Comparison of fibre angles between hand draped carbon fibres and draping simulation

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Abstract
The mechanical properties of carbon fibre reinforced plastics, short CFRP, are highly sensitive to its respective fibre angles. Small deviations result in a high decrease of stiffness in the manufactured parts. In the first steps of industrial engineering for CFRP parts, draping simulations are used to give an approximation of fibre angles that the real draped fabrics adjust to when draped in its three dimensional state. Since the draping simulations are based on mathematical models they do not match the draping results of the manual performed production processes. In order to compensate these manufacture errors, tolerance ranges for fibre angle deviations are set very high. One way to control the fibre angle after draping is to use optical camera systems for quality assurance.

The approach at DLR Augsburg to measure fibre angles is realised with a CCD camera, which is mounted on an industrial robot. The measurement system is highly sensitive regarding the reference orientation. Every deviation from the normal axis results in deviation of the measured angle. The setup with the robot guaranties high reproducibility in measurements and a high accuracy to the reference.

In this paper a specified cut piece was used to perform draping simulations with different mathematical models. The cut piece was manually draped onto a tooling. The resulting fibre angles were measured with the robot controlled measurement system. In the end a comparison between the simulated and draped fibre angles was done. The result provides hints which solver delivers the lowest errors for the draped cut piece. With this information the tolerance ranges could be reduced which lead to fewer plies of carbon fibres. Less carbon fibres lead to less material cost, weight and manufacturing time.

Keywords: Draping simulation, fibre angle measurement, robotic controlled measurement
1. Introduction

Carbon fibre reinforced plastics nowadays are an established material for high tenacity manufacturing parts. Carbon fibres have extremely good mechanical properties along their fibre orientation. Unfortunately they decrease rapidly when force is applied out of the fibre longitudinal axis. The advantages from carbon fibres result in very complex manufacturing and design processes. In a first step the designer needs to know the load cases of the manufacturing part. The engineer then has to create a stack up of carbon fibre cut pieces that can handle the forces and no boundary conditions are harmed. Boundary conditions for example are the maximum deviation in fibre angle between each ply, symmetrical stack ups, maximum width of fibre material, force inducing areas and many more [1]. A crucial influence on the stiffness lies in the tolerance ranges that are applied on each ply regarding the fibre orientation.

The fibre materials used in this case are carbon fibre woven fabrics which are advantageous for handling and draping processes. These fabrics consist of warp and weft rovings which are in plane state perpendicular to each other [2]. If a double curved deformation is applied to these fibres, for example a 3D-shape of a tooling in production, they have to shear and change their respective angle to each other. To compensate these changes in fibre orientation the tolerance ranges are expanded. To estimate the shear in draped fabrics, draping simulations can be done. The draping simulation estimates the fibre angles with the help of mathematical models. Two common methods are kinematic algorithms and finite elements methods. Kinematic algorithms are a fast way to estimate the fibre orientation but have relatively high errors [3]. The finite element methods are more difficult to calculate and require much more input and time to calculate, thus are more precisely.

After the engineering the manufacturing can begin. The worker has to place the fabric cut pieces exactly where the engineer has calculated it. Therefore a laser projector generates the outlines of the cut pieces on the tooling for orientation. To have a defined start mostly a line on the side of the cut pieces are placed to its projected line and gets fixated. From this line the worker drapes the cut piece till it fits the complete projected outline. The start line and the outline also are boundary conditions and results of the draping simulation.

In this paper a double curved generic tooling was used to drape a generic shaped cut piece manually on it. The tooling and cut piece were also used for draping simulation. The draping simulation was performed with several kinematic solvers. At the German Aerospace Center in Augsburg an optical fibre angle measurement system is used to measure fibre angles on multi curved surfaces. With the help of this system we want to compare the fibre angles from simulation and real draped fibres at defined points on the cut piece to get better knowledge of the relation between draping simulation and manually draped carbon fibres.

1.1 Main issues

The question that will be answered in this paper is, to what extent the fibre angle results of the manual process can be compared with the simulation results. First, the robot system needs to be calibrated to ensure the measurement is conducted at the correct positions. When the connection between reality and simulation was established the measured values had to be compared between the simulated ones. Since the material was a fabric, the fibre angles for warp and weft and the resulting shear between them had to be compared and evaluated. The last step is to check which solver results in the lowest deviations from the measured ones for this set up.
2. Experiments

The experiments can be divided into four parts. At first an experimental set-up had to be established. To get the knowledge of how the fibres propagate on the surface the draping simulation had to be done. After finishing the set-up and the simulation the experiment can be executed with draping the cut piece and then measuring the fibre angles with the fibre angle measurement system. In our work a total of six identical cut pieces were used.

2.1 Experimental set-up

The tooling that was used in this research has a double curved concave shape (Figure 1).

![Figure 1 Double curved Tooling](image)

Since the tooling is not symmetrical and not circular, the radius is different for each curvature. The depth is approximately 1000mm. The red outlined contour was used for the cut piece. The boundary conditions to this contour were that the piece must be as large as possible. There needs to be a short distance (white line) from the starting edge (yellow line) to the other side. It also inherits a long distance (purple line) from the starting edge. Also a curved edge (green line) and a corner (blue line) should be included. The flat cut piece was approximately 2000mm long and 1200mm width.

The robot is a standard KUKA KR 120 R2700 extra HA. This robot has a very high repeatability accuracy which ensures that it always measures at the same points for every draped cut piece.

The measurement system is an optical system from the company PROFACTOR. The system is based on the reflective behaviour of carbon fibres. The system takes pictures of the fibres with different directions of illumination. The software combines the pictures and calculates the fibre angles out of their respective reflections (Figure 2) [4].
The movement strategy for the robot and the measurement plan were generated in CATIA and the FAST Suite. With the help of the offline programming it can be guaranteed that the robot moves parallel to the starting edge and levels our measurement system correct. The measurement system mounted onto the robot, the tooling and the measurement plan can be seen in Figure 3.

The measurement plan covers 100% of the cut piece. The measurement system makes a picture of 40 mm by 40 mm, therefore the measurement points have a distance of 40 mm from each other. A total amount of 903 measurement points were scheduled.
2.2 Draping simulation

The draping simulation for this research was performed with CATIA and the respective toolboxes. The standard toolbox for composite design inherits two solvers called Symmetric and Minimum Distortion. With the addition of the toolbox Composites Fiber Modeler (CFM) three additional solvers called Optimized Energy, Optimized MaxShear and FEFlatten could be used. All of these solvers are kinematic solvers. The Symmetric solver forces the fibres to propagate symmetrical which is for usage of symmetric toolings. In the Minimum Distortion solver the propagation of fibres is done with the lowest deformation of the fibres itself. From the more advanced toolbox CFM the Optimized Energy solver tries to minimize the shear strain energy on the extending edge. For the Optimized MaxShear solver the maximum shear gets limited. The FEFlatten solver is the most advanced one. It considers strain along the fibres and contains finite element methods which reduce errors from the geometrical solvers. While the lines for the other solvers leave the surface for reaching its next shear point the FEFlatten solver always stays on the surface while propagating. Every calculation needs a material, a rosette, a seed point or a seed line, the size of the net and a solver. For the material the material data from our cut piece was put. The rosette defines the fibre directions, for our material 0 degree and 90 degree. The 0 degree is perpendicular to the starting edge and the 90 degree orientation is parallel to the starting edge. The seed point/line is the definition from where the simulation starts to propagate. The seed point was in the middle of the starting edge and the seed line was the starting edge. The net size defines how long a line from the kinematic approach will be, the shorter the lines the higher the calculation time but the more accurate the solver gets. For our calculation a net size of 4 mm was used which corresponds with the weave of our fabric. These inputs were then used to perform a calculation for each solver with a seed point and seed line. The calculations took about 1 minute for every solver except the FEFlatten. It took about 20 minutes for one calculation with that solver. After the calculation the measurement plan was loaded into the calculation model. A report function of the toolbox generates a list of each point and its respective coordinates and fibre angle. This list just gives you the information for the main direction. Therefore the export had to be done a second time for the 90 degree direction and the resulting shear was then calculated manually. The result for the Minimum Distortion (left side) and the Optimized MaxShear (right side), both for the 90 degree orientation, can be seen in Figure 4. The green areas are areas with fibre angle deviation below 1 degree, the yellow areas are above 1 and below 3 degrees and the red areas are above 3 degrees [5].

![Figure 4 Results of draping simulations for Minimum Distortion and Optimized MaxShear](image-url)
2.3 Draping

The cut pieces were provided by an industrial cutting machine and then stored on a table. Now the cut piece was manually laid into the tooling. At first the starting edge was levelled to the drawn contour from the tooling. After the cut piece starting edge matched with the shape on the tooling it was fixated. Like the behaviour of the kinematic algorithms the draping was started perpendicular to the starting edge at the height of the rosette. You could see that the cut pieces were very accurate in reaching the other side of the tooling shape since the 0 degree line suffers almost no angle deviation. After that the further draping was into the corners of the cut piece starting from the rosette. After reaching the tooling shape the complete cut piece was fixated onto the tooling. In the lower part were the distance to the rosette is short the cut piece matched fairly well. In the upper part with the high distances a lot of draping had to be done to get the cut piece into the shape of the tooling shape. When considering the time it needed to get the cut piece into the shape we assumed that in the lower side would be less change in fibre directions and a lot in the upper part. We also assumed that the resulting shear angle in the lower part raised and in the upper part decreased because we had to sweep over them in the lower side and on the upper part had to push them into the tooling shape. An example of a draped cut piece can be seen in Figure 5.

![Figure 5 Draped cut piece](image)

2.4 Fibre angle measurement

After each draped cut piece a fibre angle measurement was made. Before the measurement started a reference point on the tooling was measured if the robot and the measurement system are still calibrated. The robot moved to the tooling and the respective measurement point and then remained still for 2 seconds. This ensured that the robot is not vibrating and the camera has enough time to refocus and gather enough pictures. The measurement data is saved and that the robot moved to the next point. After finishing the measurement a list of data was saved. The list contained the number of measurement point, the robot positions to reach the respective point and its fibre angle. The measuring system can be seen in Figure 6.
3. Discussion

In the first step the repeatability of the manual draping results was controlled. Therefore the standard deviation for each point over the 6 cut pieces was calculated. This was done for the 0 degree, 90 degree and resulting shear angle. The results showed that the standard deviations were relatively high but this was expected for only 6 samples. The standard deviation was 2.17°, 1.53° and 2.06° for 0°, 90° and resulting shear respectively. With these high standard deviations there was no use to check every cut piece one by one. Therefore the mean fibre angle for each point over the 6 cut pieces was used for further calculations.

After the repeatability was checked the assumptions made while draping had to be controlled. Therefore, plots of the fibre angle from the measurements over their coordinates were made. These plots can be seen in Figure 7 where the left plot is the 0 degree orientation, the middle is for 90 degree and the right for resulting shear.

Here it could be seen that our assumptions were right. The lower part had less change in fibre angle than the upper part. Also the resulting shear looked as expected. The right side of the
lower part suffered an increase in the resulting shear angle and the upper part a decrease. One very important aspect is that the fibre angle of the 90 degree fibres changed much more than the 0 degree orientation. Our explanation for this behaviour is the weave of our fabric and the roughness of the tooling. The fabric has an atlas weave, which means that the warp fibre lies under a minimum of two weft fibres before crossing one weft fibre on top, and therefore more fibres of one direction on each side than the other. In this case the 0 degree fibres were lying on the bottom and therefore in touch with the tooling surface. Since the tooling is made out of Ureol it has a relatively high roughness. Therefore we assume that the 0 degree fibres were held in place due to friction between fabric and tooling and caused the 90 degree fibres to deflect more to reach the necessary shear angle.

The next step was to compare the measured angles with the simulated ones. To get values for comparison, the difference in fibre angle between reality and simulation was calculated for each point. This was done for the 0 degree and 90 degree orientation and the resulting shear. These differences were used to calculate the highest error in negative and positive direction of fibre angle deviation. To get a better overview about the distribution over the whole cut piece the absolute values from these deltas were added up to an error sum. The differences for positive and negative deviation and the error summation were compared between seed point and seed line. For the positive deviation the seed point had the lower errors. The best result for negative deviation was achieved with a seed line. Compared with the error sum the seed point was better. Over all the seed point had the lower errors. To evaluate which solver has the lowest difference to the reality the lowest delta for positive deviation, the lowest delta for negative deviation and the lowest error sum was searched for each fibre direction and resulting shear. The results can be seen in Table 1.

<table>
<thead>
<tr>
<th>Positive deviation</th>
<th>Optimized MaxShear Seed Line 5.17°</th>
<th>FEFflatten Seed Line 0.84°</th>
<th>FEFflatten Seed Point 1.26°</th>
</tr>
</thead>
<tbody>
<tr>
<td>Negative deviation</td>
<td>Minimum Distortion Seed Line -1.54°</td>
<td>Minimum Distortion Seed Line -4.17°</td>
<td>Optimized Energy Seed Point -9.72°</td>
</tr>
<tr>
<td>Error sum</td>
<td>FEFflatten Seed Point 1335.37°</td>
<td>FEFflatten Seed Point 1149.58°</td>
<td>Optimized MaxShear Seed Point 2201.40°</td>
</tr>
</tbody>
</table>

The result shows that no clear favourite could be generated. For every boundary condition the solver with the lowest error changes. This shows that with the high standard deviation in hand draping the definition of which solver would be the best is near impossible. What gives a better view about the outcome of the comparison can be seen in Figure 8, were the difference between solver and reality is plotted over their coordinates for each point.
With help of the colour scale the results of the solvers are more apparent. The pictures are sorted in the same way as in Table 1. If you look on the left column for the 0 degree direction the Optimized MaxShear solver has the lowest difference in positive direction but also inherits a high difference for negative direction. For the negative deviation the Minimum Distortion solver has the lowest difference but has a high positive deviation. Looking now on the error sum the FEFflatten solver has the lowest summation of differences and looks much smoother without that high peaks in it. The exact same behaviour can be seen for the 90 degree direction and the resulting shear. This would lead to the conclusion that the solvers with the lowest error sum tend to have the same trend as the reality but lack in accuracy and would then be more suitable. With this comparison the FEFflatten solver with a seed point could be declared as the best fitting solver to our draped cut piece. It has the lowest error sums for positive and negative direction and also a low error sum for shear. Only the Optimized MaxShear solver was better for the resulting shear but had much higher error sums for 0 and 90 degree orientation.

At last a check if the solver would always have higher fibre angle deviations than the reality was made. This would ensure that the engineering can use the simulation for calculations since the error would be higher than in reality. The comparison can be seen in Table 2.

<table>
<thead>
<tr>
<th></th>
<th>Reality</th>
<th>FEFflatten Seed Point</th>
<th>Minimum Distortion Seed Line</th>
<th>Optimized Energy Seed Point</th>
<th>Optimized MaxShear Seed Point</th>
</tr>
</thead>
<tbody>
<tr>
<td>0° Max</td>
<td>3,46°</td>
<td>1,27°</td>
<td>1,54°</td>
<td>2,62°</td>
<td>3,59°</td>
</tr>
<tr>
<td>0° Min</td>
<td>-3,31°</td>
<td>-5,96°</td>
<td>-8,56°</td>
<td>-5,75°</td>
<td>-5,50°</td>
</tr>
<tr>
<td>90° Max</td>
<td>91,73°</td>
<td>91,16°</td>
<td>90,74°</td>
<td>91,21°</td>
<td>91,04°</td>
</tr>
<tr>
<td>90° Min</td>
<td>82,59°</td>
<td>85,37°</td>
<td>85,72°</td>
<td>87,02°</td>
<td>86,67°</td>
</tr>
<tr>
<td>Shear angle Max</td>
<td>90,21°</td>
<td>94,42°</td>
<td>95,15°</td>
<td>93,64°</td>
<td>93,49°</td>
</tr>
<tr>
<td>Shear angle Min</td>
<td>83,11°</td>
<td>88,33°</td>
<td>85,19°</td>
<td>86,40°</td>
<td>86,45°</td>
</tr>
</tbody>
</table>
Here it can be seen that over all the solvers do have wider ranges and bigger errors. Due to the fact that in reality the 90 degree fibers suffered more angle deviation than the 0 degree direction the reality can have bigger deviations then the simulation. This would lead to weaker mechanical properties at some areas of the part than expected from the simulation.

4. Conclusion

Within this research an experimental set up was created that can measure fibre angles in a way that they can be compared to draping simulations. A process to evaluate the data of the experimental set up to find the best fitting solver was established. The boundary conditions for the draping simulations could be understood much better. It was possible to declare a best fitting solver for our experimental set up. The best fitting solver can change for different materials and toolings. It could be shown that the kinematic solvers used for draping simulation neglect crucial parts of real draping like roughness of the tooling which lead to high errors. The conditions to realize manual draping in production have huge disadvantages for working with fibre reinforced plastics and thus generate higher fibre angle deviations. Knowing these circumstances the next approach will be to use a kinematic end effector for draping. This means the end effector can pick up a cut piece in its flat position drape it by changing its own shape while holding the cut piece. The end effector also can place the cut piece into the tooling. This would ensure that each cut piece would be draped the same and has no random influences like draping manually. Since this would eliminate boundary conditions made for manual draping like the starting edge, the other boundary conditions could be changed to suit the draping process better. The rosette for example could be placed in the middle of each cut piece which would reduce errors drastically due to the shorter distances to the edges. The biggest improvement would be the repeatability of the robotic system which would lower the standard deviation and would deliver a much more accurate declaration of which solver generates the lowest errors.

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References


