Dipl.-Ing. Andreas Knote

German Aerospace Center DLR,
Institute of Composite Structures and Adaptive Systems
Lilienthalplatz 7
38108 Braunschweig
Phone +49 531 295-3289
andreas.knote@dlr.de

Education:
Mechanical Engineering with specialization on Aeronautical Engineering at Technical University of Braunschweig

Professional Experience:
At DLR since 2008:
- Design of composite aircraft structures
- Research on draping simulation
- Development of composite aircraft door surround structures
- Lattice structure design

Current Main Field of Activity:
Research on lattice structure aircraft fuselage design

Draping simulation – the key to low cost high performance net shape parts?

Author: Andreas Knote, DLR German Aerospace Center, Institute of Composite Structures and Adaptive Systems, Braunschweig

To increase the competitiveness of composite parts, it is most important to lower the recurrent costs. The Liquid Composite Molding (LCM) technology offers a great potential over prepreg by much lower material costs with equal mechanical properties. Yet the challenge is that highly complex 3D parts must exactly be draped from the flat fabrics to keep up their good performance and lower the amount of work. Draping simulation software predicts the flat pattern geometry and checks their producibility. To understand how the parameters of a draping simulation impact on the flat pattern precision and to find methodologies to achieve best net-shape accuracy, an extensive parameter study for different simulation software products has been performed. This paper shows the results of the parameter study and the developed methodologies.

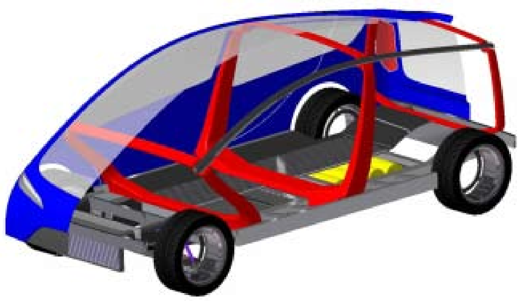
Introduction

For the layup of almost any shape of a part made out of dry fiber reinforced plastics precise flat patterns are required for the preforming process. During preforming the flat patterns of the fabrics get draped on a tool where depending on the complexity of the final shape the flat patterns get strongly deformed. In order to obtain a high quality preform with good draping results, those flat patterns have to be precise in matters of fiber angles and geometry. Draping simulation pro-grams can be used to simulate the draping process and such fabric shear behavior of NCF or woven textiles and to generate 2D flat patterns of the draped fabrics. By the use of draping simulations the development and manufacturing of composite parts is sped up and preform quality is improved. Highest preform quality would be a so called net-shape preform where the draped fabric precisely matches the foreseen layer boundary, thus making edge trimming obsolete. Apart from flat pattern generation, draping simulation software also calculates the fiber angle deviation during draping which is important for the design, sizing and manufacturing process. In this paper a draping simulation program benchmark combined with an input parameter sensitivity analysis is shown, which illustrates the capabilities of the programs as well as the influence of the different input parameters to the flat pattern accuracy.

The drape simulations of all previously characte-rized programs are based on kinematic algorithms and thus all programs have similar input parameters. The kinematic algorithm is described and enhanced by several authors ([1] to [8], [10], [11]). This type of algorithm has two main as-sumptions: the length of an element between two nodes is fixed and the distortion of the fabric is simulated through rotating and translating ele-ment movement around the nodes along the tool surface. The meshing is achieved e.g. by the method of intersecting circles [10]. Thereby, shear in the fabric is the only deformation mode that is considered during simulation. Locking of rovings or any other deformations, particularly out of plane deformations like wrinkling or cross over point movements and yarn slippage, are not covered by kinematic algorithms. The input parameters of the drape simulation (e.g. seed curve, mesh element size) have strong effects on the quality of the simulation result. Non-optimal parameters can lead to very imprecise results in the draping simulation so that the results are inaccurate up to unusable or result in wrong predictions for fiber angle deviation.

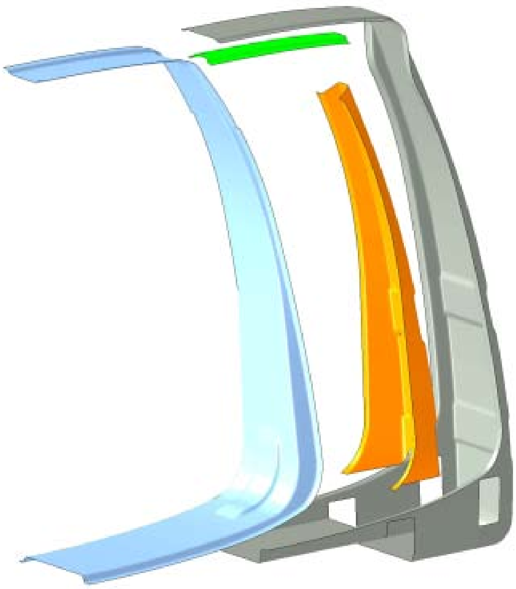
Therefore it is very important to investigate and understand the effects of each single input parameter to the draping simulation in order to obtain the most accurate results, especially precise flat patterns and reliable prediction of fabric shear.

This paper uses generic parts like an innovative CFRP car frame and an aircraft fuselage C-frame to illustrate common problems during draping of dry fiber fabrics. The car frame is part of a vehicle structure in Rib and Space Frame Design for a vehicle in the upper middle class [9]. The basic Space Frame structure, which consists of three ring frames instead of A, B and C pillars, is fitted



Innovative DLR Space Frame vehicle structure [9]

onto the floor structure. In the overall development, the focus of this Rib and Space Frame Design is initially on the ring frames with their higher design and dimensioning complexity. The car frame, which replaces a standard automobile's B-pillar, was selected as an example. The frame was constructed from two shells with internal Ω-stiffening. From the manufacturing point-of-view, these three frame parts present highest challenges for draping and simulation for a part of very high production numbers.



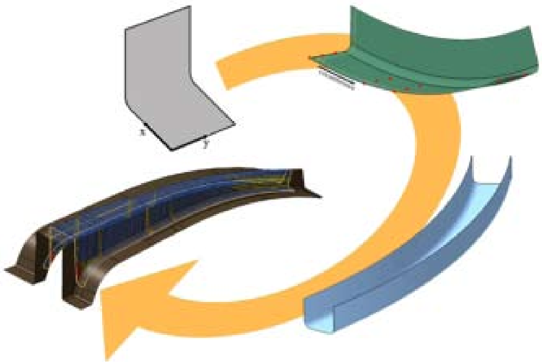
Explosion view CFRP car frame

Evaluation Method

The input parameters whose mode of operation and impact on the simulation result were investigated in this sensitivity analysis get described in detail in this section. Input parameters to draping simulation can be: part geometry, simulation mesh size, fiber direction, simulation algorithm, seed point position, seed curve configuration and thickness update. To understand each input parameter of a draping simulation, it is important to examine these as isolated as possible, even if they are not independent from each other. This was achieved by keeping all input parameters but one constant and varying just one parameter at a time. This results in a very high number of simulations because of the large number of possible parameter combinations. Due to this large amount of simulations, an automation based on Visual Basic for Applications (VBA) macros as well as mouse and keyboard macros were developed to reduce human input and monitoring to a minimum. All necessary input to the macro is read from an Excel spread sheet which contains every single variation of the simu-lation input parameters. The results were stored for each single simulation run and automatically analyzed by custom programmed MatLab routines which created the output tables and diagrams.

Four different part geometries with increasing complexity were used for the draping simulations to validate that the results of the sensitivity analysis are independent from the geometry. The first part is a rather simple L-bracket. The benefit of an L-bracket is its unique solution for a flat pattern in opposition to more complex free form shapes. Basically the solution for the flat pattern of an L-bracket could be calculated by hand without numerical simulation. This is due to the fact that an L-bracket has only one radius around a straight axis, thus in theory there is no shear deformation. Hence, a validation of simulation results was possible on a pure mathematical basis without the need for physical trials. During the simulations of the L-bracket it quickly became clear, that the draping simulation even of such a simple geometry shows strong effects of the variation of the input parameters.

The second geometry which was evaluated is an L-frame which has the basic geometry of the L-bracket with a second bend around a second axis, perpendicular to the first one. The second bend increases the complexity as little as possible, however the complexity is raised so much that there is no unique solution for the flat pattern anymore. Further simulations are run for third and a fourth even more complex geome-try to validate the derived parameters from the first two. The third part is a C-frame which gets commonly used in aircraft fuselages and the fourth part is the highly complex Ω-frame from the vehicle space frame. The C-frame and Ω-frame flat patterns were validated by a real-life manufacturing trials.



Increasing part complexity

Results

Four different draping simulation programs were evaluated according to the previously described methodology:

- Composite Part Design (CPD), a Module of Dassault Systèmes Catia (V5R18 SP6)
- Simulayt AFM 1.0n
- Vistagy FiberSIM 2009
- Anaglyph Laminate Tools 3.4

In order to make a comprehensive evaluation, the programs were reviewed in three main cate-gories which get summarized in a table by the end of this chapter:

- Performance (Precision, Robustness)
- User options and input
- Interfaces

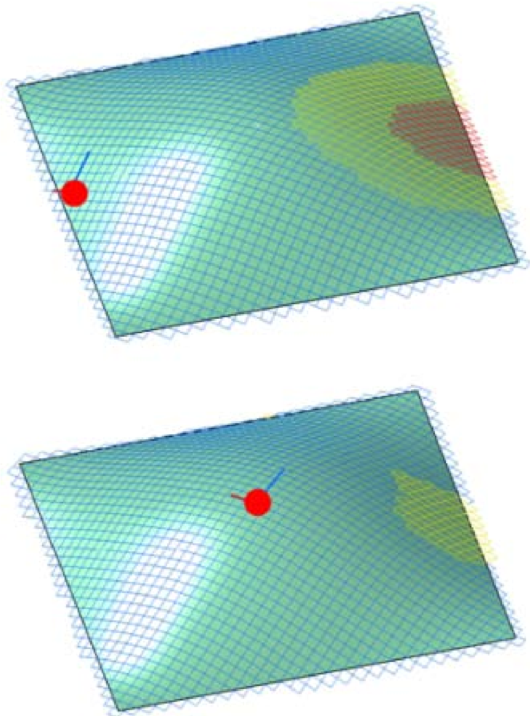
The first category performance strongly depends on the flat pattern precision which is directly related to the input parameters. Not all of the input parameters mentioned in the previous chap-ter had a significant influence on the result of the draping simulation. For example the precision of the flap pattern remained constant for all part sizes and radii. The evaluation category perfor-mance got split up into

- Seed point/seed curve
- Mesh size
- Algorithm

because they are the most important and most influential input parameters to draping simulation and must be understood in detail. The results are based on an 8-dimensional parameter range which originates from the eight identified draping simulation input parameters. Thus, results in an 8-dimensional range are practically impossible visualize. Usually, only up to three or four dimen-sions can be shown in a comprehensible chart. Therefore, some simplifications had to be made in order to obtain analyzable figures. For example a plot regarding the influence of seed point position on flat pattern area was made for a constant mesh size. Thus, it can be assumed that the mesh size has a negligible influence on the conclusion of the plot.

Seed point/Seed curve

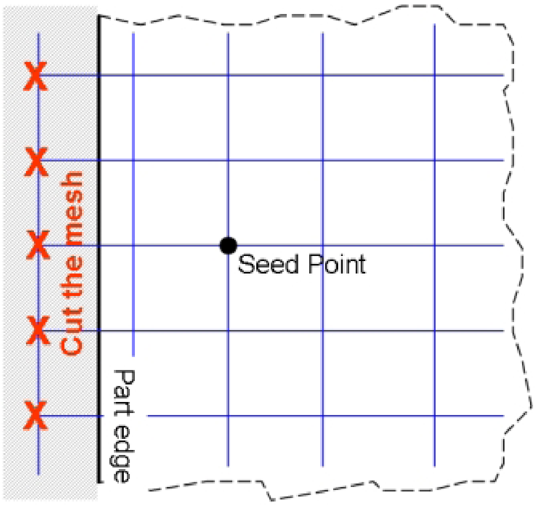
The seed point is the starting point for the meshing algorithm and its position strongly influences the simulation result. It can be compared to the fixation point in a real draping process. Depending on the draping software, different meshing strategies are used.



Seed Point position influence on draping

Catia CPD only uses a seed point and does not offer an additional seed curve definition. CPD generates the mesh across the edges and cuts the mesh down on them; respectively the initial mesh is larger than the part surface. In the case that the seed point is defined right on the edge, the area of the flat pattern tends to increase. In contrast to CPD, AFM calculates the mesh not across the edges; respectively the mesh is smaller than the actual surface.

If necessary the mesh will be interpolated from the closest node to the edge. Most accurate results are obtained with the seed point either right on the edge or with a seed point which distance to the edge is larger than the mesh size. The same applies to the positioning of the seed curve. Most likely this behavior is due to the interpolation of the mesh from the mesh edge node to the surface edge where the algorithm runs into problems if the mesh edge is identical with the seed point or seed curve.

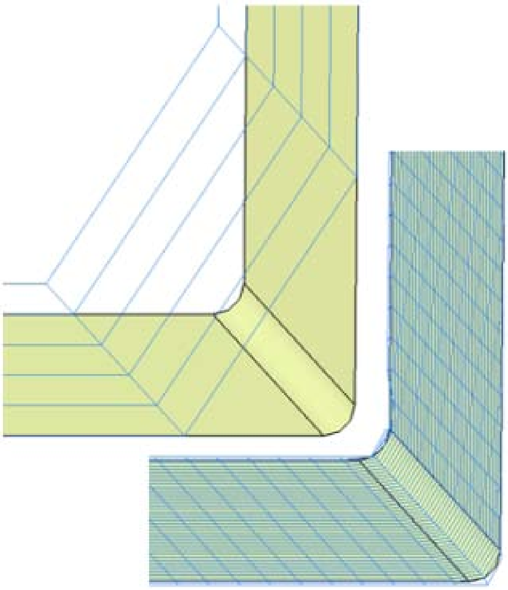


Cutting the too large mesh at Catia CPD

Vistagy's FiberSIM (FS) provides additional features to the seed curve definition in order to appoint a specific behavior of the mesh creation. For example there is the possibility to automatically calculate a geodesic seed curve from the seed point in a defined direction. For a less complex part like the L-bracket FS produces accurate flat patterns independently from the seed point and seed curve positions. Anaglyph's Laminate Tools (LT) exclusively provides the option to set two seed curves and even more options to define the mesh propagation from the seed curve than FiberSIM. In this evaluation, besides the configuration just with a seed point, the geodesic and planar seed curves have been examined. All of them generate flat patterns as accurate as FS in regard to low complex parts. There was also no quality change of the flat patterns with varying seed point and seed curve positions.

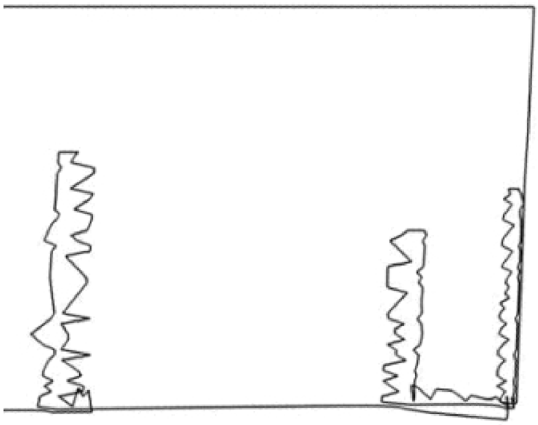
Mesh size

The mesh size of the simulation mesh is important for how well small details of the part geometry are represented in the mesh and thus in the flat pattern. Some simulation software automatically adapts the mesh size locally for example at radii. Furthermore, the draping simulation software differentiates in mesh size definition methods: it can either be directly defined by a discrete size in millimeters, or by a factor which sets the mesh size in relation to the part geometry.



Mesh size in relation to part details (example L-bracket)

In Catia CPD the mesh size can be defined un-equal in warp and weft direction. To achieve the highest accuracy the mesh should be selected with identical warp and weft as this also applies to the majority of woven fabrics or biaxial NCFs. A smaller mesh size results in flat patterns with increasing precision. With a mesh size larger than 10x10 mm a precise flat pattern cannot be ex-pected. Accurate results at little simulation time can be achieved with 5x5 mm meshes. Though smaller meshes in regard to the meshed geometry result in more accurate flat patterns, chances for singularity errors have been found to be increasing.



Flat pattern error due to singularities

The higher precision of flat patterns at smaller meshes is due to the meshing of radii with a higher resolution. In opposition to CPD the AFM does not simulate a more precise flat pattern with a smaller mesh. Because AFM uses a mesh which automatically adapts its size to the surface geometry, the mesh turns to a higher resolution in the radii. In no case the mesh size should be smaller than 2x2 mm. Again the warp and weft should be equal like in CPD. For less complex parts the upper end of the mesh size is only lim-ited by the surface size itself (at least one mesh cell has to fit inside the part edges). Within FS the mesh size is set by the Fiber Spacing Factor. The user does not have the possibility to set a discrete mesh size in millimeters, because FS chooses the mesh size itself depending on the part geometry. The factor lets the user refine or enlarge the mesh size, although it is not published in relation to what the factor is applied. Generally, the flat pattern precision increases with decreasing Fiber Spacing Factor. Nevertheless FS simulates accu-rate results with a factor up to 5. With a factor of more than 5 the accuracy decreases above aver-age. To achieve a high precision with acceptable calculation time a factor of 1 to 2 should be se-lected. LT provides both methods for defining the mesh size: discretely like in CPD and implicitly with a factor like in FS. Again no information was available in relation to what the factor multiplies.

The implicit method was examined in this evaluation. It was observed that for all three algorithms of LT (see the following section) a factor of 5 results in the most precise flat patterns.

Algorithm
The algorithm of a draping simulation is responsible for calculating the mesh propagation and shearing of the mesh. For each simulation software, different kinds of algorithms are available, which differentiate mostly in the type of shearing behavior. CPD provides two algorithms: Symmetric (Sym) and Minimum Distortion (MinD). The mesh calculation by Sym is forced by the geometry. It will generate a mesh with symmetric shear deformations. MinD on the other hand iterates the mesh to the target of the minimum sum of shear. This results in the effect, that MinD simulates a mesh with higher maximum value for local shearing than Sym does, but generates overall less shear deformations. This is more close to the reality, provided that in a real draping process the textile will more likely wrinkle and thereby relieve the shear deformation energy, so that in the end a less deformed fabric with wrinkles will be generated instead of a widely and homogeneously sheared one. Furthermore MinD generally shows more accurate and more robust results (fewer simulation aborts). There are four algorithms available in AFM of which two were used in this evaluation: optimized Energy (oNRG) and optimized Maximum Shear (oMS). The other two algorithms are for UD-tape material and thus were not of interest. The algorithm oNRG iterates the shear deformation energy, which is directly proportional to the shear, to the lowest sum. oMS iterates the mesh to the lowest maximum value of shear. So oMS generates a higher sum of shear deformation with a lower maximum shear value than oNRG. This is generally comparable to the two CPD algorithms mentioned previously. FiberSIM does not present a choice of different algorithms as there only appears to be one.

It cannot be ruled out though that FiberSIM automatically chooses between several algorithms There are three different algorithms implemented in LT. Geodesic (GEO) is driven by the geometry of the part and generates the fiber directions comparable to the creation of geodesic lines. Maximum shear (MAX) optimizes the mesh in regard to minimize the maximum shear occurrence. Energy (NRG) minimizes the sum of the overall shear deformation energy. Therefore MAX produces a mesh with higher shear deformations, while NRG has local shear maxima, but overall less shear deformations. Thus NRG is more close to realistic draping, because a draped fabric will have more likely lower shear deformations with few local wrinkles. All three algorithms simulate accurate flat patterns when draping parts with less complexity. Due to the apparently less complex iteration GEO generates less frequently singularity errors. Therefore GEO should be used for low complexity parts. NRG and MAX are more precise with complex parts, while NRG is slightly ahead of MAX.

User options and input
This section gives a brief overview to which extend the user can define the precise behavior of the ply during simulation in each program. This includes ply contour definition, definition of ramps, implementation of core material into the stacking or derivation of surfaces like outer mold lines (OML). Some programs also offer multiple approaches for seed curve definitions and mesh propagation.

Catia CPD offers a basic range of functionalities like core material implementation, ramp definition or OML derivation in various manners. This gets strongly enhanced by Simulayt AFM which additionally lets the user define a seed curve and order-of-drape functionality, which supports to obtain a more realistic draping result. They share Catia CPD's approaches for ply contour definition which can be zone-based, grid-based or ply-by-ply. Vistagy's FiberSIM offers the most options to define ply behavior during draping simulation, which occasionally can increase complexity for the user. It also offers core material implementation, derivation of OML in various manners and multiple ways of ply contour definition. Especially in regard to handling of large number of plies and custom definition of ramps it has strong advantages. Anaglyph's Laminate Tools offers the largest number of options to define ply propagation over the tool surface and even various methods for mesh size definition. Concerning features like core implementation or complex definition of ply contours it offered the lest options.

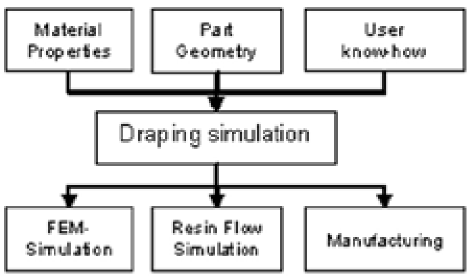
Interfaces
Catia CPD along with the additional Simulayt AFM options and algorithms feature the highest integration into the Catia user interface. Additional interfaces to other software like FEM can be installed with separate programs like Simulayt Composite Link. Vistagy's FiberSIM has its own user interface surface and interacts with Catia primarily on geometry level, but is also compatible to other CAD software. It offers a large number of input/output-interfaces to other software or machines. Due to its own user interface changes e.g. to geometry or draping strategies can be quickly implemented across the whole laminate unlike with CPD and AFM which work with the Catia tree. Anaglyph Laminate Tools is a complete stand-alone draping simulation which only requires one-time geometry input from any CAD software. Compared to all evaluated programs, it features the closest link to FE-simulation. Concerning other interfaces Laminate Tools showed disadvantages.

Summary
Based on the presented results the four draping simulation programs mentioned previously were reviewed in three main categories. The results from the DLR point-of-view are presented in the table below and originate from the objective analysis of the programs and user questionnaires.

	CPD	AFM (+CPD)	FS	LT
Robustness	o	+	+++	++
Precision	o	++	+++	++
Ply contours and surface derivation	++	++	+++	o
Feature management (Ramps, Cores...)	+	++	+++	o
Fiber orientation steering	o	++	+	+++
CAD-user interface integration	+++	+++	+	o
FE-Interface	o	+	++	+++
Other interfaces	+	++	+++	o

Tool chain integration

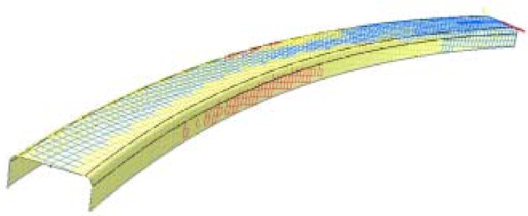
In a wider context, the draping simulation is an essential part of the tool chain. Required material parameters like the critical shearing angles must be fed into the simulation as well as the design of the part. In addition, the acquired user know-how which has been previously presented is fed into the simulation.



Draping simulation in the tool chain

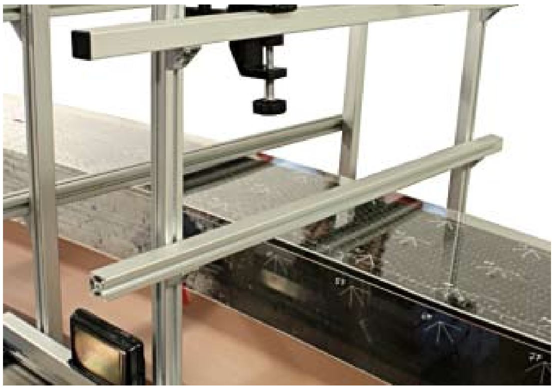
The simulation results are not only used to create flat patterns, but information about fiber directions can be used as well. For example resin flow simulation can import fiber directions to determine the local resin permeability. FEM-simulation also benefits from accurate fiber directions to calculate true part stiffnesses which may defer from the stiffness of the theoretical layup. Closely related is the information of changing material thicknesses due to draping, which is required for calculating tensions as well as obtaining mold surfaces (outer mold line).

Currently the tool chain gets applied to the previously mentioned aircraft C-frame at the DLR. The results from the draping simulation software evaluation were used to create the flat patterns of the frame which shows high complexity due to multiple radii around several axis. NFC-material



C-Frame with simulation mesh

was draped onto a wooden tool and the fit of flat patterns examined. Furthermore, the true fiber angles were optically measured and get currently analyzed. In a further step, the measuring will be repeated with laser light sectioning. Once it is proven that the simulated fiber angles match the real fiber angles after manual draping, simulation results will be transferred to FEM. Thus it can be analyzed to which extend the stiffnesses from the draping-simulated and non-draping-simulated frame defer.



Measuring fiber angles on the aircraft C-Frame

Discussion

By making an extensive evaluation of draping simulation software in order to benchmark and understand them, user guide lines could be established. By understanding how draping simulation works, it can be the key to low-cost, high performance and net-shape parts. The user will be able to save time by doing simulations first time right and avoiding typical errors. Furthermore, design-ers will to some extend be able to estimate the draping complexity of the part geometry beforehand and draping can also quickly be adapted to design changes. Using the tool chain is also a valuable help to build high performance parts for example by utilizing simulated fiber orientations in FEM simulation. It has been proven that with the right draping strategy, simulated fiber angles are close to real fiber angles and hence they may be transferred to FEM. In addition to that, parts can also be optimized in regard to weight by using the knowledge of the fiber angles in the part. Once the flat patterns have the optimal shape, draping can be sped up, up to full automation. Net-shape or near net-shape parts also help to reduce manufacturing cost by minimizing lost excess material.

Conclusion

Because draping simulation plays an essential role in the manufacturing of composite parts, it is important to understand how the programs work and which impact the input parameters have on the simulation result. Thus, the user must be aware of the manners of the results from draping simulation software and how to interpret them in order to achieve low-cost, high performance and netshape parts. In addition to that the value of draping simulation results can be further enhanced by making full use of them in the tool chain.

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