INVESTIGATION ON FIBER PREFORMING WITH DRAPING SIMULATION

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Abstract

Automated laminate preforming for continuous fiber composites enables the rapid production of parts for a variety of fabrication technologies. During preforming, fabric is cut, stacked, and draped over a mold to produce a semi-finished, near-net-shape part. The preform can be made from dry or impregnated fabrics. Using a draping simulation to predict wrinkle formation and fabric shear behavior allows the preform operation to be tailored to reduce wrinkles and determine the proper blank geometry, thus reducing waste. The preform process potential is analyzed for automotive applications using a generic preform mold shape. An associated draping simulation is performed using AniForm to determine the effects of fiber orientation, layup, and geometry. With this knowledge, automated preforms can be produced with less waste and better control over the final part. In this paper, the results of the draping simulations are examined to determine the general trends for preforming. These trends are compared with double-dome geometry experimental trials to highlight the simulation effectiveness. Also discussed are the critical material parameters required for the simulation accuracy and several techniques to simplify the simulation setup.

Background

The use of composite materials in structural automotive applications requires suitable high volume composite processing techniques. One major technology used to achieve structural parts is high-pressure resin transfer molding (HP-RTM) due to the use of continuous fibers in a stitched or woven fabric. However, a secondary process is required to fabricate the dry fiber preforms at least as fast as the HP-RTM cycle time, which is presently nearing the 60 second regime.

The preform process starts with dry fabric rolls from which blanks are cut and stacked. A schematic of the preforming process equipment is shown in Figure 1. To help the preform retain its shape, the blanks typically have a small amount of binder added, either at the point of manufacture or just prior to being stacked. Blanks could also be cut from prepreg material. The blank stack is heated before being formed into shape in a preform tool. Preform tools can either be a net-shape, progressive forming tool or a blank-holder tool with which subsequent trimming of the parts is necessary. In either case, knowing the proper blank shape is required to minimize cutting and/or trimming waste.
During the forming, relative fiber motion, fiber-fiber and fiber-tool interaction, and fiber bending lead to fabric deformation and wrinkling. Thus it is desirable to be able to predict the fabric drape behavior both to eliminate wrinkling and to accurately predict the initial blank shape. Secondary goals include the prediction of the peak fiber stresses during forming, post-drape fiber orientation and residual stress.

Only recently have studies been initiated to understand the characterization methods of impregnated fabrics [1-2]. Thus there is a deficit of information relating to the material characterization and also the application of those properties to the in-mold drape-ability of engineering textiles.

In this work, a new software, Aniform, is employed to determine the wrinkling behavior and blank shape prediction of a simple part geometry. Several setup studies are conducted to determine the simulation performance as it relates to mass, stiffness, and thickness scaling. Application studies compare the effects of fiber layup on the wrinkling prediction and the blank prediction.

Other software could be used to conduct the same simulations, each with their individual caveats and tradeoffs. LS-DYNA R7.0, for example, does not have any defined material models with similar behavior to an impregnated fabric subject to large deformation, resulting in user defined models being required [2]. This places the onus for implementation of the material behavior on the part designer. Further, multi-ply laminates require increased effort to input all the individual ply data and the ply interactions or require effort to determine a suitable single-ply representation.

**Simulation Setup**

The software Aniform is used to run the draping simulations [3]. Aniform uses an implicit solver designed to account for the draping physical phenomena: ply-ply friction (for laminates), tool-ply friction, fabric bending, and fabric shear, which is not typically possible when using kinematic formulations. Aniform supports multiple material models and contact implementations to account for a variety of linear and non-linear material response.
To set up the simulation model some initial preparation steps were necessary. The geometry of the mold and blank was modelled as surface bodies using a CAD-Software, in this case Solidworks. The parts can then be imported into Aniform as “.msh” mesh files. These mesh files were generated using the software GiD [4]. The complete software tools and modeling sequence is presented in Figure 2.

![Software tool sequence and their purpose as used in this study.](image)

The upper and lower tool surfaces are modeled as rigid bodies. As the tool model only needs to capture the basic geometry, the mesh does not require high order convolution. Aniform handles the fiber-tool interaction as a distinct set of interfacial properties and primarily uses the tool mesh for contact and penetration checks. In large flat areas fewer elements are needed whereas smaller elements should be chosen for curved regions. For the present study, the demonstrator double dome geometry is used since it contains the requisite curvature and features and is sufficient complexity to relate to actual production components. Figure 3 highlights the curvature-based mesh for the upper double dome mold surface.

![Mesh of the upper double dome mold.](image)

The blank mesh for the preform, however, must be created in a unique way. For properly
modeled behavior of the non-isotropic material, it is necessary to align the element edges with the fiber orientations [5]. Therefore the blank mesh is first created with GiD and then transformed with a Matlab-Script, provided by Aniform support, as in Figure 4. There are a number of available options to create the appropriate mesh for unidirectional, biaxial, and triaxial or non-crimped fabrics. A single simulation can utilize multiple different meshes, each representing a type of fabric or fabric orientation. The fiber directions and properties are applied to the corrected mesh.

![Figure 4 Adjusted blank mesh for off-axis fiber orientation from a Matlab transformation script](image)

The upper and lower tool each contained 12,000 elements while the blank mesh used 35,600 elements. In the simulation, one tool surface was held stationary while the other closed at a speed of 10 mm/s over a distance of 100 mm to yield a simulated time of 10s. The individual elements can be implemented in a number of ways, the most common being 4-node tetrahedra with linear shape functions or the default 3-node shells.

To demonstrate the fiber orientation prediction during a simulation, a single, unidirectional ply was virtually preformed with the double dome geometry. The preform mesh pictured in Figure 4 was selected and the fiber orientation was set to -35°. The three plots presented in Figure 5 show the beginning, middle, and end of the preform simulation with the tool geometry hidden. The colour map on the plots indicate the Green-Lagrange strain which ranges from -0.5 (blue) to 0.5 (red) with green representing a null strain condition. The fiber orientations during the simulation are shown in the overlay vector map.
a) Figure 5 Three simulation steps of single, unidirectional ply; fibers initially oriented at -35°

The material properties used for these simulations were obtained from Sebastiaan Haanappel’s publication “Forming of Fibre Reinforced Thermoplastics”, reproduced in Figure 6.
The data for the material model and contact model is based on a nonspecific unidirectional carbon fiber reinforced thermoplastic. The Discrete Kirchhoff Triangle (DKT) elements model the carbon fiber behavior while the membrane elements model the polymer behavior. The decoupled approach is taken to model the fabric properties as the combination of the DKT and membrane elements. The fabric interaction properties come from the associated contact elements.

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<td></td>
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<td>Penalty model</td>
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*Figure 6 Material properties from the work of Sebastiaan Haanappel [6]*

**Simulation Development**

The performance of the simulation largely depends on the chosen parameters for density and fiber stiffness [7]. Increasing the density and reducing the fiber stiffness both lead to shorter runtimes, but decrease the simulation accuracy. This sort of mass scaling leads to differences in the progression of the deforming blank and final formed state. If these differences are acceptable depends on the required accuracy of the simulation. The required accuracy will be application dependent: fiber stress can be predicted in a mass and stiffness scaled simulation, while accurate deformed geometry is best predicted without scaling. Different wrinkle occurrences of the final state can be seen in Figure 7 where the highlighted wrinkling areas are similar. The z-displacement scale is set such that green represents the mid-plane of the sheet with blue and red being the maximum wrinkle heights positive and negative to the plane respectively. The double dome shape is seen as a red blob since it is well beyond the minimum wrinkle depth.
From Figure 7 in the mass-scaled version, there are many small wrinkles as opposed to the non-mass-scaled version which has fewer, but more pronounced wrinkles over a larger wrinkling area. The runtime of the mass-scaled version is reduced by ~30% over the datum simulation.

Mass-scaling refers to the density of the in-plane material. The density of the bending model is set to $2 \times 10^{-4}$ tons/mm$^3$, as opposed to a more realistic value of $2 \times 10^{-9}$ tons/mm$^3$. As Aniform is using an implicit solver this “mass-scaling” effect takes on a different meaning than in an explicit code. Here the function is based on reaching convergence of the damping effect due to large inertial forces. By selecting an arbitrarily high density as a starting point for a simulation, inertial effects can be initially ignored. A similar scaling effect can be achieved by using an unrealistically low fiber stiffness; Aniform recommends a Young’s modulus of 1000 MPa. Together, the mass and stiffness scaling must be balanced to achieve a realistic simulation with low run time. As long as the fiber strain is smaller than 3% there is no need to increase the stiffness to realistic values since the element deformation will closely match reality.

For example, increasing the fiber modulus from 1,000 to 5,000 MPa reduces the highest strain in the model from 12% to 3%. This causes a visible increase on the out-of-plane deformation and wrinkling though the time to run the simulation also increased by over 100%. Table 1 provides an example of several simulation times for different material densities and fiber stiffness. For reference, the simulations were conducted on a quad core Intel Xeon E5 with 32 Gb memory capable of 160 GFLOPS.

Table 1 Approximate simulation times with mass and density scaling for a single, UD ply

<table>
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<th>Density</th>
<th>Stiffness</th>
<th>1000 MPa</th>
<th>5000 MPa</th>
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<td>$2 \times 10^{-5}$ t/mm$^3$</td>
<td>7 hr.</td>
<td>15 hr.</td>
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<tr>
<td>$2 \times 10^{-7}$ t/mm$^3$</td>
<td>12 hr.</td>
<td>26 hr.</td>
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The combination of mass and stiffness scaling can lead to unintended inertial effects which do not mirror reality as illustrated in Figure 8. Over the simulation time of 10 seconds, the peak fiber strain increases until the mold is fully closed at the 10 second mark. If the simulation was
stopped at the point the mold was closed, the fiber strain would be erroneously high. Adding a 2 second ‘relaxation time’ shows the inertial effects of the scaled simulations as the fiber strain decreases over time. Even though this effect is minimized as the fiber stiffness increases, this negatively impacts the required run time.

Also, it should be noted that scaling the fiber modulus does not interrupt the prediction of fiber breaking. Since the applied external forces are still seeking equilibrium with the material response, the result of a lower modulus would be that there is more extension in the fiber direction, rather than lower stresses. So peak stresses in the simulation can still be used in a linear-elastic fashion to assess the fiber response.

Another important way to increase the performance of the simulation is by reducing the simulated layup. For example, a layup of 8 unidirectional plies with the same orientation can be simulated as one single virtual ply. This requires ply thickness and material parameters to be scaled to this simplified version. To illustrate this, two simulations with the same material parameters but different thicknesses (T) were executed (Figure 9). There is no wrinkling in the 1.6mm ply whereas the 0.2mm ply shows significant wrinkling areas. Increasing the thickness from 0.2 mm to 1.6 mm (a factor of 8) resulted in a bending stiffness increase by a factor of 512 (proportional to $T^3$). Whereas the shear stiffness was increased by a factor of 8 (proportional to T). The thick panel therefore tends to deform via shear while the thin panel bends, causing the observed wrinkling.
To represent a layup of 8, 0.2 mm plies in only one mesh the total stiffness should be increased by a factor of 8 but not by a factor of 512. Therefore these proportional material property behaviors are very important to consider when a multi-axial layup is simplified into a single blank mesh.

**Simulation trials**

Using moderate mass and stiffness scaling with similarly scaled properties, and allowing a relaxation step, is a balanced approach to draping simulations for both accuracy and simulation speed. The following studies refer to a 0.2 mm single UD-ply modeling of the aforementioned 8 ply layup. In these first tests, two aspects are examined:

1. How does the fiber orientation influence the draping behavior in terms of wrinkles?

2. How does the fiber orientation influence the draping behavior in terms of the final part geometry? Or alternately considered as: what is the required blank geometry to achieve a net-shape preform?

Nine simulation runs representing different fiber orientations between 0° and 90° are considered. The following figure shows an overview of the results.

*Figure 9 Ply thickness comparison using identical property simulation*
The influence of the anisotropic blank stiffness on the forming behavior can be seen as the change in the perimeter shape. The stiff fibers resist load parallel to their axis, but are free to slide relative to each other. Therefore transverse displacement is necessary to compensate the material needed to form the curved geometry of the double dome. For an engineered textile such as the one simulated in Figure 10, the deformed shape changes relative to the fiber placement. A laminate consisting of unidirectional plies will require a unique blank for each unique fiber orientation. If a 0° ply were placed atop a 90° ply, they would each experience relative fiber motion localized to the areas where aligned fibers are bent around large curvatures. In the case of woven or stitched fabrics, the above deformations are superimposed based upon the relative fiber angles, resulting in in-plane shear. When a fabric is sheared beyond a locking angle (in-plane shear limit) unique to each fabric architecture, it can buckle out of plane, causing a wrinkle to appear.

Wrinkles appear in all simulated versions mainly in the red highlighted regions of the part (Figure 11). The amount and magnitude of the wrinkles is consistent between the different simulations. However, the orientation and location of the wrinkles varies with the fiber orientation as a result of the peak shear stresses at areas of high mold curvature.

Figure 10 Deformed blank geometries for several fiber orientations.
Figure 11 High shear areas containing varying degrees of wrinkling.

Based on the results of these simulations, the ideal blank geometry for each of the fiber orientations is predicted. A Matlab based script, provided by Aniform Support, compares the deformed blank mesh with an ideal geometry (shape of the required part). The script deletes all blank elements that exceed a specific distance to the surface of the ideal geometry. It then uses the displacement field to re-calculate the original flat shape of the remaining elements. The result is an ideal cutting of the former blank shape to yield a net-shape preform blank. IMPLIED here is the requirement that the starting virtual blank is larger than required, even when using a blank holder.

To evaluate the quality of the blank prediction, the new blank is used for a further run of the simulation with the same settings. The edges of a blank influence the draping behavior of the whole part, therefore it is expected that the smaller blank will behave slightly differently than the larger original as tool friction is reduced. It is recommended to conduct the blank prediction in a two-step sequence. After the first run, the deformed blank is cut with a higher tolerance to include more elements outside the edge of the required geometry. This new blank is used as an input for a second simulation. The draped geometry of this second simulation can be used for a final blank prediction. Finally, the blank is cut close to the edge of the ideal geometry. The edges of the preformed blank and the required geometry are not expected to match precisely given the irregular element size and shape. This process is summarized in Figure 12 and Figure 13. Figure 13 presents the two step cutting blanks for a 20 degree unidirectional fiber ply to achieve the desired double dome geometry. Figure 12 shows an enlarged quadrant of the final blank prediction against the desired double dome geometry edge.
Figure 12 Two-step blank prediction: 1) first pass, orange area 2) second pass, yellow area after running the simulation using the first cut as the input blank (black arrows indicate fiber orientation)

Figure 13 Comparison of second blank simulation edge (dark blue) with the desired geometry (solid line)

Application

Using the developed model, several double dome geometry simulations were conducted to mirror experimental preform trials using a material similar to that of the simulations. Actual properties of the material are essential to accurately simulate the preform process, but they were not available at the time of the studies. All properties used in the model were as previously stated in Figure 6, with no subsequent model tuning. Although there is no ability to quantitatively compare the experimental with the simulated results, a qualitative assessment can be conducted based on the magnitude and location of the observed features. This was done by creating as a simplified single ply mesh for the different experimental layup cases.

In this first case, Figure 14, a balanced, symmetric laminate was considered to examine the accuracy of the wrinkle prediction. Here the wrinkle locations, grouping, and size of simulated and actual part coincide and relate at nearly 1:1 scale between the prediction and reality. Note that both the simulation and the experimental samples used a rectangular blank for the
preforming, but that the experimental part was subsequently trimmed to the final shape. In this example, the blank prediction was not conducted since the wrinkling behavior was of primary concern. The black rectangle in Figure 14b) was a digitally added mark to obscure proprietary information; these marks were also added to Figure 15 a) and b) for a likewise purpose.

![Figure 14 Wrinkle formation comparison for a [0/±60]s layup.](image)

The second test examined the blank prediction for an orthotropic [0/90]s layup as in Figure 15. In this example, the experimental part was formed, trimmed and then flattened to observe the shape of the required preform. Using a heated press to flatten the preform is thought to be an easy way to determine a close approximation of the expected preform. The first image depicts the preformed part after trimming, the second image depicts the same part subsequently flattened in a heated press (the experimental blank geometry), and the third image shows the predicted blank geometry. Even though springback and residual stress in the experimental part are expected, it is a simple method to check the geometry estimation. This flattened shape is very close to the simulation predicted blank which contains some additional roundness as a result of the way the experimental blank was obtained.

![Figure 15 Blank prediction for a [0/90]s layup compared to a flattened profile.](image)

The above examples were for laminates where each layer has identical properties and orientations. Plies with different orientations, materials, or geometry can all be simulated by adjusting the properties for each ply and the ply stack sequence. To simulate such a part would require material knowledge for each ply and all the ply-ply interactions. Simplifying the mesh would not be possible, though mass and stiffness scaling could be conducted if it were assumed that all the interactions scaled likewise. This would dramatically increase the initial characterization time and cost until such a time as a textile database were available with the
necessary engineering data.

Summary and Next Steps
This study provided a first result of using Aniform to conduct draping simulations. The simulation software was utilized to examine the impacts of mass, stiffness and layup scaling to achieve a fast simulation which captures realistic fabric behavior. Using a scaled mass of $2 \times 10^{-4}$ t/mm$^3$ and a scaled fiber stiffness of 1000 MPa produced simulations with enough accuracy to model the expected drape behavior in a reasonable 5 hour simulation time.

The double dome geometry was used to compare the effects of fiber orientation on the predicted wrinkle formation and blank geometry. These results were compared against experimental results in a qualitative fashion for two different layup schemes.

The next step in this project is to use the actual material properties in the simulation for quantitative assessment of the fiber drape ability. This will then enable a study to examine methods to minimize the wrinkle formation, including the use of darts or the addition of a blank holder. Further work will also examine complex laminate schemes and multiple material systems.

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Bibliography