apparition of gaps between tows. These defects, the gaps and the misalignment of the tows, affect the mechanical performance of the final part.

Keywords: AFP, Automatic Fiber Placement, Automated Fiber Placement, Additive Manufacturing, AM, Multi-Scale Analysis, Simulation

Corresponding author: Pierre-Yves Lavertu – Pierre-yves.lavertu@hexagon.com

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1. INTRODUCTION

Today, more and more CFRP structures are manufactured by automated processes such as fiber placement robotic systems (Figure 1).

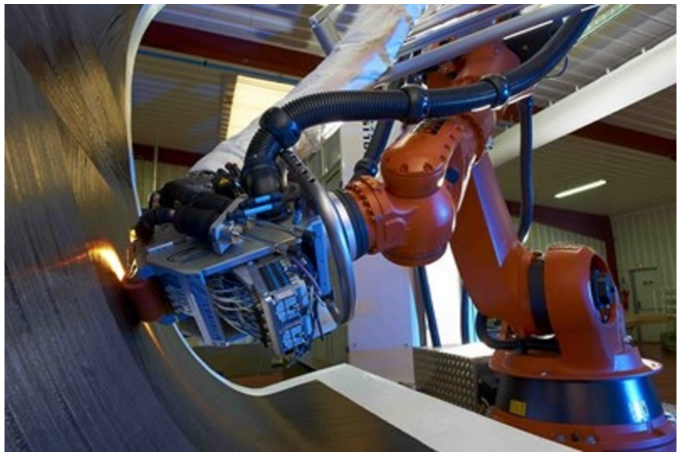

Figure 1. Automated Fiber Placement robotic system (Coriolis Composites).

Those structures are designed in standard CAD environments (such as CATIA CPD or NX/FiberSim), and then offline path programming is done on separate CAM software systems. The problem is that iterations between composites design definition and manufacturing path programming model, especially for doing conceptual trade-off studies, can't be efficiently done. Another issue is that design optimization tools for composites manufacturing are often complex and difficult to implement in the designer environment. The expected system should be very easy to use and to customize (i.e. Excel spreadsheet, with VB or Python scripting and automation). Moreover, such analysis systems are not able to reach a good compromise between performances, level of details and results accuracy (close to detailed offline NC programming tools). The expected computation time is about seconds or minutes, and several analysis runs should be done in parallel in a few hours only. Designers and stress engineers need robust tools and methodologies to help them testing large number of configurations (material width, maximum number of tows by course, maximum fiber deviation angle, etc) of representative laminates, i.e. large aerospace panels with double curvature and hundreds of plies. The target system should also be able to address various layup strategies, such as steered-fiber design. The design choices must also be validated by accurate FE structural analysis, taking local layup defects into account.

2. USER INTERFACE AND CORE ARCHITECTURE

The implemented solution is based on a Microsoft EXCEL spreadsheet, for defining all the user input parameters (material, process, strategy) and to launch the background batch processes in silent mode.

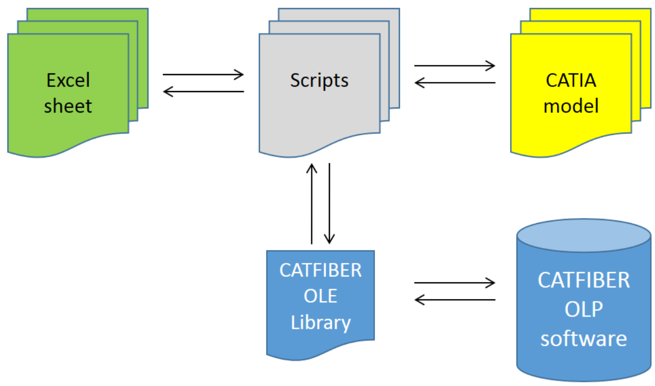

Figure 2. Core architecture of the implemented software solution.

This spreadsheet is also used to collect the output results data, and ease comparative studies between several runs. All the standard Excel graphical tools help to better visualize results (histograms, 2D and 3D plots, etc). The core system is based on CATIA V5 software and the CATFiber© standard solution for composites offline path programming. All the geometrical outputs (surfaces, wireframe geometry) are then contained in a standard CATPART document. It also allows to have a unique environment for CAD, CAE and CAM analysis. A specific OLE-based CATIA library was built, to drive the different additive manufacturing algorithms of CATFiber© and collect the results data. This generic library is directly used through a VBA or Python scripting, in order to easily customize the analysis, depending on target application (Figure 2).

2.1 Additive Manufacturability analysis

The manufacturability (or producibility) analysis of plies is based on the existing Automatic Ply Sectorization algorithm already implemented in the CATFIBER OLP software. The technique is based on an iterative algorithm and consists at doing path parallels on the layup surface, and then split the ply boundary in several pieces if the engineering or manufacturing requirements are no longer respected (fiber deviation, steering radius). A new course centerline path is then computed, optimized to minimize triangle of gaps and maximize the number of parallel strips. This step is repeated to fill the entire ply boundary (Figure 3). Here are the main input parameters for the algorithm:

- Geometrical layup surface
- Engineering rosette axis
- Ply contour
- Initial seed-point

- Material width
- Maximum number of tows by course
- Maximal angular deviation
- Minimum steering radius

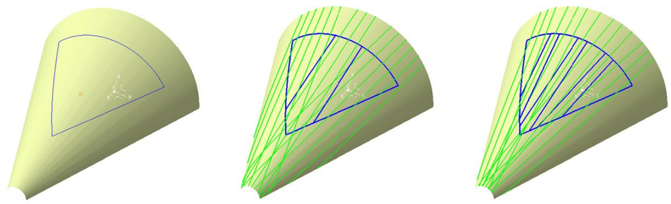

Figure 3. Left: initial conical surface with boundary, rosette and initial seed-point, Middle: splicing with 10 deg of deviation tolerance leading to 3 sectors, Right: splicing with 5 deg of deviation tolerance leading to 7 sectors.

The output result is a list of ply sectors, each made of a closed contour and one or several optimized guide curves. The system was also improved to integrate the following additional engineering and manufacturing requirements:

- Take results inside the engineering edge of ply only
- Avoid ply cuts and tow drop off located in a specified zone (example: stringer bonding area).
- Adjust the tape width (number of tows) if roller conformance is not compliant (excessive crush and/or fiber bridging defects)
- Minimize the lateral gap and overlap between adjacent tape courses, with automatic tow length adjustment (Figure 4)
- Automatic management of sequence of several plies in a same layer ("patch" areas)

It is also possible to define a (father) cutting pattern for plies with same orientation, and apply it to the children plies, for a better control of splicing curves location through the laminate thickness.

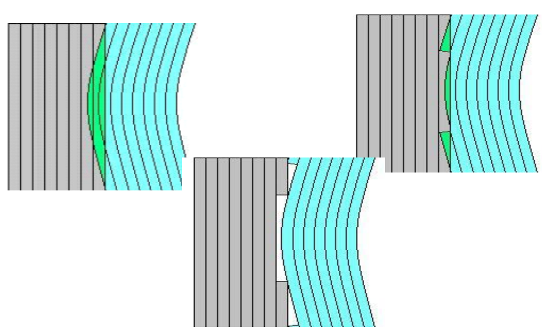

Figure 4. Gap & Lap management between tape courses (first image is initial design, and others are possible tow adjustments depending on engineering requirement.

2.2 Material covering analysis

In order to accurately compute and analyze the engineering requirements, the same covering algorithm as the one available in the full CATFIBER NC programming (OLP) software is used. Starting from the optimized course centerlines and ply cuts (sectors) computed using the automatic splicing algorithm, the ply boundary is filled with (tow) strip surfaces. This allows to capture all the process and material specificities, such as triangle of gaps, tow overlaps, minimum course length (MCL), minimum distance between tow cuts (Figure 5). It is important to know that parallel course strips can be time consuming, especially for very large layup areas. But the coverage algorithm is very fast thanks to a surface tessellation definition and highly parallelized computations.

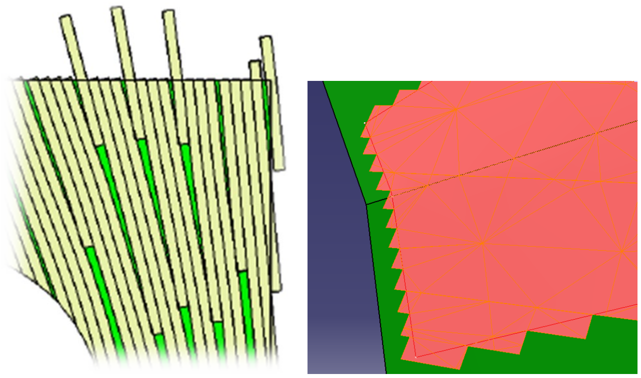

Figure 5. Tape coverage examples, with tow drops and minimum course length (left) and tessellation surface rendering (right).

2.3 Variable-stiffness design

The variable-stiffness design approach consists at defining curvilinear course path within layer, allowing optimized non-conventional (tow-steered) composites stacking (Figure 6). This is possible using fiber placement process.

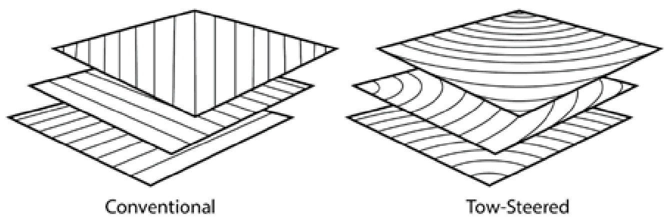

Figure 6. Conventional (left) and tow-steered (right) laminates.

The path programming and manufacturability analysis tools are based on advanced rosette transfer features. Those features enable user to easily customize the engineering rosette to better reflect the internal load path of the structures. The rosette transfer can integrate one or several guiding curves, extracted from the geometry (stringer or spar location curves for example). The transfer algorithm will then compute by interpolation the new updated fiber direction (Figure 7).

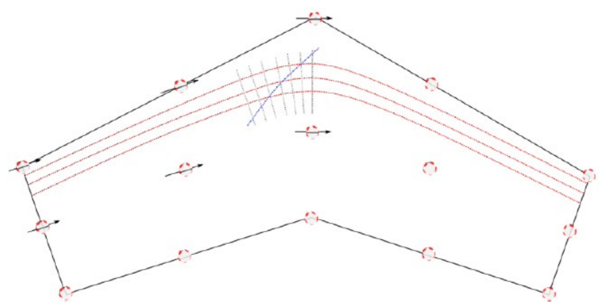

Figure 7. Example of rosette curves (in red), for horizontal stabilizer application [4].

This generic rosette operation feature is based on a grid structure made of individual and independent local rosettes [5]. Thus, it is possible to import input discrete fiber angle distribution, either from FEA principal stress vectors, or from an external genetic optimization algorithm. With such a rosette grid, the course coverage algorithm can generate smoothed interpolated tow-steering paths (Figures 8a & 8b).

We could also notice that ply boundaries can be computed by topological optimization solvers (Simulia Tosca, Altair Optistruct, or others), in order to define the optimized plies shape and stacking thickness (Figure 8c).

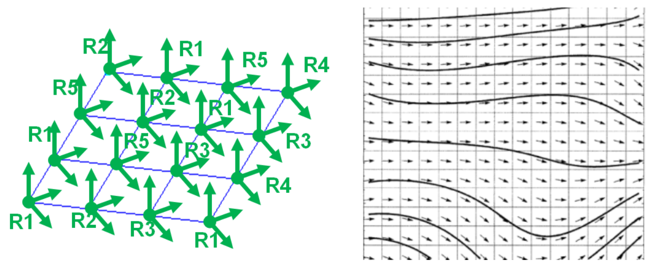

Figure 8a,b. Grid of rosettes (left), and example of smoothed courses built from load paths (right).

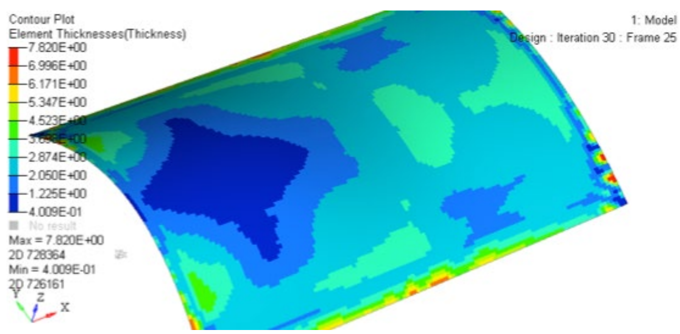

Figure 8c. Topological optimization of Aerospace panel for Automated layup (courtesy of Altair Engineering).

2.4 Manufacturing cost estimation

The design analysis system is also able to compute and output several cost indicators, to help designer to better sort the manufactural design proposals. Since the final manufacturing cost is too complex to determine (layup cycle time, non-productive time, tooling preparation, inspection, etc), and because the layup time strongly depends on target machine and material, we decided to define the following intermediate cost estimators:

- Number of tape courses with average centerline length (gives a rough overview of productivity)
- Number of ply cuts (indicates the number of tow drop-off within the layer)
- Number of tow drops (helpful for identifying the less productive courses / sequences, and the machine cutting knives maintenance cost)
- Buy-to-fly ratio (split of ply material area with engineering edge of ply)

There is also the possibility (as an option) to compute an estimation of the toolpath, using generic AFP & ATL machine layer settings. This allows to get an additional cost indicator for layup time, taking variable feed-rate into account (feed and cut speed limitation) and part curvature as well.

2.5 Structural Analysis validation

It is important to check the structural strength of the manufacturable and cost-optimized design proposals. That's why the software solution integrates an add-on to transfer all the manufacturing data (tape courses) for accurate Finite Element Analysis. This allows stress engineers to validate the layup strategies, especially if using the variable-stiffness approach, by taking true "as-manufacturing" fiber directions and effect of the presence of gaps and resin-rich areas. This is done by using a data mapping between the tape triangle mesh and the structural shell mesh, through a core sampling technique. This mapping is done using the Digimat Platform and concerns the transfer of the as-manufactured fiber orientation, the exact location of the gap and resin-rich area. Such information can be transferred automatically to the Finite Element Model used for sizing activities by Stress Engineers. In this case, Digimat also generated the composite layup command cards with the local as-manufactured fiber orientation over each ply. In addition, the effect of the gaps on the local stiffness can be handled in two ways, depending on the reconsolidation process. The first one considers that the gaps affect the local thickness while the second one considers that the gaps are filled by resin and affects the local fiber volume fraction of the composite. Using a micro-mechanical model of the material, this local variation of the fiber content is computed at each Gauss point of the FE Model. With such approach, verification of the global stiffness and strength of the component under working conditions become extremely efficient. Local post-processing can be performed as well with the verification of the local stress field discontinuities due to the presence of gaps within the plies (Figure 16).
This current validation simulation approach operates under important assumptions that need to be highlighted:

- There is no process analysis being conducted and therefore, the bonding between each tape layers are considered ideal (perfectly bonded).
- In case of thermoset prepregs being used as tape, no curing analysis of any kind is being conducted which again will lead to the assumption that the layers were fully cured and bonded together.
- The validation simulation includes fiber steering but does not take tape wrinkle into considerations.

It is also known that when working with FEA, the element size impacts in some ways the results of the analysis. When mechanical performances are evaluated, geometrical features will impact the part mechanical response locally and elements may generate geometrical artifact. In the current approach, two new important geometrical features must be captured: the tape strips and the gaps on top of all other part geometrical features. Consequently, a maximum element size must be defined and should be smaller than the gaps to represent. In the current approach, while the element size isn't fixed, it must be equal or smaller than the gaps. No element size sensitivity study has been done in this case and but is highly recommended when working on a new application.

3. APPLICATION ON AIRCRAFT WING SKIN

The software solution for design analysis was applied on a typical aircraft wing extrados skin (Figure 9). The CATIA composites stacking is made of 100 sequences (about 24 m2 of layup area), using the following nominal process and material settings (defined through the Excel spreadsheet):

- 8 tows of 38.1mm (1.5in) width

- Full tapes only (8 tows min)
- Fixed angle path strategy (with parallels)
- Minimum course length of 100mm
- No tow overlaps
- Nominal gap between courses of 0.5 mm
- Maximum gap allowed of 1.5 mm

The part integrates a rosette transfer made of guiding taken from the sub-structure (spars), allowing to better catch the load paths of the structure, leading to variable fiber directions in the layer. The wing skin surface is slightly double-curved, but the selected rosette transfer induced tow drops in the middle and on the edges of the ply (Figure 10). An advanced capture of those triangle of gaps (and resin) was done, to accurately check the impact on global and local structural strength (Figures 14 & 15).The full part analysis was launched in automatic using the batch framework in about 250 minutes (including all the output results data collection).

At the end of the process, all the output geometrical results (course centerline curves, ply boundary splices, ply layup surfaces) are stored in the CATIA part model and can be easily visualized and inspected (Figures 11a & 11b). It was also possible to launch a study on the influence of the maximum fiber deviation allowed on the total gap area for a given tow material width, and directly plot the results in the Excel file (Figure 12). Another example of design study is the influence of maximum deviation angle and minimum steering (turning) radius targets on manufacturing indicators. Some results on first full plies are given in Tables 1 & 2, with comparative results for the 0 deg ply. It appears that the input targets (especially the steering radius) can't be respected here since we ask for fixed angle paths and full tapes only. Those data are automatically consumed to the CATFIBER NC Programming OLP system (in the same CAD-CAM environment) for tool-path simulation with machine kinematics (Figure 13).

Configuration	Nb tows by course	Tow width (mm)	Max deviation Target (deg)	Min Steering radius Target (mm)
A	6	63.5	5	20
B	6	63.5	3	1000
C	6	63.5	3	20

Table 1. Design configurations (main input parameters).

Ply Angle	Config	Nb tapes	Nb ply cuts	Max angle dev (deg)	Min steering (mm)	Gap max (in)	Coverage (%)
90	A	49	0	5.3	1227.33	0.51	100.34
45	A	38	2	12.05	3690.37	38.1	101.48
135	A	47	3	9.01	1157.48	34.54	101.2
0	A	21	3	4.41	3025.14	18.03	101.6
0	B	21	16	2.48	2890.52	19.05	101.6
0	C	21	7	2.87	5097.78	19.05	101.6

Table 2. Analysis results for 4 full plies

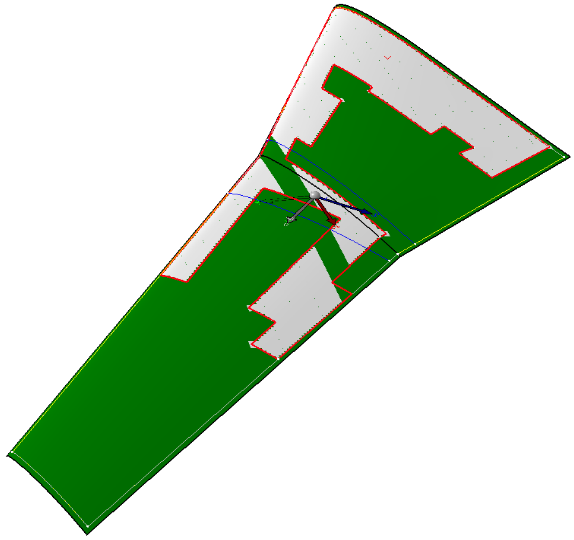

Figure 9. Wing skin CAD model with an example of ply boundary.

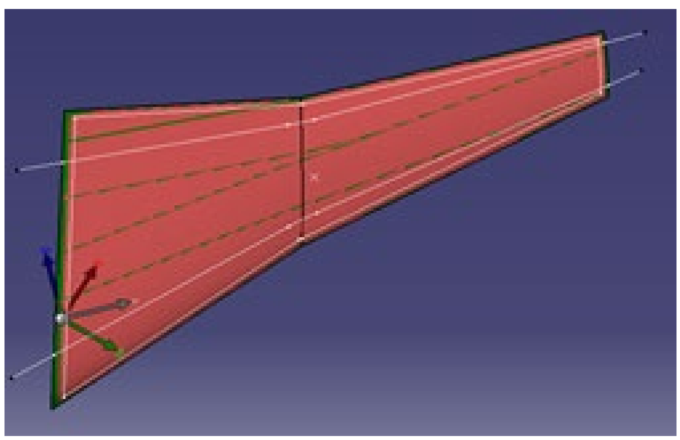

Figure 10. Wing skin with global Cartesian rosette (on the bottom left) and advanced rosette transfer with guiding curves (in white), and the resulting material coverage for a full 0 deg ply (with tow drops).

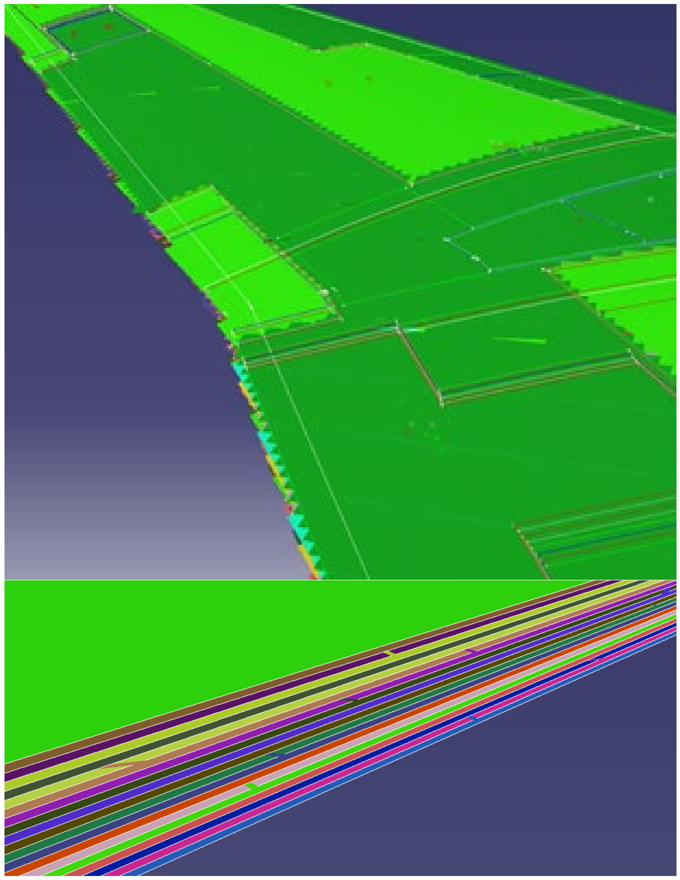

Figure 11a and 11b. Complete wing skin fiber-placed material build-up (one color by sequence).

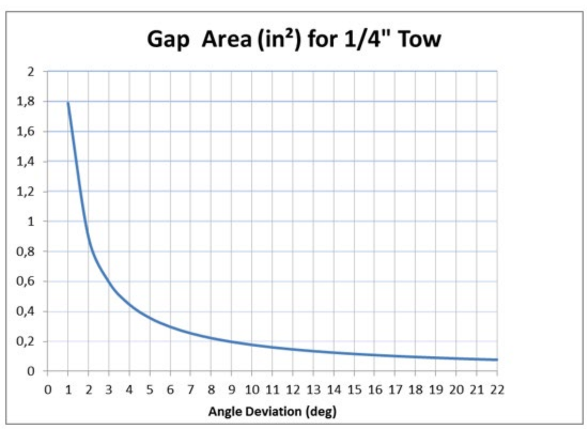

Figure 12. Example of analysis study on the influence of angle deviation on total gap area (Excel chart).

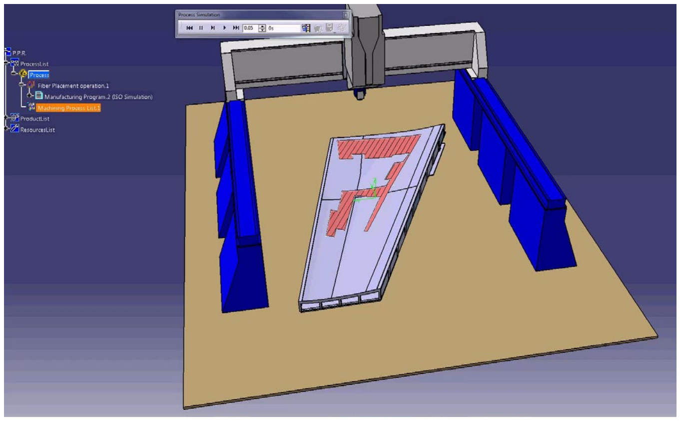

Figure 13. Layup simulation with a CNC Gantry AFP machine kinematics in CATFIBER OLP software.

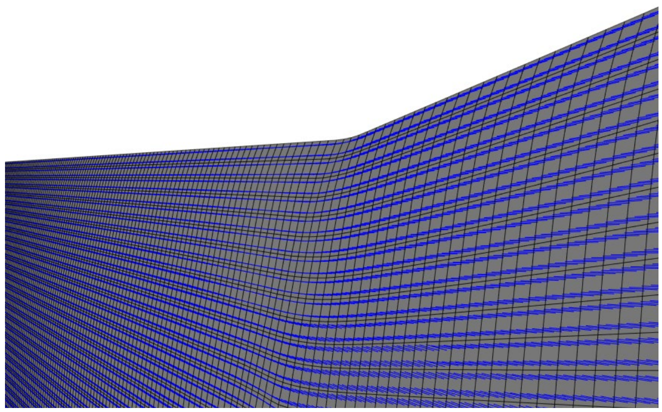

Figure 14. Fiber directions mapping on FE structural shell mesh (2D Mesh).

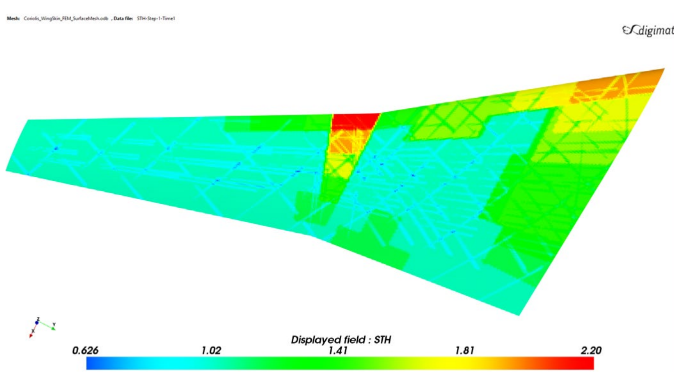

Figure 15. Thickness map analysis (quasi-isotropic laminate) with tow gaps.

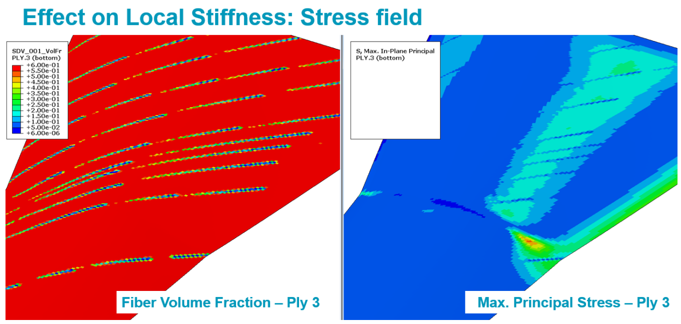

Figure 16. Local stress field per ply and effect of gaps computed.

4. CONCLUSION

Design optimization of composites structures made by additive manufacturing process is efficient and reliable by taking into account engineering requirements, material, machine limitations, and manufacturing cost. The offline programming system, traditionally used by NC programmers for the detailed layup program, should be packaged for designers and stress engineers, in order to eliminate useless iterations between CAD and CAM systems. Such a design system must be easy to use and flexible enough, with the possibility to check and compare various design proposals, including tow-steering capability and advanced structural strength validation. Such a solution, based on automation and scripting, was successfully implemented on a typical aero panel case with a large laminate size. Improvements will be done as a next step, and process simulations such as curing, layer bonding, crystallization can be added to help predict any defects during the manufacturing to better optimize the results and enhance the global performances. In addition to that, in-situ tape placement data could be added for digital twin generation. Finally, Other complex geometries will be also tested (wing spars, fuselage frames, engine fan blades).

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