MANUFACTURING SIMULATION ENABLING COMPLEX COMPOSITE SINE WAVE SPARS

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Abstract

The spar of an aircraft is a highly loaded massive beam, whose structural performance can be improved by a sinusoidal shaped web. Premium AEROTEC demonstrated the manufacturing of a 2.5m long segment of a full-scale sine wave spar for a typical short range aircraft using carbon composites and the VAP resin infusion process. Multiple fiber architectures like UD, NCF and Fabrics, thicknesses ranging from 4.0 mm to 20.0 mm and highly curved areas have been combined into one single part, making it a challenge for manufacturing. The early demonstrators revealed constant offsets of the measured shapes vs. CAD while maintaining tight geometrical tolerances over several parts, highlighting reproducible manufacturing effects. To enable the application of sine wave spars to industrial aircraft programs, those manufacturing effects need to be compensated and more automation is necessary, especially for the labor intensive layup and draping process. The optimization and validation of the manufacturing process by simulation is the key to ensure that the investment into expensive manufacturing equipment is a positive business case. Within this paper the simulation of key manufacturing steps like draping and curing is shown for the sine wave spar example, using ABAQUS in combination with user defined material models.

1. Introduction

A spar is a highly loaded beam in the wing of an aircraft running from the fuselage to the wing-tips. While the spar is also subjected to high bending loads it is carrying virtually all the shear force at the wings. Thus buckling of the web is a major threat to the spar while it must be able to carry multiple times the aircraft weight, which makes it a massive part near the wing-root. It is known that sinusoidal shaped cross-section improves the stability of the web while maintain a low overall weight. But the superior structural performance of a sine wave spar is currently limited to niche applications as its complex and expensive to manufacture, especially the junction of the curved web to the flanges is a challenge.

In a previous project Premium AEROTEC (PAG) and Boeing demonstrated the manufacturing of a sine wave spar from carbon composites using the Vacuum Assisted Process (VAP) resin infusion process. By using the good drapeability of dry-fiber materials and a combination of multiple fiber architectures including non crimped (NCF), woven and unidirectional (UD) fabrics the spar can be produced as one solid part with a single infusion and curing step, not requiring any assembly or significant machining operation afterwards. Three full-scale demonstrators were produced representing a 2.5m segment of a sine wave spar including all design features necessary for application in a short range aircraft like a B737 or A320. Detailed geometrical measurement revealed a significant but constant offset for the manufactured parts vs. designed shape. The small scatter between the demonstrators highlight reproducible manufacturing effects which need to be compensated to achieve the desired close tolerances. To enable the application of sine wave spars to industrial aircraft programs, those manufacturing effects need to be compensated and more automation is necessary, especially for the labor intensive layup and draping process. A typical short range aircraft has four up

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to 20m long spars, which would require high investments for tooling and manufacturing equipment. Therefore simulation is necessary to optimize and validate the manufacturing process before the first hardware is ordered.
Within this paper Premium AEROTEC demonstrates the application of finite element based draping and curing simulation to the sine wave spare. The draping simulation is performed using ABAQUS explicit solver with an user material. ABAQUS standard also in combination with an user material is used for simulating the curing process.

Figure 1. Sine Wave Spar, 2.5m long 1:1 scale segment of a heavily loaded wing spar made from CFRP, Ref. [2]

2. Industrialization

The manufacturing of the demonstrators revealed remaining technological questions, which need to be answered before industrial application. Even though PAG showed that the quality requirements and process stability are reached for the demonstrators, the hand lay-up process and several iterations to find an adequate infusion process is not applicable on industrial processes. The process needs to be highly automated to limit recurring costs, but also nonrecurring costs for toolings and the automation equipment must be reduced. The complete process should be simulated in advance to ensure the manufacturability in terms of draping and infusion of the component with all design features needed and avoid rework on toolings to obtain the final geometry within the tolerances. The wing spar fiber preform is realized with four separately produced performs, the cap and the web, each split in two parts. The demonstrator is produced by hand lay-up, that needs to be automated before moving into industrial use. Because of its general capability for high degree of automation, good capability for serial production and significantly lower manufacturing cost, the resin infusion process is realized.

Critical steps for manufacturing sine wave spars are the fabric draping behavior, dry areas following an insufficient resin infusion and curing induced distortions on the final part, which affect either the mechanical performance or the assembly tolerances of the spar. The complex shape of the web leads to high shear deformations on the fabric.
The draping process requires a material, which is capable of high shear deformations without losing the fiber architecture. The draping tests with woven and non crimped fabrics showed that non crimped fabrics cannot be used for the web, as the occurring deformations causes significant gaps up to the loose of fiber architecture. With fabric material it is possible to drape the web. The next important step for the successful manufacturing is the definition of the flat pattern for each layer. In CATA V5 the tool Advanced Fiber Modeler (AFM) is a kinematic draping algorithm to generate the flat pattern and it gives an indication if draping problems might occur. This algorithm gives good results for the 0/90° plies, but fails for the ±45° plies, as shown in Figure 2. PAG determines the cutting for the ±45° plies experimentally and iteratively during the hand lay-up process of the demonstrator.

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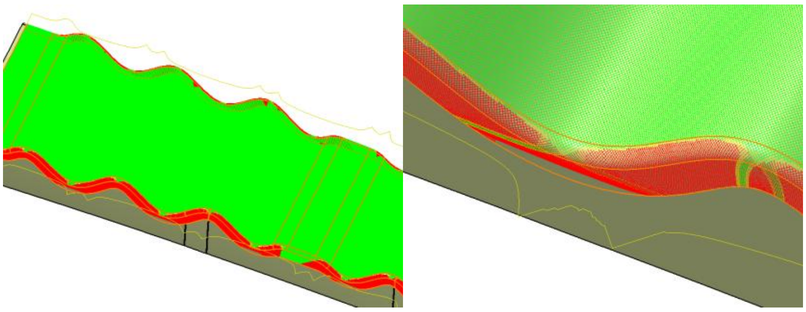

Figure 2. Flat pattern extracted with CATIA V5 AFM for ±45° ply

3. Simulation

The industrial manufacturing of complex composite parts requires a simulation process to minimize rework and ensure manufacturability before invest. For the spar PAG simulates the draping process and thermal induced distortions after curing.

3.1. Draping simulation

The draping simulation is performed in ABAQUS using user subroutine VUMAT with a material model by PENG et. al. [1] which developed a hyperelastic constitutive material model. The material model simulates fiber stretching in warp and weft direction and fiber shearing. The goal of the simulation is to show the drapeability of the material and it is not considered to predict fiber orientation or local fiber volume content.

The finite element model for draping simulation consists of three independent parts the tooling, the fabric and the end effector, with in total almost 1 000 000 elements. The boundary conditions consist of the fixation of a single node on the tooling, which is modeled as rigid body. The end effector is moving in the direction of the tooling, draping the fabric. A friction interaction exists between the fabric, the tooling and the end effector.

The material data for the woven fabric are taken from Ref. [1]. To examine the usage of the material model for NCFs, PAG performed bias extension tests to characterize the shear behavior. The test results are implemented to the material model. The initial shape of the simulated fabric is rectangular and follows the curvature of the tooling. After simulating the draping of the ply, the elements, which are outside the final ply geometry are removed from the model and the analysis is rerun with the new ply shape. This procedure is performed several times until the draped ply shape is close to the nominal ply geometry. Figure 3 shows the initial and final ply shape.

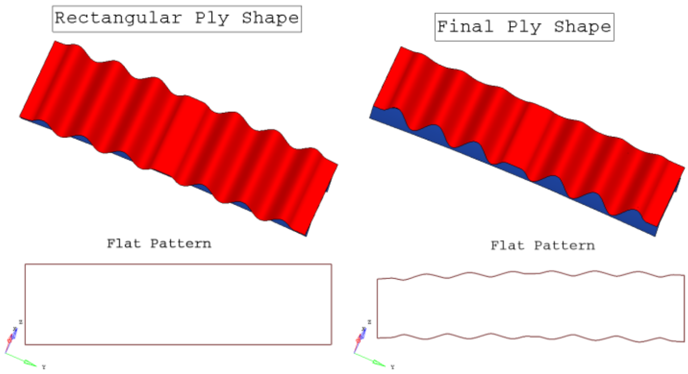

Figure 3. Shape of the cutting geometry

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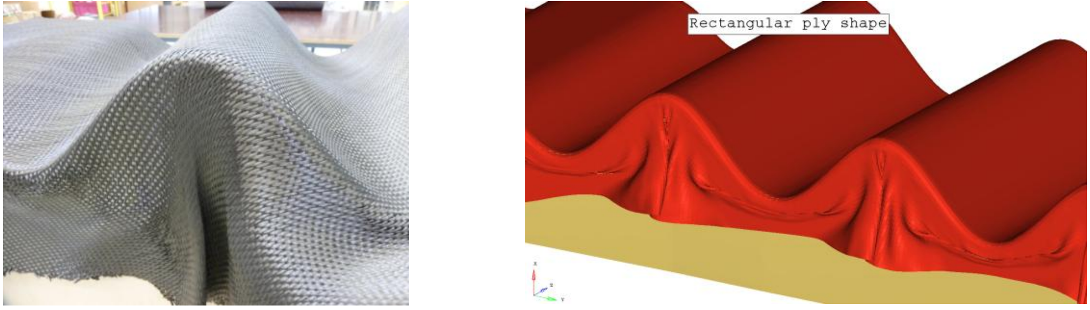
The simulation shows a good correlation with the manufacturing trials on the demonstrator. In Figure 4 it can be seen, that location, size and shape of wrinkles is similar.

Rectangular ply shape



Final ply shape

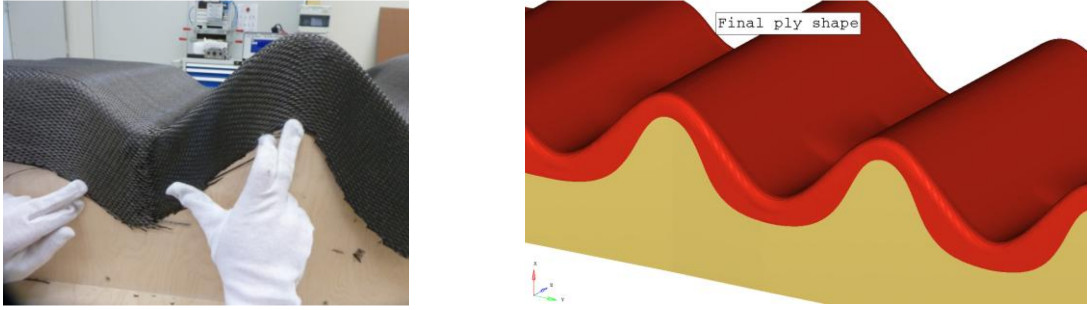


Figure 4. Woven fabric: comparison of manufacturing trials with simulation

To examine the usage of the material model for non crimped fabric materials, the draping simulation is additionally performed with NCF material properties. This simulation confirms that the material cannot be used for the web, as wrinkles occur on areas which are heavily deformed, see Figure 5.

Figure 5. Draping of ±45° NCF ply

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3.2. Simulation of curing induced distortions

The curing of composites results in manufacturing induced distortions. The component is cured at elaborated temperatures. At this temperature the curing tool expands and the tool geometry distorts. Therefore, the most important factor for simulation of curing induced distortions is probably the thermal expansion of the curing tool and the thermo mechanical distortions due to the anisotropic thermal expansion of the composite component during cooling to environment temperature. The polymerization of the epoxy resin within the isothermal curing state after the liquid resin infusion process shrinks the resin volume and generates material strains that additionally distort the component. These effects interact with each other with the thermal mechanical deformation of the curing tool and composite component. Additionally the component geometry, the composite material behavior, the stacking sequence and draping behavior as well as the temperature field and heating rate are essential parameters for the distortional behavior of the composite component.
It is often not necessary to simulate these effects in all their details for an industrial relevant application. The most important factors are the thermo mechanical expansions and volume shrinkage which are influenced by the component geometry, fiber orientation in terms of the draping behavior and the part tool interaction. PAG developed a nonlinear thermo mechanical finite element simulation, which includes these effects. The model of the sine frame consists of nearly 100 000 elements which include the geometrical draping behavior and stacking sequence of the composite material. Figure 6 shows the CAD geometry, the complex distortion of the frame and the increased deformations at the outmost areas. Although the correlation of the distortions to measurements is difficult to accomplish, the simulation shows the most critical areas and permits an assessment of the distortion sensitivity of the structure in terms of variation of fiber orientations.

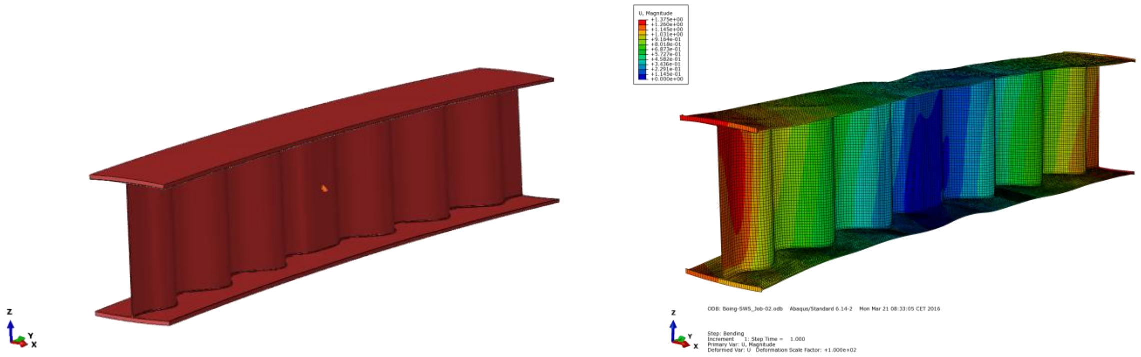

Figure 6. CAD model for curing simulation and curing induced distortions

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4. Conclusion

The manufacturing simulations enable the virtual production development of complex shaped parts made from composites. The draping simulation reduces the number of iterations for the definition of the flat pattern, studies on drapeability and the definition of the layup strategy. In addition different handling processes and manufacturing concepts can be evaluated. The curing simulation provides the distortions of the final part. Beside these the simulation also identifies the critical areas of the part in an early state. It allows to define the tolerances for single manufacturing parameters. While the industrial trend in smart manufacturing is the monitoring of all manufacturing parameters and measuring more and more areas of the part, the simulation helps to collect only the relevant data. The relevant locations and process parameters are identified in advance and assist to develop an integrated manufacturing monitoring concept.

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