Deutscher Luft- und Raumfahrtkongress 2011
DocumentID: 241434

UPPER WING COVER FOR NATURAL LAMINAR FLOW - ULTRA-PRECISE SHAPE BY PROCESS SIMULATION

J. Bold,
DLR Institute for Composite Structures and Adaptive Systems
Braunschweig D-38108
Germany

OVERVIEW

In the scope of developing efficient future aircraft, fuel saving becomes one of the main issues. The idea of the project LaWiPro – Laminar Wing Production – is to develop and manufacture a part of a wing upper cover fulfilling the aerodynamic requirement of laminar flow. The surface has to be much smoother compared to current wings. Waviness coming from either manufacturing or load has to be kept in a much smaller tolerance band than at current aircrafts. Also steps and gaps coming from assembly should be disregarded.

Two completely different ways may lead to fulfill these requirements:
- Either by stiffening: The structure can be stiffened until it will be within the requested waviness. This could increase weight and therefore fuel use
- Or by the shape of the tool: It is adapted by predicting the local deformations caused by the manufacturing process, like spring-in, warpage, and loads

Multi-Material, Multi-Functional Design:
A multi-material design is developed to eliminate steps and gaps using monolithic carbon with integrated stiffeners for primary structures, metal-hybrid for secondary structures and load introduction areas. The multi-functional design provides the opportunity to integrate anti-icing devices or connectors into the same curing process. Developing innovative process simulation methods gives the possibility to predict the deformations caused by the manufacturing process. The required adaptation of the tooling will be determined first time right, without today's time and cost-consuming iteration loops. The developed methods will be implemented into the Virtual Composite Platform (VCP). Comparing virtual results with real 3D optical measuring from tests ensures the improvement of the methods. Automation is another key issue to produce a part with acceptable costs and quality for the high production rate of single aisle aircrafts. Based on the first investigations done for spring-in, warpage and pre-deformation, automation concepts will be developed to produce the upper wing panel including part of the nose structure. Eventually, the innovative simulation and integration of manufacturing discrepancies and displacements under load on the Virtual Composite Platform might lead to an environmental sensitive design for future aircraft designs.

1. LAMINAR REQUIREMENTS

The requirements for laminar flow on wings can be divided into two main areas:

1) Waviness
2) Steps and gaps

While the waviness is a result of the aerodynamic load but as well the manufacturing tolerances, steps and gaps are purely driven by assembly.

The values for both requirements are very small compared to the dimensions of a wing for a single aisle aircraft and are in the range of the thickness of a single ply.

2. UPPER COVER DESIGN FOR LAMINAR FLOW

In a first step before even beginning with simulation a design for the upper cover was evaluated taking into account the aerodynamic requirement.

The strong request of having no disturbances on the surface led to an integral design with stringers and rib caps cured in one shot. The standard design used in today's aircrafts with cured stringers on a wet skin and riveted rib caps for vertical tail planes or wet stringers on a precured skin again with riveted rib caps for wing covers could not be used. The two main reasons are that rivets would destroy the laminar flow and discrete stringers would lead to non homogeneous surfaces.

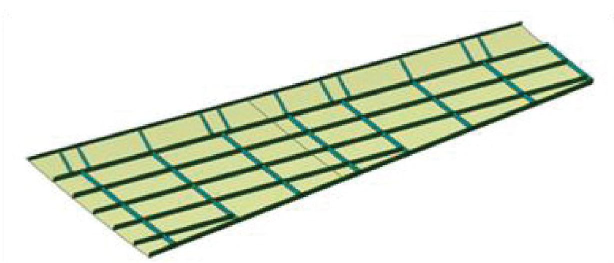

FIGURE 1: Integral design of Upper Cover (1)

The design is an evolution of the U-shape stringer manufacturing used today for flap panels and centre wing box. The U-shape of the stringers has the advantage that no rivet is necessary because the part is co-cured. This philosophy was also used now for the rib caps and resulted in a so called shoe-box design.

3. PARAMETERS FOR ULTRA-PRECISE SHAPE

The parameters influencing the laminar flow in a composite wing vary from pure mechanical behaviour of fibre to the tooling material.

The following list (1-2) will give an idea on the different parameters investigated in the project LaWiPro. The parameters mentioned under 3 will be part of the next project.

1) Mechanical Parameters
   a) Fibre
   b) Resin
   c) Semifinished Prepregs
      i) Unidirectional Tapes
      ii) Fabrics
   d) Layup
      i) Stacking sequence
      ii) Angle Tolerances
         (1) Local
         (2) Global
      iii) Thickness tolerance
2) Manufacturing Parameters
   a) Process
      i) Autoclave
      ii) Out of autoclave
   b) Tooling
      i) Type
         (1) Open
         (2) Closed
      ii) Material
3) Assembly Parameters
   a) Shim free design
   b) Temperature
   c) Exchangeability
   d) Repair

All this parameters cannot be investigated by building full scale parts but have to be simulated before and the main drivers have to be found in senility and robust design analysis.

4. PROCESS SIMULATION

In the past, simulations, especially finite element calculation, were mainly done to dimension parts for strength and stability, having the displacements and therefore the waviness as a result. For laminar wings further simulations are necessary. Additionally to the above mentioned criteria, the resulting local displacement on wing covers could be one of the main drivers of the design. But also the influences of the manufacturing tolerances have to be taken into account for the design.

Composite structures need an even more integrative approach between engineering, manufacturing engineering and manufacturing. The capacities of the simulation software enable also manufacturing engineering to find the key drivers for tolerances.

In the following chapters the simulations will be shown and the benefit in simultaneous working highlighted.

4.1. Simulation of the Mechanical Behaviour

Finite element models are used to simulate the mechanic behaviour of structural parts (2) (3) (4) (5). In general, the global deformation of a wing is calculated based on a coarse mesh with single elements for each area between ribs and stringers. The resulting displacement can be seen in FIGURE 2.

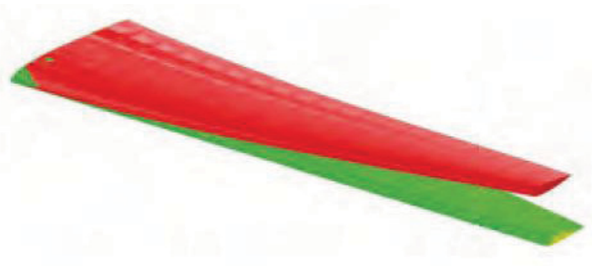

FIGURE 2: Global and local Displacement of a Wing (6)

4.1.1. Waviness

Local deformations inside these areas can be only seen using fine meshes. In the project LaWiPro only the outer wing will be investigated. The local displacements resulting from aerodynamic pressure distribution are only from interest. To neglect the global deformation the part is pinned on stringers and spars. A typical fringe plot can be seen in FIGURE 3.

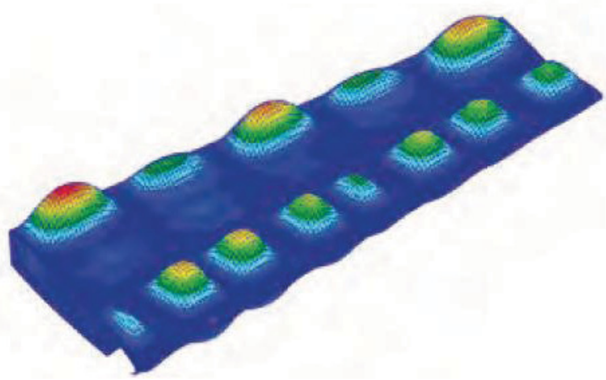

FIGURE 3: Waviness under Aerodynamic Load (6)

Mechanical Parameter Study

The main driver for the layup is the resulting strength in the part and therefore the layup from stress engineers. Here the influence on design and manufacturing costs is the highest.

The fibres available today have a range from high tenacity (HT) to high modulus/ high strength (HMS). Different than in automotive industry or formula one, only a small range of fibres is qualified with dedicated epoxy resin systems. The two main fibre types - HT and IM - were compared with different semi-finished prepregs. In a first investigation different layups were simulated on a cut out of the upper cover with the largest free dimensions and the highest displacements from aerodynamic loads.

To find the most influencing fibre direction, 4 different layups with the same thickness made from IM unidirectional material were investigated:

1) 0° Layup in span wise direction
2) 90° layup in rib direction
3) 0°/90° Layup
4) ±45° Layup

The smallest displacement was achieved using the 90° layup (FIGURE 4)

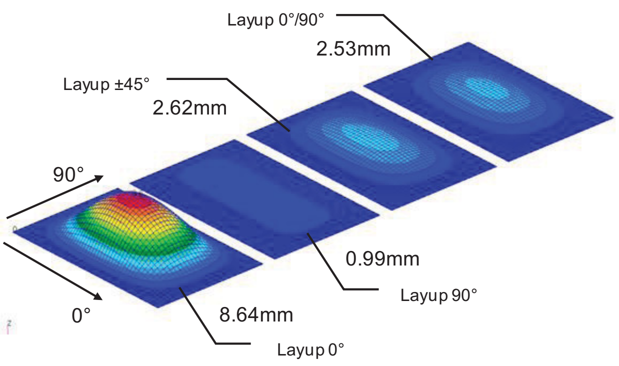

FIGURE 4: Displacement plots for main fibre direction (7)

Based on this result the stacking sequence was varied resulting in a reduction of displacement by keeping the same in-plane properties (FIGURE 5).

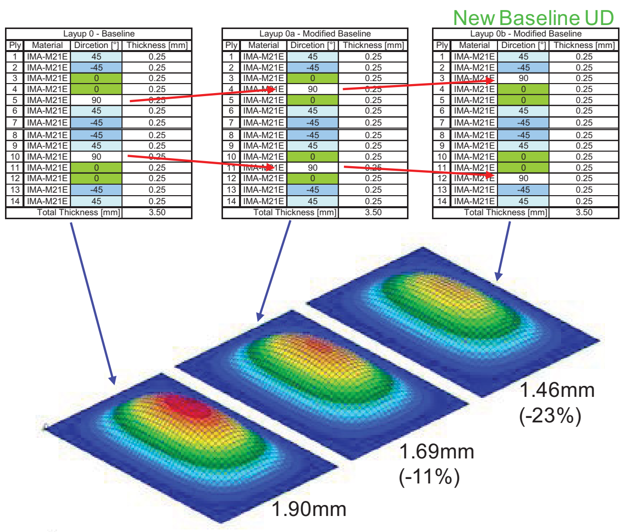

FIGURE 5: Displacement plots modified layup (7)

In a final step for the best laminar layup the ±45° unidirectional plies were replaced by HT and IM fabrics with the same thickness as a single unidirectional ply. This results in the same out of plane stiffness for HT fabric also the fabrics are in general softer. With IM fabrics – which are not qualified today – even less displacement was calculated. These results with fabric are especially very important, because then the shoe-box design will have symmetric layups in the skin as well as in stringers and rib cabs. Also fabrics as outer ply have better impact behaviour and are easier to drill.

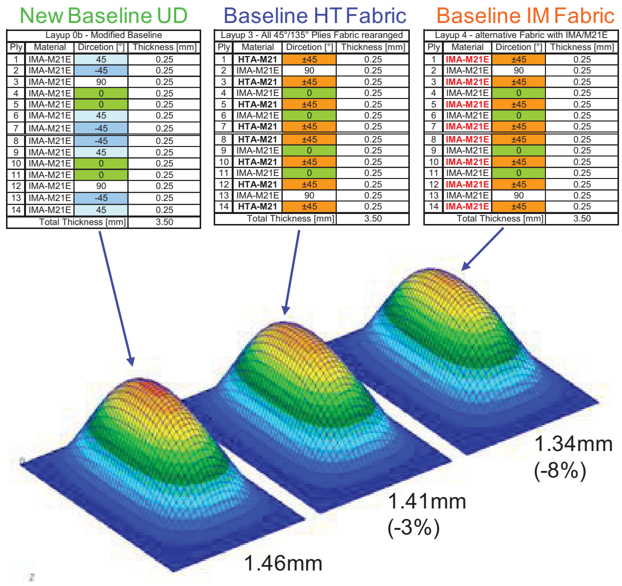

FIGURE 6: Displacement plots fabric layup (7)

Parallel to the layup investigation for maximum stiffness and minimum weight, the influence on fibre angle and thickness tolerance was simulated. While local and global fibre angles changes - between ±5° - have a minor effect on the displacement, the thickness tolerance is the main driver. Here, the fibre volume fraction was varied by the known tolerance and new stiffness values for the ply was calculated and simulated in the finite element model.

Standard analytical formulas to calculate the stiffness of a ply based on fibre and resin properties were used to reverse calculate the single stiffness for standard fibre volume fraction. Base on these values the stiffness of the ply was automatically calculated using the capacities of MSC.Patran.

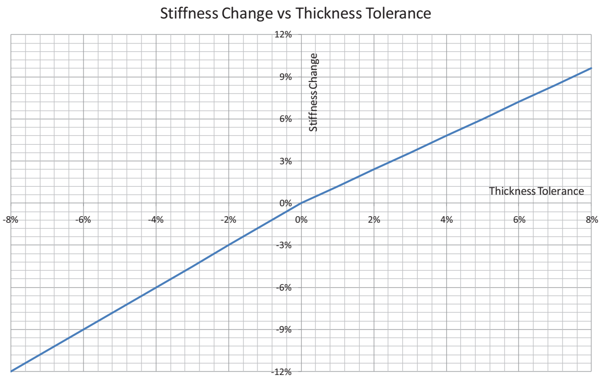

FIGURE 7: Influence of FVF on stiffness (7)

The results can be seen in FIGURE 7 were the fibre volume fraction was recalculated into a change in thickness. The graph shows the over-proportional behaviour and leads to the conclusion, that the thickness tolerance of the cured part is the most critical parameter for laminar flow.

This finally leads to a layup for a laminar wing upper cover with ±45° fabrics and unidirectional plies in load and cross load direction with as less tolerance in thickness direction as possible from manufacturing point of view.

4.1.2. Steps and Gaps

The simulation of the connection area between upper cover and nose cannot be done by simple linear calculation as for the waviness. The non linear behaviour of this area asks for a precise calculation using contacts between the different parts. The two different displacements coming from mechanical loads can be seen in FIGURE 8. In the simulation the difference in displacement between two finite element nodes was evaluated.

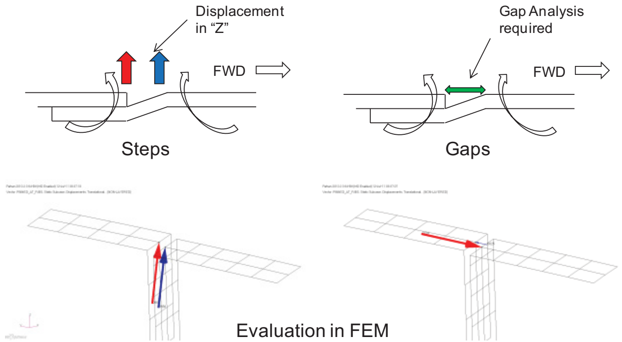

FIGURE 8: Steps and Gaps Definition (1)

Different designs are still under investigation. All show that the thickness tolerance of the overlapping area has to be on the negative side to be able to have a negative step which could be shimmed to the required aerodynamic requirements.

4.2. Simulation of the Manufacturing Behaviour

4.2.1. Thermo-Elastic Effects

Looking at the title of this paper, clearly the process simulation has to be the focus. Based on the above illustrated investigations two effects are from interest:

1) Spring-In
2) Warpage

Spring-in is typically found at angles and between stringers where the inner ply in the radius is shrinking more during the curing process than the outer one. As a result the angle is getting smaller.

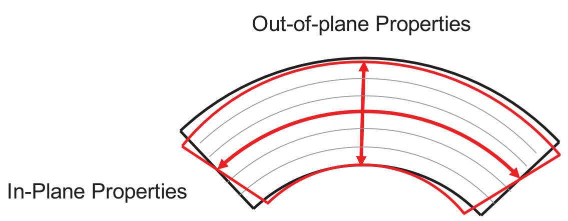

FIGURE 9: Spring-In Effect (1)

Warpage is an effect related to the tooling material and leads – also with symmetric and balanced layups – to a bending of the part.

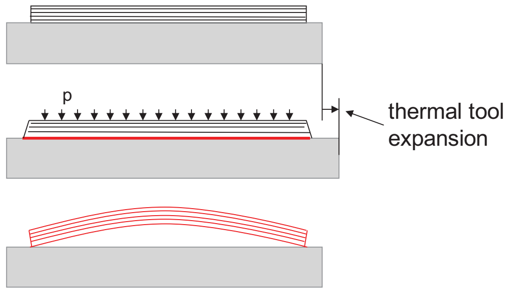

FIGURE 10: Warpage Effect (1)

These effects can be investigated in three different ways:

5) Empirical
6) Semi-analytical
7) Simulation-based

The empirical based approach with trial and error is based on experience.

The semi-analytical approach uses phenomenological investigations based on element manufacturing trials and simplified meshes. This method will be easy to use for manufacturing engineering.

The last, simulation-based method is a phenomenological and mechanical based approach which needs high experience in structural mechanics and composites.

The last two methods will be highlighted more deeply in the following chapters.

Semi-analytical Method

The idea is to have an easy to use method which is also applicable to full scale structures, e.g. an upper cover. The simulation is based on the mesh used for structural analysis and therefore no additional meshing is necessary in manufacturing engineering (8) (9).

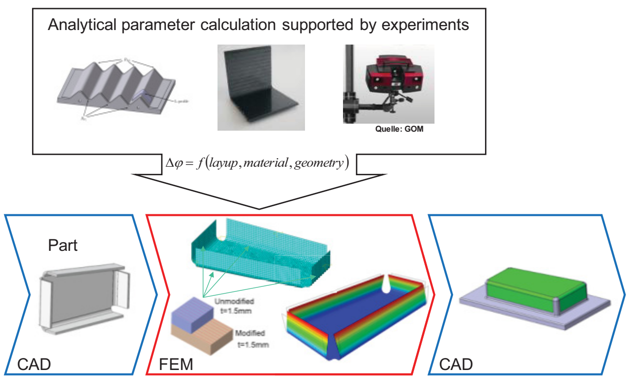

FIGURE 11: Simulation Procedure for the Semi-analytical Method (1)

The material values will be derived from simple manufacturing trials with different radii, stacking and layup method in female and male tools. The tooling as well as the sample will be measured with the 3D optical measuring equipment ATOS of the company GOM and the appropriate factors were calculated. Validation was done on a more complex part already having the principle shape and design of the shoe-boxes used in LaWiPro (FIGURE 12).

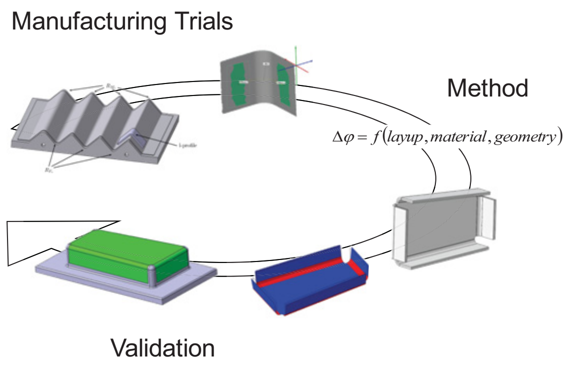

FIGURE 12: Validation of the Semi-analytical method (1)

Simulation-based Method

The high sophisticated simulation-based method is dedicated to experienced simulation engineers. Compared to the method mentioned before, fine meshes are needed to represent the 3D behaviour of a single ply. Therefore solid element meshes for every layup are used with at least one element for a ply in thickness direction. The complexity of these models - even for small test samples - is already very high.

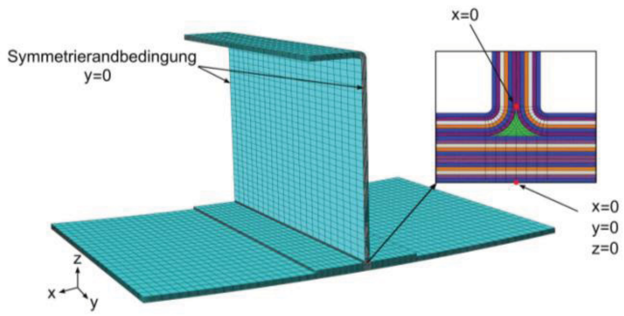

FIGURE 13: Typical FE-model for the Simulation-based method (10)

The calculation simulates the complete curing cycle and therefore the mechanical and thermal behaviour of the resin during the curing has to be measured and used as input parameters for the transient analysis.

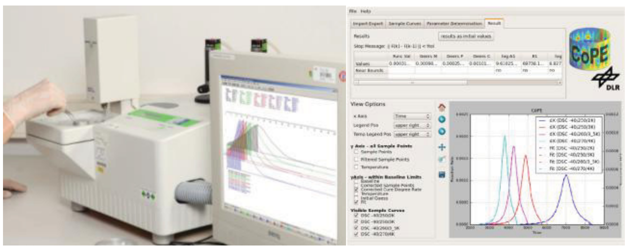

FIGURE 14: Measurement of reaction kinetics of the resin (10)

As output, not only the distortion of the part can be examined but also the frozen residual stresses. These stresses might lead to smaller reserve factors in areas where anyway the failure will occur first and have to be added to the mechanical stress from aerodynamic loads.

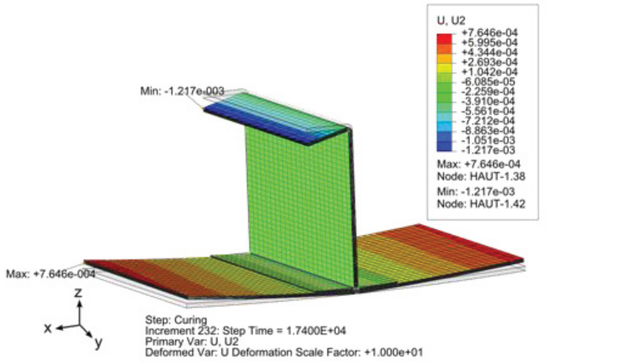

FIGURE 15: Distortion from Simulation-based Method (10)

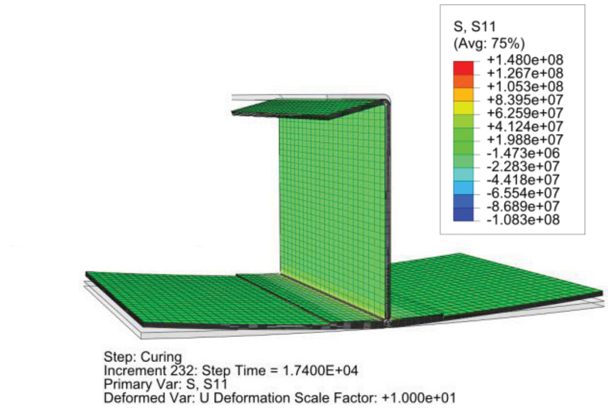

FIGURE 16: Residual Stress from Simulation-based Method (10)

4.2.2. Draping and Flattening

The simulation of draping and flattening of plies is standard in a lot of industries dedicated to composite manufacturing. Based on the idea of paper free offices, MSC.Laminate Modeller was used to investigate different ply shapes and the corresponding flattening and ply shape. The other advantage is the direct coupling to the design software CATIA V5 with CPD and AFM modules.

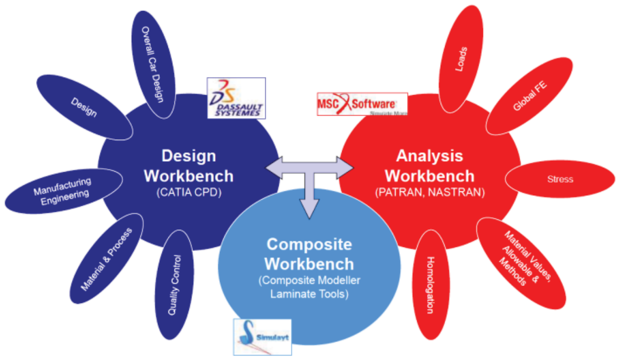

FIGURE 17: Software programmes used for draping simulation (11)

First simulations done in MSC.Patran showed that the design with ribs in flow direction would lead to unbalanced and non symmetric layups. For ribs perpendicular to stringers would allow easier manufacturing. The amount of parts necessary per month led to a redesign of the upper cover with a standard design where ribs are perpendicular to stringers.

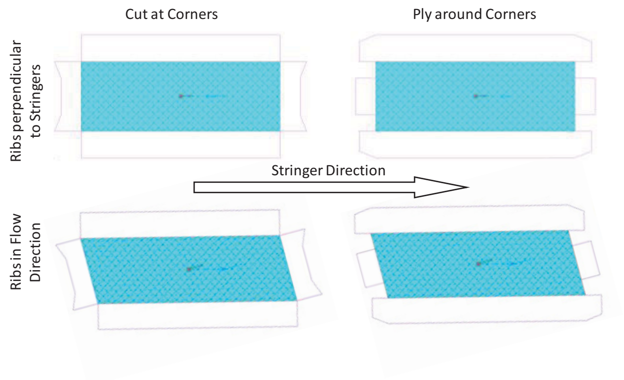

FIGURE 18: Comparison of different draped plies and geometry

The design of the show-boxes is still a challenge in today's software because overlapping plies – although they can be manufactured – cannot be simulated properly. A flattened ply as seen in FIGURE 19 can only be done by hand. Here improvements for the future are clearly necessary.

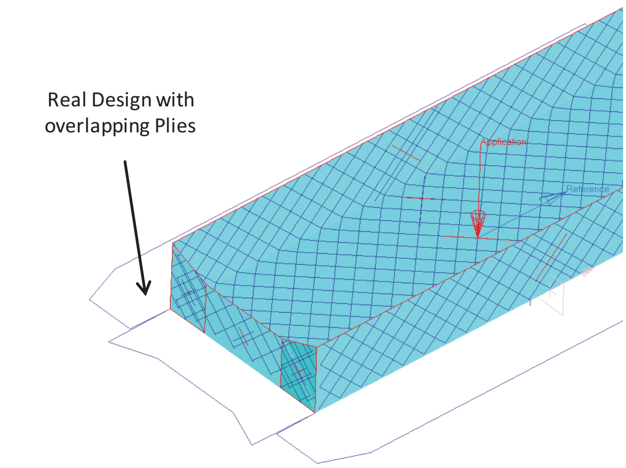

FIGURE 19: Flattened Ply with overlapping plies

4.2.3. Manufacturing Process

As a last step the automated manufacturing process will be simulated to find the bottle neck in production.

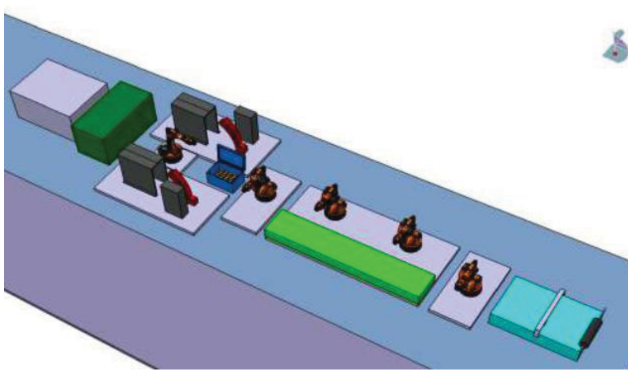

FIGURE 20: Simulation of the manufacturing process (1)

5. VALIDATION OF SIMULATION

Simulations always have to be validated by simple tests. A small stringer stiffened panel with two stringers and two rib cabs was chosen to verify spring-in and warpage, the draping simulation as well as the automation.

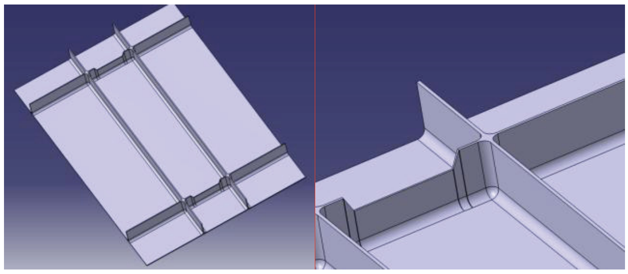

FIGURE 21: Verification Panel (1)

To understand the different effects in detail and verify the simulation by test, parts were getting more and more complete as shown in FIGURE 22.

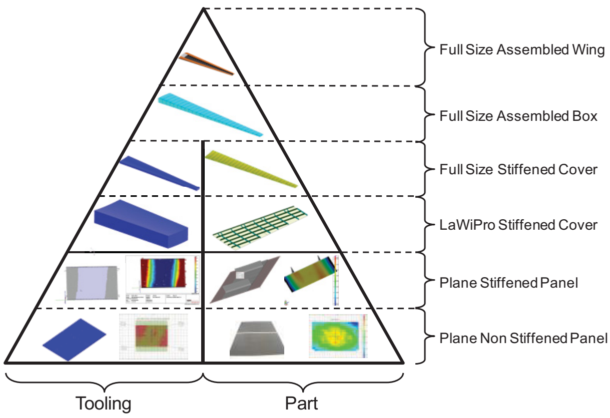

FIGURE 22: Verification Pyramide (1)

The different effect mentioned in the chapters before were divided into different parts. Single effects as layup, tooling material or the influence of fabric could be seen for manufacturing.

Validation Matrix	Part	Investigation
Aluminium Tool	Non Stiffened Plate 7.5mm Unidirectional	Warpage
Aluminium Tool	Non Stiffened Plate 3.5mm Unidirectional	Layup
Invar Tool	Non Stiffened Plate 3.5mm Unidirectional	Tooling Material
Invar Tool	Non Stiffened Plate 3.5mm Fabric and Unidirectional	Influence of Fabric

TAB 1: Validation Matrix (1)

The test parts as well as every tooling were measured using the optical system ATOS of the company GOM.

The manufactured parts were then used in a so called snap-through test to verify the mechanical behaviour under aerodynamic loads (FIGURE 23).

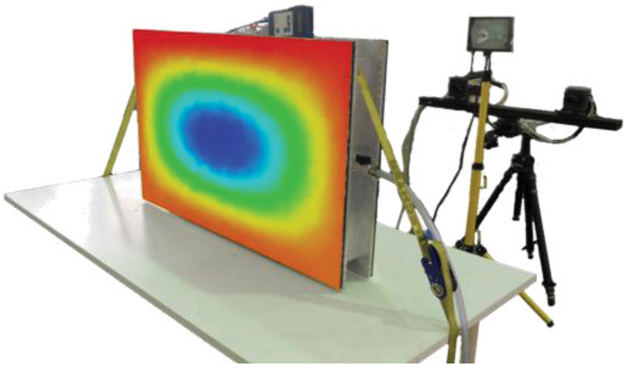

FIGURE 23: Verification Test for mechanical deformations (1)

6. THE VIRTUAL COMPOSITE PLATFORM

Development time in aerospace is normally longer than the time in scientific projects as LaWiPro. Different departments and disciplines are involved in the normal process of aircraft development. Based on the experiences in formula one where the development time is one season, the idea of a common platform was created to share all information and work in parallel: the Virtual Composite Platform (VCP). In contrary to a process chain, here all developments are done simultaneously and information's are exchanged electronically. The project was used to follow this way and showed that with today's software no paper s necessary anymore.

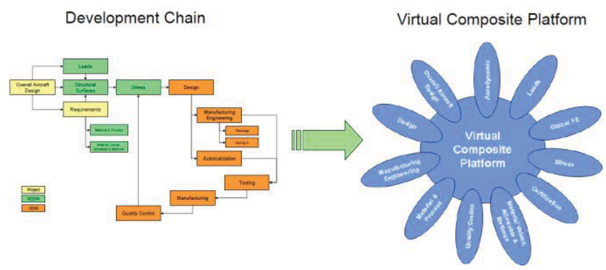

FIGURE 24: Virtual Composite Platform (11)

7. CONCLUSION

Simulation tool can be used in various fields during the development of an aircraft structure. Today's software allows the exchange of data without paper and therefore can deal with much more information than in the past. Easy to use simulations methods as well as high sophisticated ones have to be used in parallel to have a precise wing upper cover first time right. Still verification on a smaller lever of the quality pyramided is essential to save time and cost.

Literaturverzeichnis

1. **Bold, J., et al.** LaWiPro – Meeting Braunschweig April 12th - 13th 2011. Braunschweig : DLR, 2011.
2. **MSC Software.** *MD Nastran 2010 Documentation.* [Acrobat] Santa Ana : MSC Software, 2010.
3. **MSC Software .** *MD Nastran MD Demonstration Problems.* [Acrobat Document] Santa Ana : MSC Software, 2010. MDNA*V2010*Z*Z:Z*MN-DPM.
4. **MSC Software.** *MD Nastran MD Demonstration Problems.* [Acrobat Document] Santa Ana : MSC Software, 2010. MDNA*V2010*Z*Z:Z*MN-DPM.
5. —. *MD/MSC Nastran 2010 Quick Reference Guide.* [Acrobat Dokument] Santa Ana : MSC Software, 2010. MDNA*V2010*Z*Z*Z*DC-QRG-VOL-1.
6. **Bold, J.** *Upper wing cover for natural laminar flow - Ultra-precise shape by process simulation.* Braunschweig : DLR, Innovationsberecht 2010.
7. —. LaWiPro - Layup Investigation. Braunschweig : DLR, 2011.
8. **Kappel, E.** *Gegenüberstellung verschiedener Modellierungsstrategien unter Verwendung in ABAQUS implementierter Elementtypen am Beispiel eines isotropen gekrümmten Profilkörpers der Dicke 4mm.* Braunschweig : DLR, 2011.
9. **Bold, J.** *Comparison of different Element Types in MD NASTRAN based on an Isotropic Angle under Tension.* Braunschweig : DLR, 2011.
10. **Wille, T.** *Vergleich von Methoden zur Vorhersage herstellungsinduzierter Residualspannungen und Verformungen von CFK-Bauteilen.* Wiesbaden : NAFEMS-Seminar, NAFEMS 2011.
11. **C. Hühne, J. Bold.** *Virtual Composite Platform - State of the art (day-after-tomorrow)?* Braunschweig : DLR, 2010.