ATL/AFP DESIGN TOOL FOR TOW PATH OPTIMIZATION

Joseph Wyatt and Hossein Haj-Hariri
University of Virginia.
Charlottesville, VA 22903
Mark Gruber, Accudyne Inc.
Newark, DE 19713

ABSTRACT

The automated tape-laying technique is used to construct lightweight, composite components by building up layers of fibrous tows on a mold at various orientations so as to meet specific thermal and structural needs. An algorithm for this process is developed and applied to industrial applications to calculate optimal tow paths, constrained to prevent overlap and to minimize tow gaps. This design tool calculates natural paths, optimizes initial conditions for the natural paths, forces tows off natural paths to close remaining gaps and quantifies various design metrics. These metrics include fiber strain, compression wrinkle caused by bi-normally bending trajectories, and folding wrinkle created by rapid substrate variations. Near-realtime solutions allow for design analysis of tow sizes and starting locations, and increase the quality and speed of part production. This tool provides a simple, automatic connection between a computational substrate model and the physical machine paths.

KEY WORDS: Automated Tape Laying/Tape Wrapping, Fiber Placement/Automated Tow Placement (ATP)

1. INTRODUCTION

Evolving industrial needs are creating a growing dependence on lightweight material solutions and rapid machining processes. Composite materials are a leading force in this industry, allowing extremely light weight parts that can be designed to suit specific thermal and structural needs. For example, the aircraft industry heavily depends on composites for lightweight, strong components. The Boeing 777 is seventeen percent composite materials by weight, while the new Boeing 787 is approximately fifty percent composite material (1). Such revolutionary steps demonstrate the evolution and future of airplane manufacturing and place an even greater demand on these materials. However, this growing dependence on high quality composite parts requires an equally matched process to satisfy demands in terms of production speeds and quality. Existing techniques for creating composite parts include molding, pressing, laminating and bonding; however, these processes can be somewhat limited, slow and expensive, often requiring significant manual intervention (2). For composite solutions to be competitive with metals, manufacturing costs must decrease, which will result from better upfront design and analysis, increased quality of material production, faster composite part production, and greater versatility of parts and applications.

One common solution to this problem is automated tape-laying (ATL) or automated fiber placement (AFP). This is a technique for layering composite filament tows across a mold to build the part to a desired thickness at prescribed tow orientations. This creates a composite part through an automated process with material properties given by the filament properties and orientations. While the general concept is fairly simple, difficulties arise when desired parts are geometrically complex. These complexities have lead to a large variety of solution techniques. For complicated shapes, tows are often laid by hand or entered manually into a computer controller; however, this is very time consuming and expensive. This paper discusses a new tool viz, a numerical technique that answers this challenge by effectively eliminating intermediate human involvement, speeding up the manufacturing process and providing prefabrication analysis capabilities (3).

A technique for calculating optimal tow paths for an arbitrary surface is thus developed and presented through physical applications. The program imports a surface model then calculates machine paths to construct the composite part from a pre-selected tow size, while considering user inputs such as orientation and tolerances. It takes a simple, geometric approach to this problem and addresses design issues by quantifying strain and wrinkle parameters at the outer edge of each tow allowing for the optimization between geometric definitions and material restrictions. An example of tow coverage over a simple sinusoidal surface is shown in figure one, including the centerline and edge trajectories, patches (tow graphics) and the strains and wrinkles of the tow edges. Due to the algorithm's simplicity in not requiring material or dynamic constraints, the approach allows for near real-time solutions with little demand on time or computing power.

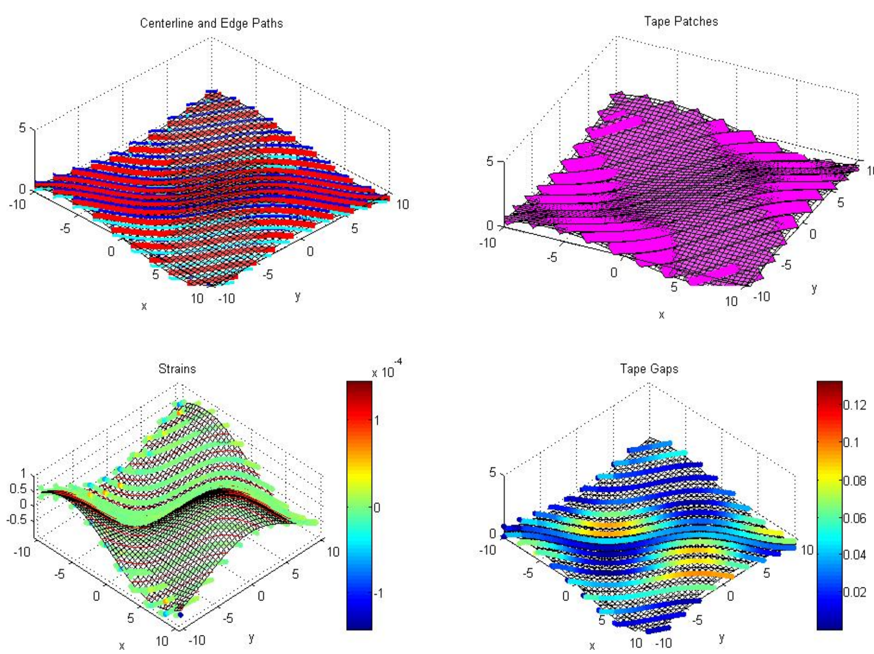

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Figure 1. Tow trajectories, patches, strains and gaps for ATL model of a sinusoidal surface.

2. ATL DESIGN ALGORITHM

2.1 Mathematical Description

The algorithm covers analytically defined surface functions, discretely defined surfaces or CAD surface geometries, with geometric tows of a given width, while minimizing gap distances between the tows and preventing overlap. A single tow is defined by sequential arrays containing the x,y,z coordinates for the tow centerline, right and left edges. The wrapping follows natural paths, as defined by mathematical geodesics, for the centerline of the tow. A geodesic is the shortest path between two points along a three-dimensional surface in Cartesian space (4). Additionally, the local orientation at each vertex may be established using a local orthonormal basis consisting of the normal, **n**, tangential, **t**, and binormal, **b**, vectors which describe both the curve direction and orientation.

This approach calculates each tape centerline along a surface. The edges are simply calculated as half a tape width from the centerline along the local binormal. The algorithm computes the gap distances as the relative distances between edges along binormal projection.

2.2 Path Optimization

The natural path optimization varies the two initial conditions, the location **x** along the part's edge and the starting angle θ to minimize the total gap between tows through a simple search-based optimization technique.

To optimize the starting location, a basic line search algorithm is implemented to minimize the minimum gap distance, as constrained by a spacing tolerance. This ensures that two tows are coincident within the spacing tolerance at a single point for a constant initial angle. Let α represent the position along the closed curve forming the boundary edge of the part, the optimization objective is to minimize $f(\alpha)$, where f is the minimum gap distance for the natural path at α_i. This is subject to the constraint $g(\alpha)$, which gives a user-defined interval along the edge to lay tows, λ which indicates the direction of line search, the initial stepping size $d\alpha$ and the minimum stepping tolerance $\alpha_{tolerance}$ that indicates convergence.

1. Initial $\alpha_0 \rightarrow f(\alpha_0)$ & $\lambda = 1$
2. $\alpha_i = \alpha_{i-1} + \lambda\,(d\alpha)$
3. Evaluate $f(\alpha_i)$
4. If $f(\alpha_i) > f(\alpha_{i-1}) \rightarrow \lambda = -\lambda$ & $d\alpha = d\alpha/2$
5. if $d\alpha < \alpha_{tolerance} \rightarrow$ END
6. Loop 2-5

Additionally, the angle optimization implements the same line search technique however it minimizes the *average* gap distance between two tows as opposed to the *smallest* gap distance. To apply the algorithm, let α be the initial tow angle, $f(\alpha)$ be the mean gap at α_i with respective stepping angle $d\alpha$ and tolerance $\alpha_{tolerance}$. For simultaneous optimization, the **x** search is nested within the angle search so that the smallest gap is minimized for each incremental angle step. This ensures that the overall total gap is minimized between tows upon convergence of the angle search.

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Following natural geodesic paths along substrates with large curvatures can produce large gaps, even after optimizing the initial starting location and angle. To solve this problem, the forced path algorithm shifts a tape strip off of its natural geodesic path and closes it, therefore eliminating gap distances; however this can introduce significantly large strains. The ability to predict these deformations gives the user versatile design capabilities and the choice to impose small strains over intolerable gaps.

The general forcing algorithm shifts each centerline along a tape binormal, relays the tape on the surface and reorients it locally with the surface normals. This is an iterative process that can reduce the average gap distances to within any given tolerance. Also, because local vertex values are used to generate the shift, the tow paths do not need recalculating and therefore the forcing algorithm presents little time demand.

Finally, after the spacing optimization is complete, edges are analyzed for deformations and wrinkles and then the centerline coordinates and normal vector at each coordinate are exported. The exported data serves as inputs to define the machine paths for an ATL manufacturing system.

2.3 Design Metrics

Following the calculations of the previous section, the algorithm quantifies the strain at the outer fiber edges of the tow, the tendency for the tow to wrinkle, as well as local gap widths between neighboring tows. There are two distinct classifications used to quantify the effects of wrinkling. The first is values of negative strain to measure wrinkle due to severe tape deformation, or strain wrinkle. The second type, fold wrinkle, captures the effect of severe surface curvature in which tow lengths do not coincide with their projected lengths on the surface. For example, a tow oscillating about a surface would generate finite wrinkles. To quantify this effect, the tape heights of the edges above/below the substrate are calculated. Then the derivative of these heights gives the likelihood of wrinkling. Once scaled to known experimental values for tow failure, these metrics allow prefabrication analysis, the determination of optimal tape widths and the prediction of problem areas.

III. VALIDATION AND DESIGN METRIC COORELATION

Numerical simulations and experimental tests are used to validate the results and to connect the design metrics to failure predictions in continuous, unidirectional fibers. The relevant modes of failure are the transverse buckling that relates to the in-plane strain wrinkling and the out of plane fold wrinkle. These are quantified experimentally and correlated to the computational results. This permits metric scales that may predict failures during the tape laying process.

First, a set of simple numerical simulations serves as a physical check to validate the method. The ATL design tool was checked against a flat surface with zero curvature with $\pm$45, 0 and 90 degree tows giving no strains, no wrinkles, and gap widths within a specified tolerance of 0.05mm.

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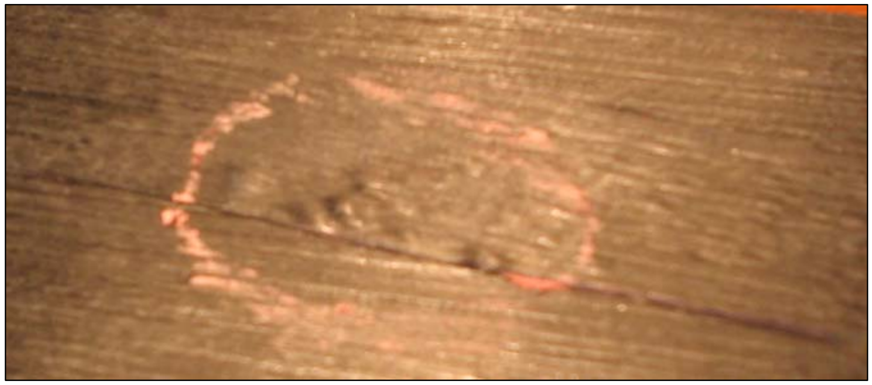

Figure 2. Macro buckling of a 13mm tow aligned along a radial path of 900 mm.

The first experiment manually laid graphite/epoxy, thermoset tows with a 13mm width along curved trajectories on a flat surface to predict the onset of macro buckling. Beginning at an infinite radius, the trajectory curvature was increased until an unacceptable level of buckling was detected. An example of unacceptable buckling is shown in figure two. Any path with a non-zero in plane curvature will create deformation; however, a degree of micro buckling is permitted until the point at which out-of-plane deformation occurs. This may cause ply defects and increases in stress concentrations that may lead to other types of failures.

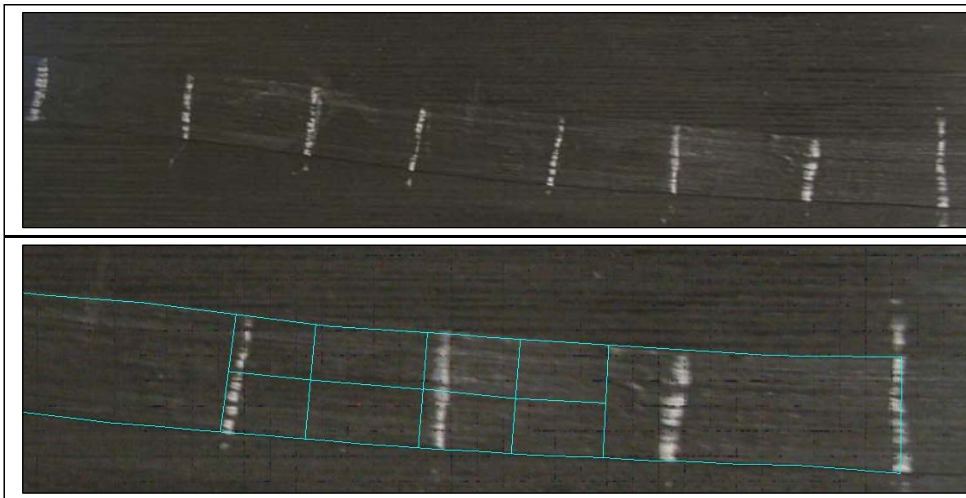

Figure 3. Image processing used to calculate strains of tows along curved trajectory.

Through image processing of the strained tows, as shown in figure three, the changes of edge lengths relative to centerline lengths were determined. A minimum radial trajectory of approximately 1m, corresponding to 0.65% strain, is the limit in which macro buckling occurred. Decreasing the radius beyond this resulted in intolerable deformations. This bounding value may now scale the results in numerical solutions to identify problem areas.

A second experiment was used to identify fold wrinkle over non-planar surfaces. Computational results from the ATL design tool of laying a 13mm tow over a hemisphere was compared against experimental results. An example of a computational analysis using the ATL tool is shown in the top of figure four, while the corresponding experiment in shown in the

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bottom of figure four. Expected results show that as the surface curvature decreases, the wrinkle effect at the edges worsen and the experiment provides a bounding tolerance for this effect.

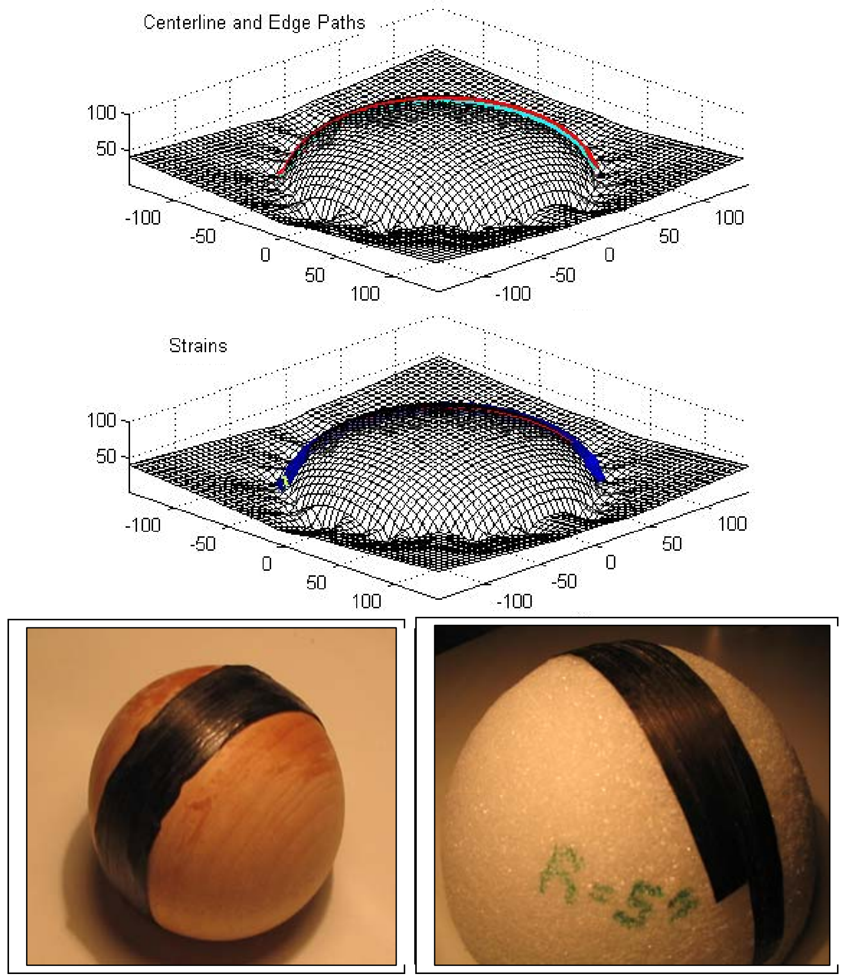

Figure 4. Computational (top) and experimental wrapping (bottom) of tows around spherical surfaces with constant curvature.

Experimental results showed that a significant wrinkling effect begins around a minimum radius of 1.5 corresponding to a computational fold wrinkle value, as defined above, of 4.8%. The wrinkle values for a range of radii are given in figure five and a bounding value of 4.75% is chosen for the analysis tolerance. The region of unacceptable wrinkle, outside this bounding tolerance, is also indicated in the figure.

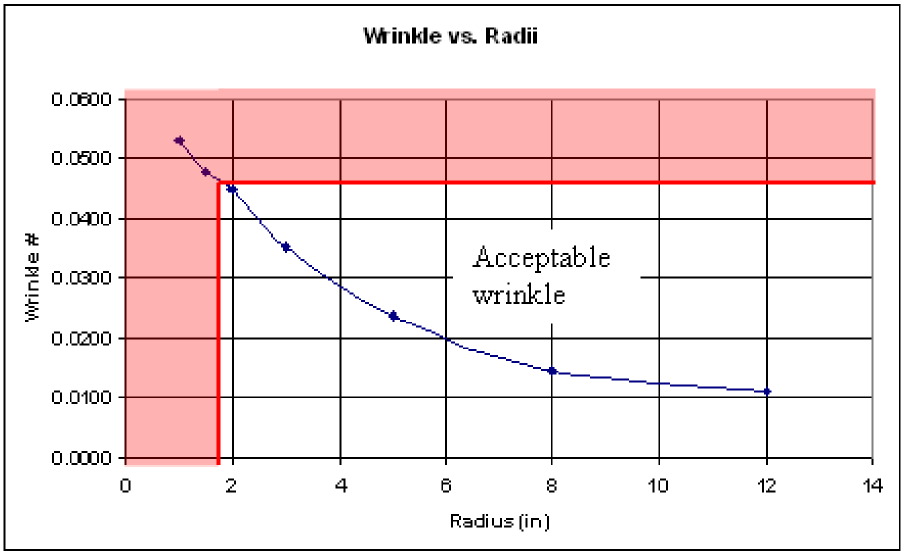

Figure 5. Computational wrinkle values corresponding to a give surface radius. Problem wrinkles occur at a wrinkle value greater than 0.0475.

IV. APPLICATIONS

4.1 Analytical Hump

Prior to proceeding to actual test geometries, analytical geometries provide simple test cases allowing for the verification of methods and length scales. It provided a foundation for comparing the solution techniques and examining the benefits of the optimization techniques providing more confidence on the more difficult geometries.

First, consider a simple hump-shaped geometry given by the two-dimensional tension product of two hyperbolic secants so that we may observe the required strain values to eliminate gaps for forty-five degree, 75mm bands. The surface is given by

$$z = h*\text{sech}(x*r).*\text{sech}(y*r)$$

where the height of the hump is specified by h and the length scale is given by 1/r. Next, consider tape wrapping given by a strictly natural path with constant initial orientation, shown in figure six, a natural path with angle varying optimization, shown in figure seven, and finally a forced path with angle optimization, shown in figure eight.

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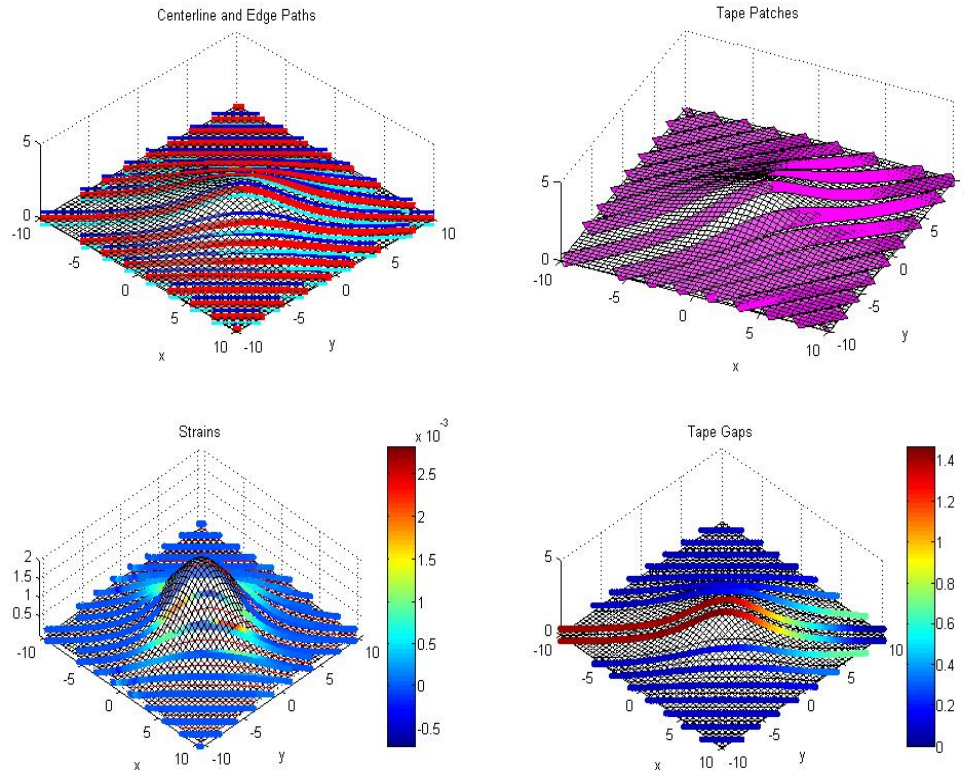

Figure 6. Natural paths over single hump geometry with constant initial angle of 45deg.

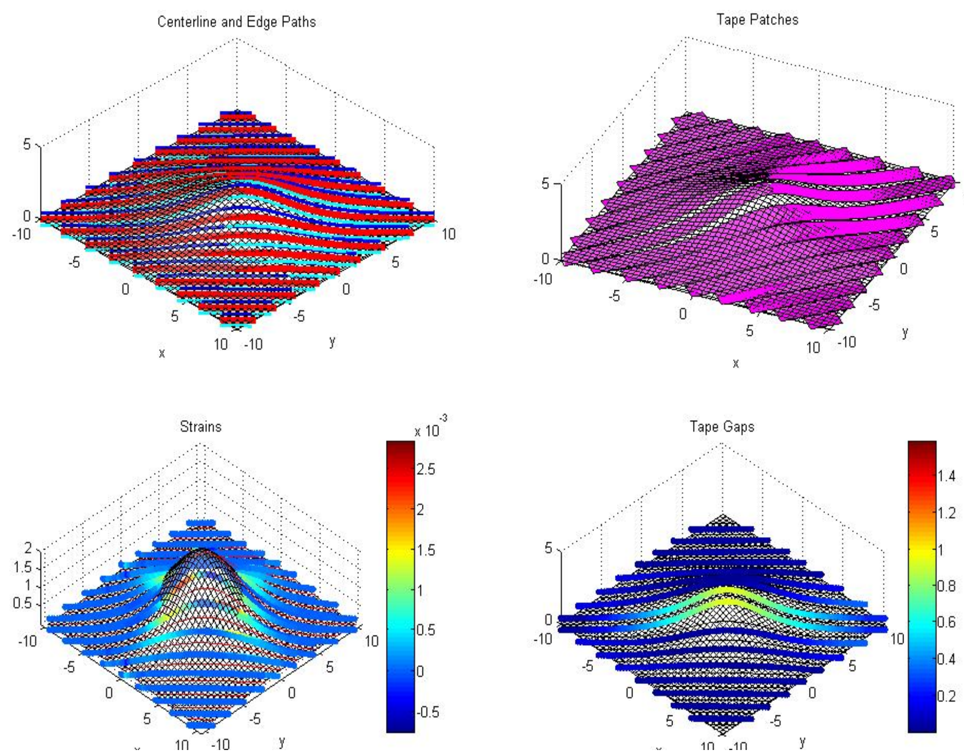

Figure 7. Natural paths with optimized initial angles

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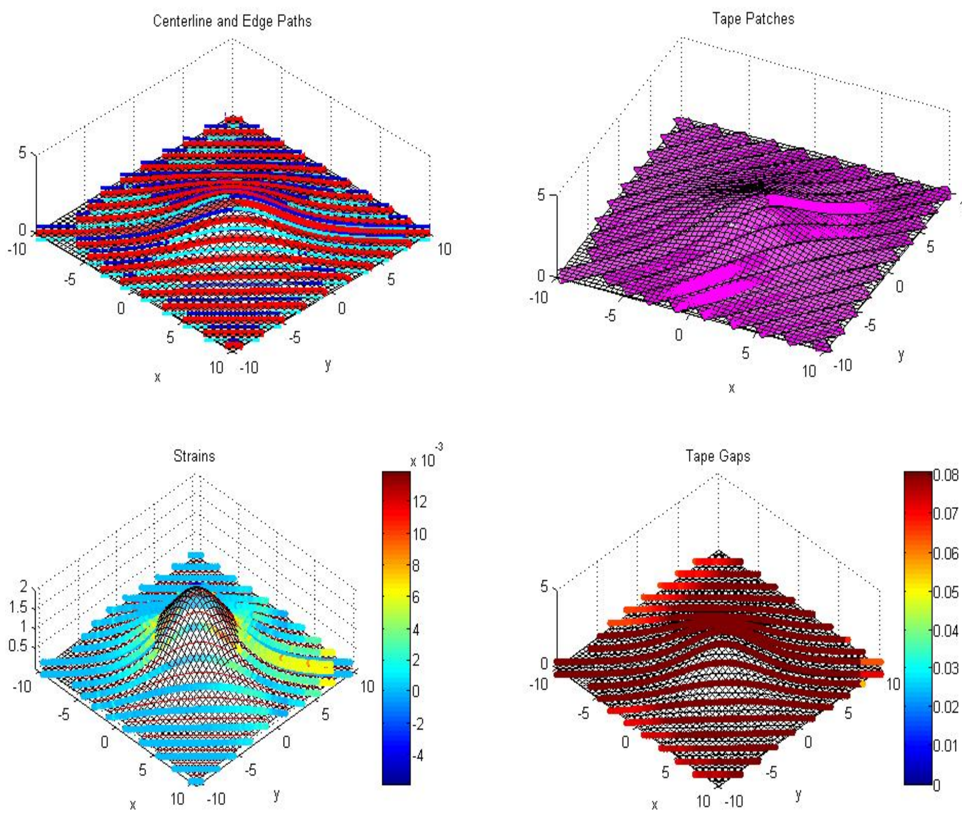

Figure 8. Single iteration, forced paths over single hump geometry.

Each figure contains four plots: centerline, right and left edge paths (upper left); tow graphic (upper right); strains (lower left); and the gaps or separations between adjacent tows (lower right). Notice the progression of closing gaps and the associated effects on strains between figures six through eight. The average gap from natural paths with a constant initial angle is approximately 0.9mm. This value reduces to 0.25mm when the initial angles are optimized to a range of 45±5 degrees and finally, the gap separation becomes 0.08 after implementing a single iteration, forced-path. Increasing to three iterations of forcing then reduces the average tow gaps over the substrate to 0.001mm. However, in the 70% decrease in gaps from the optimized natural path to the single-iteration forced path, the average strains increases an order of ten from 0.0002 to 0.002 over the substrate. The significant factor in this increase is focuses in areas of maximum curvature on the rear side of the hump. This is due to both the associative stretching of the edges to accommodate the severe curvature and to the significant shifts over the areas with the largest gaps, requiring significant forcing distances. However, regardless of the strain effects, a maximum strain of 0.2% presents no risk of failure and is therefore acceptable, as given by the experimental tolerances.

4.2 Pad-up Geometries

A pad-up is a common feature in aircraft panels used specifically with joints for part attachments and for areas of concentrated loading. Impregnated ply layers are built up to increase local thickness and strength without significantly increasing the weight of the total part. After the desired layering is achieved an additional layer or layers are added to smooth the thickened area and create the final desired aerodynamic shape. Like all layers, this must minimize gaps, wrinkles and strains; however, the jump discontinuities of the substrate slopes can present significant challenges. Additionally, significant wrinkling occurs as the width of the tape approaches the length of the pad-up section. These factors are also dependent on the pad-up ratio of transverse units to rise units, or measure of the ramp's slope inverse. Therefore it is important to accurately predict to relationship between the pad-up ratio and the strains and wrinkles for a given tape width.

Consider the standard 10 to 1 pad-up in the center of a cubic meter panel shown in figure nine, covered with 75mm, 45 degree tows. The pad-up section is a 10in square located in the center of the substrate.

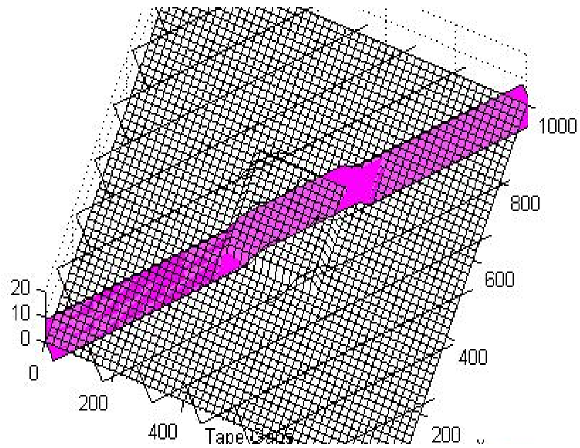

Figure 9. Single iteration, forced paths over 10 to 1 pad-up geometry.

After applying a single iteration, forced path, the gaps are all within a tenth of a millimeter, well under 0.5% strain and with 3% wrinkle.

This example demonstrates how the modeled tow widths are limited only by excessive wrinkling while strains present no difficulties. Due to wrinkle, the tow widths are limited to approximately one-third the pad-up width. These results indicate that a larger tape width is permitted to manufacture the part.

4.3 Aircraft Cowling

Next, consider a sample ply from an aircraft cowling to demonstrate the opposite issue in which strain exceeds failure limits, while the wrinkles are within acceptable limits. The ply requires forty-five degree tows with a bandwidth of 75mm to ensure rapid lay rate. Figure ten shows the natural path coverage resulting in large gaps on the rear side of the cowling. After applying the forced path algorithm, all gaps reduce within the specified tolerance of 0.75mm. Again, there was a significant increase in strain between the natural and forced path solutions, which unfortunately, causes strains to fall outside the acceptable range. This suggests reducing the tow width to reduce strains into an acceptable level.

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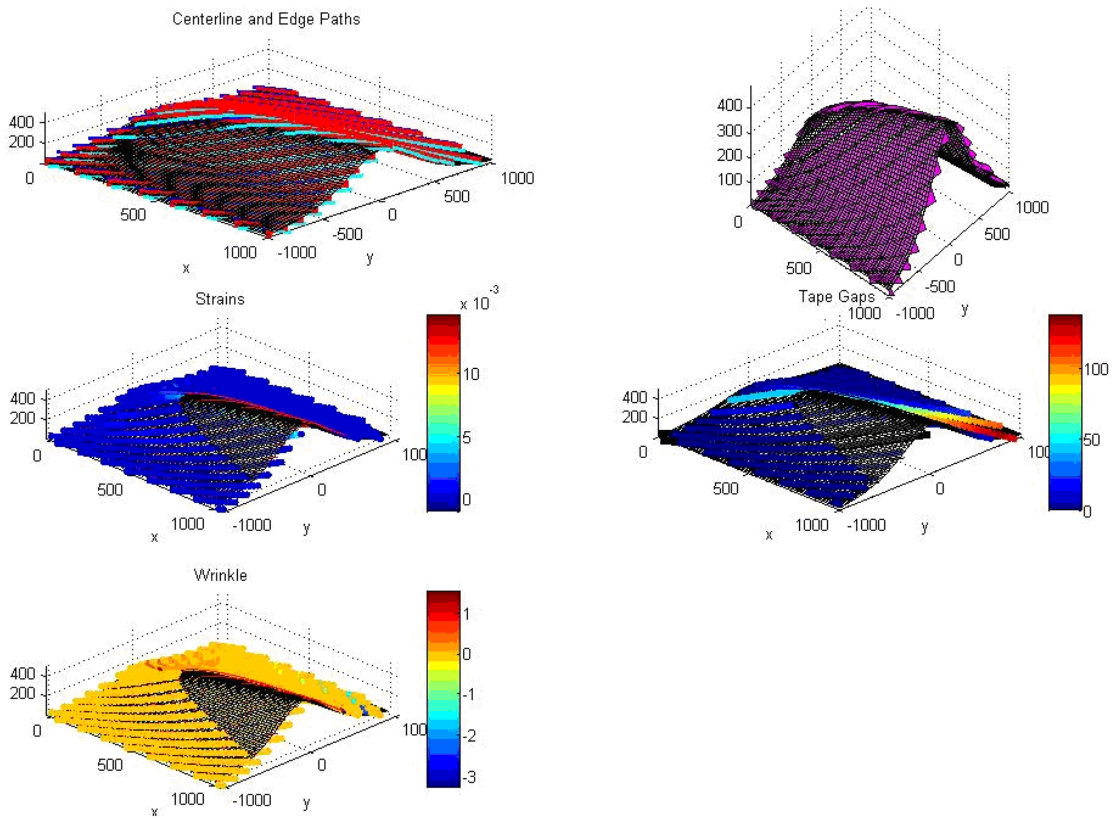

Figure 10. ATL simulated covering of aircraft cowling.

The large range in curvature across the part creates significant tow separation between the natural paths. This requires significant forced shifting from the natural geodesics, which generates the high strains. On the other hand, the local radial curvature of the part is insignificant relative to the tow width and therefore wrinkles are minimal and fall within acceptable limits. Again, the results recommend decreasing the tape width so that the maximum strains fall within the determined limits.

4.4 Fan Blade

Finally, consider two plies from a standard engine fan blade, one ply requiring ninety degree and one requiring forty-five degree tows, as seen in the top and bottom of figure eleven respectively. The challenging blade shape has both large curvature variations and adjacent areas of concavity and convexity at the raised hump near the root of the blade. These present manufacture difficulties however are required to achieve the designed aerodynamic performance. 13mm tows are desirable for rapid tow lay-up speeds and the ATL design tool is used to verify this specification.

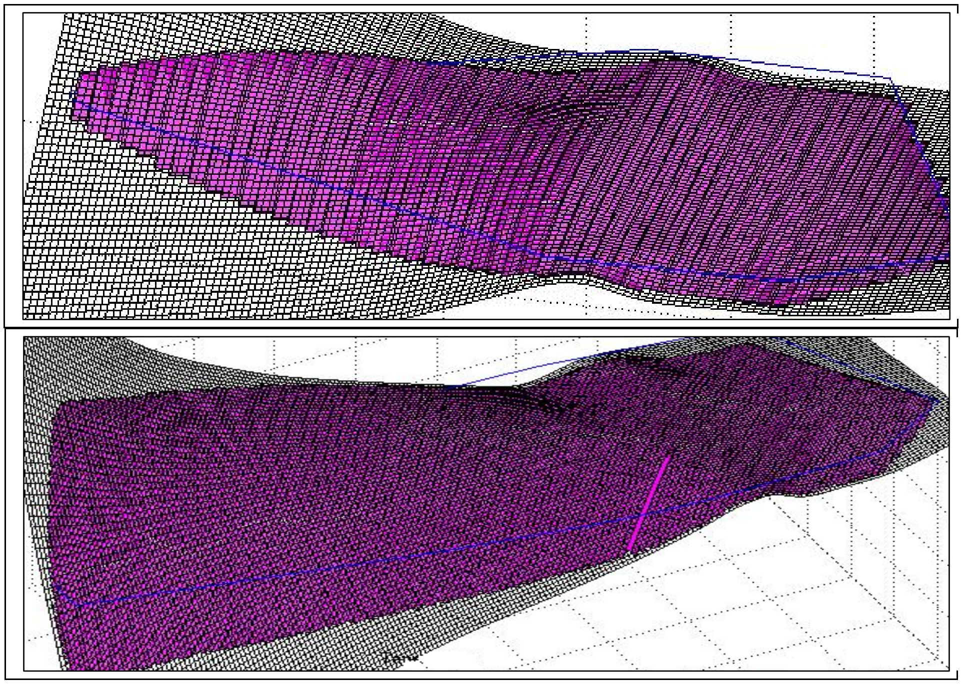

Figure 11. Top: Ninety degree rotor blade ply with 13mm tow. Lower: Forty five degree ply with 7mm tows.

Both ply orientations are analyzed with 13mm tows. With complete part coverage, the ninety degree ply yields an average strain of 0.41%, an average wrinkle of 0.006, and a tow lengths range between 55mm and 430mm. These all falls within acceptable metric limits as determined through experimentation and the calculated centerlines may then be loaded into the controller for part construction. The forty-five degree ply yields an average strain of 0.63%, an average wrinkle of 0.0008, and a tow lengths range between 50mm and 585mm. Due to the compounding curvatures near the blade tip, all tows with a length greater than 0.5m suffered strains outside the allowable tolerance.

After rerunning the forty-five ply with 7mm tows, the average strain reduced to 0.45% and an insignificant change in the wrinkle values. Reducing the tape width by a factor of two has reduced the maximum strain by 29% into the acceptable range for part construction.

V. CONCLUSIONS

This ATL design tool is a method for optimizing tow paths over a general substrate mold for any tow orientation or width. It provides an important link between the computational surface model for the ply and for the control paths for the machine head. More importantly it serves as an analysis tool allowing failure predictions, tow width selections, and tow length estimates that correlate to lay-down rates. This tool significantly reduces the time requirement in both the preproduction phase by reducing required experimental testing and in the production phase by increasing lay-down rates and effectively eliminating the need for human intervention.

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