MESO-MODELLING OF BIAXIAL NON-CRIMP FABRIC FOR COUPLED DRAPE AND INFUSION SIMULATION

J. Sirtautas[1*], A. K. Pickett[2], P. Lépicier[3]

[1]*Institute for Aircraft Design (IFB), University of Stuttgart, Pfaffenwaldring 31, 70569 Stuttgart, Germany*
[2]*Engineering Systems International, Mergenthalerallee 15-21, 65760 Eschborn, Germany*
[3]*Ecole des Mines de Douai, 941 Rue Charles Bourseul, 59508 Douai Cedex, France*
**justas.sirtautas@ifb.uni-stuttgart.de*

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Abstract
A modelling methodology to treat drape of NCF at the meso scale is presented. The model allows all dominant tow and stitch interactions to be represented, and is made deliberately coarse so that analysis of problems at the structural scale is feasible. A further novel aspect of the work is subsequent coupling of results to meso-scale resin infusion simulation. Compaction, bending, friction and specific testing of stitch mechanical properties are used to calibrate the drape model; whilst, testing of tow permeability and inter-tow race tracking for equivalent permeability are needed for the meso-scale infusion model. Final validation is performed on a coupled draped hemisphere and infusion study.

1 Introduction
Liquid Resin Infusion (LRI) techniques are today widely used for aeronautical, automotive and similar high-performance composite applications. Many variations for infusion exist ranging from Resin Transfer Molding which injects resin under pressure into matched metal tooling through to methods using vacuum and one sided tooling with membranes. The Vacuum Assisted Resin Infusion (VARI) process, for example, is one variation where vacuum and atmospheric pressure are exploited to compact and infiltrate the component under a flexible membrane. Due to low pressure gradients in resin flow (up to 1 atm (~0.1 MPa)) and potentially complex part geometry the strategy for successful infusion has to be carefully chosen.

For complex geometries the fabric may undergo severe global and local deformations. Furthermore, these deformations greatly influence permeability distribution for subsequent resin infusion. This requires either many prototype trials to be performed or numerical simulation to predict both the drape and infusion processes and account for changes in fabric deformation on permeability distribution. Methods are presented here which perform a coupled drape and infusion simulation. Due to the usage of complex fabrics (biaxial, triaxial, etc.) exhibiting highly complex behavior under deformation, a detailed meso-scale modeling approach is applied to capture accurate mechanical deformation phenomena's of the fabric. In this paper a popular biaxial NCF with chain stitching is considered.

2 Fabric FE model and mechanical characterization

The fabric under consideration is depicted in figure 1. The FE Representative Volume Element (RVE) is shown in figures 1-2. 8-node solid elements are used for tow modeling. In addition inter-tow and inter-ply gap elements that have no stiffness are used to fill empty spaces – 'gaps' – between the tows and to connect plies of the fabric. These are needed for flow modeling in the subsequent infusion simulation. Stitching is modeled by 1-D bar elements exhibiting non-linear properties. Draping simulation is performed using PAM-CRASH™ software [1].

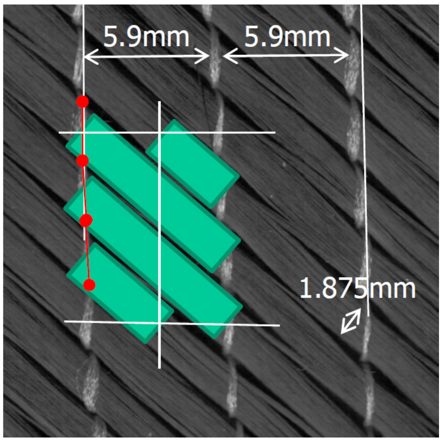


Figure 1. Biaxial NCF with a Representative Volume Element shown

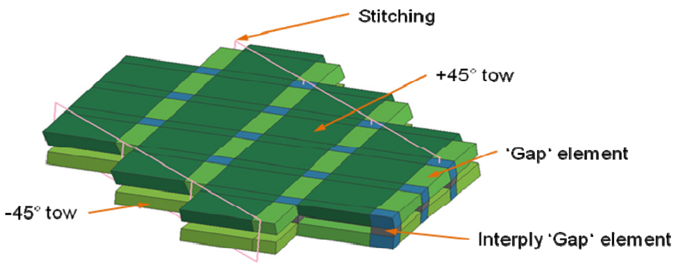


Figure 2. RVE of biaxial NCF

A highly non-isotropic fabric deformation behavior is modeled by combining a linear elastic material law for tows in the fibre direction and a hyper-elastic law for transverse compaction in the other two orthogonal directions. In plane fabric deformation behavior is the outcome of the meso-model structure.

2.1 Fabric bending behavior

Simple bending tests were performed on fabric specimens of 40mm width and different length cut in +45/-45 tow direction, so that both plies would contribute to bending stiffness. The specimens were supported at one end and allowed to bend under self weight (fig. 3). The simulation model was then calibrated to reproduce test results within 10% limits. Elastic material data for the tows is given in table 1.

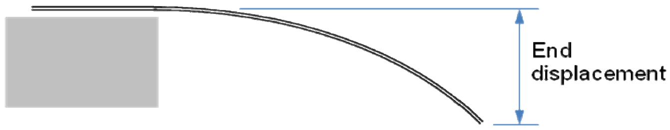


Figure 3. Fabric bending test scheme

E^f_{11}, GPa	$E^m_{11}, E^m_{22}, E^m_{33}$, GPa	G^m_{12}, GPa	G^m_{23}, GPa	G^m_{13}, GPa	ν	ρ, kg/mm^3
230	1.0E-5	0.20	3.8E-3	0.20	0.09	1.0E-6

Table 1. 'Linear tow' material parameters

2.2 Fabric behavior in compression

Fabric compaction has an influence on drapeability of the fabric, but it has even more important effect for infusion properties of the preform causing variations in local fiber volume fraction (V_f). Experimental compaction data [2] was used to calibrate the hypo-elastic through thickness compression behavior (experimental and simulated pressure versus thickness curves are given in figure 4).

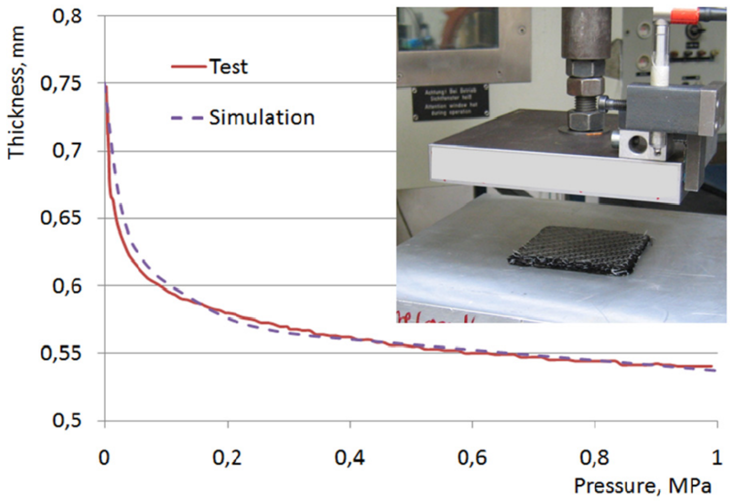
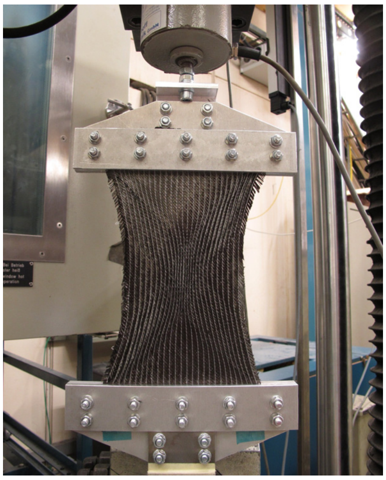
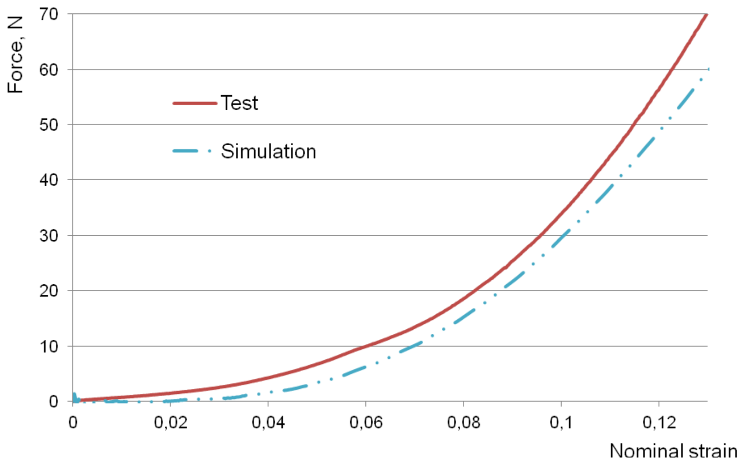


Figure 4. Fabric compaction test [2] and simulation fitting results

2.3 Fabric elongation in stitching direction

It is assumed that under low strain the stitching stiffness contribution is relatively high, and therefore a bias extension test was performed to characterize 1-D bar elements for the stitches in the FE fabric model. A test setup, test and simulation fitting results are given in the figures 5a, 5b.





(a) (b)

Figure 5. Fabric stretching test setup (a), test and simulation fitting results (b)

3 Draping test and simulation

The hemisphere draping test involves a half-sphere (150mm in diameter) over which the fabric is draped under displacement control (fig. 6). Resulting reaction force is measured. Calibrated springs apply constant pressure (3.35 kPa) to the blank holder rings that help maintain the fabric in a state of tension. Friction between aluminum blank holders and fabric was estimated to be 0.22 and included in the simulation.

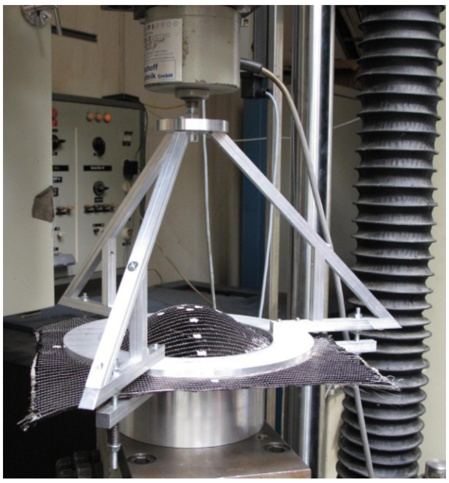


Figure 6. Hemisphere draping test setup

The draping simulation model consists of circa. 700.000 elements and CPU time required on 16x2.53 GHz processor was about 12 hrs. Figure 7 shows displacement versus force diagrams from the test and simulation.

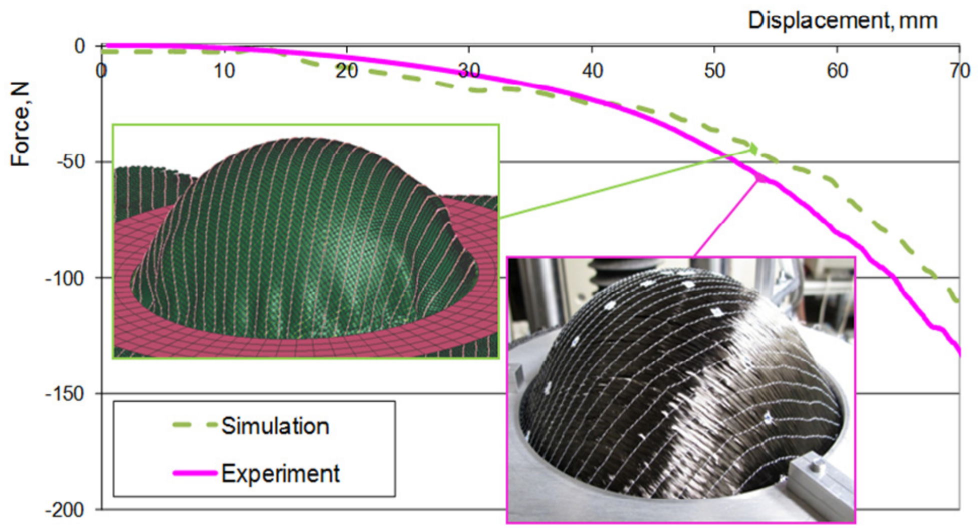


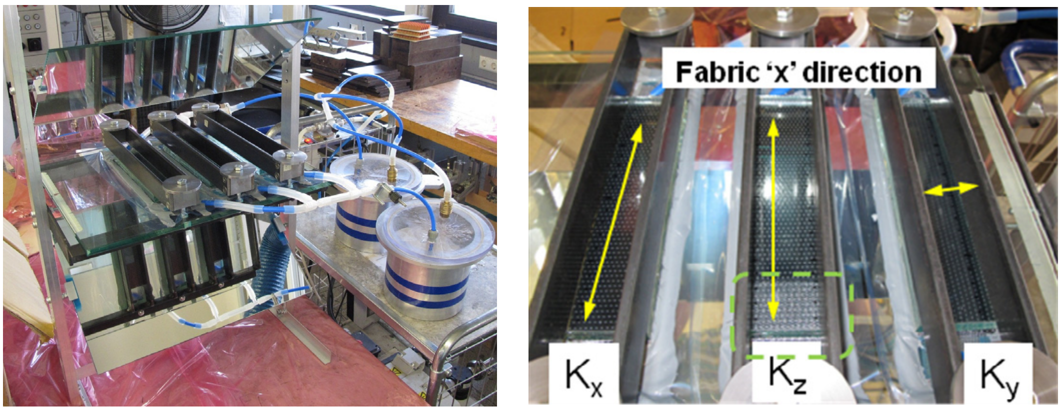
Figure 7. Hemisphere draping test and simulation results: support force comparison

4 Fabric permeability estimation

4.1 Tow permeability

Tow permeability was estimated by performing tests on a tape-like UD carbon fiber fabric, which is assumed to be similar to the dense packing of the carbon fibers within a tow. Hexion RIMR235 resin with RIMH238 hardener [3] was used.

The infusion measurement test rig (fig. 8a) had a glass plate and mirror system for resin flow observation on both sides of the preform. Constant thickness of the fabric is maintained via rigid pressure plates fixed at a constant distance by the bolted steel frames.



(a) (b)

Figure 8. Tow permeability estimation test rig (a) and specimens layup directions (b)

Testing strategy was developed to estimate all three permeability tensor components in one test. In-plane permeability's (K_x and K_y) tests were done by making inlet boundary conditions suitable for 1-D flow formation. Through-thickness permeability test strip had modified inlet (fig. 8b middle specimen, fig. 9) creating 2-D resin flow, which could then be quantified by the flow front difference between top and bottom of the specimen.

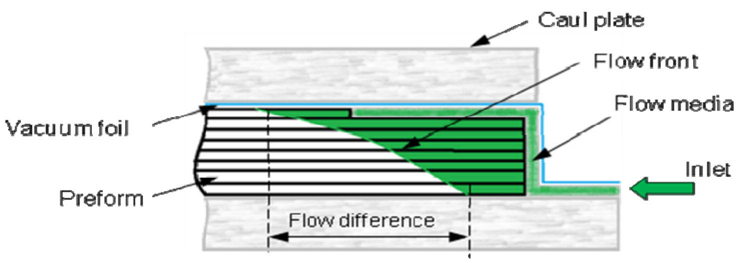


Figure 9. Tow permeability estimation: 'Kz' specimen inlet

PAM-RTM™ [4] software was used to fit simulation to the test results and estimate permeability values. Resin flow front propagations from test ('K_z' specimen) and simulations are shown in the figure 10. A summary of estimated permeability's is given in table 2.

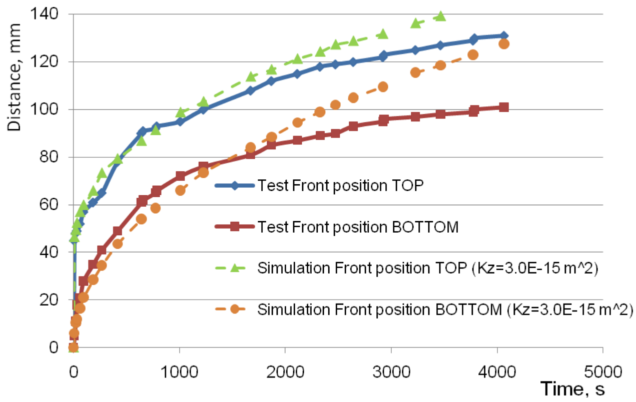


Figure 10. Resin flow front propagation test and simulation fitting results ('K_z' specimen)

K_X, m^2	K_Y, m^2	K_Z, m^2	V_F, %
2.8E-12	1.2E-12	3.0E-15	61.50 (DIN 29971)

Table 2. Tow permeability estimation results

4.2 'Gap' permeability

'Gaps' between the tows in chain stitched biaxial fabric act in a similar fashion to race-tracks giving zones of high permeability where resin propagates relatively fast compared to flow in the tows. A simple in-plane infusion test was performed for the biaxial fabric specimen $(0/90)_5$. Simulation model, figure 11, with tow permeability's readily specified was then tuned to resemble test results by calibrating the equivalent 'gap' zone permeability; after calibration this was estimated to be 2.0E-11 m^2.

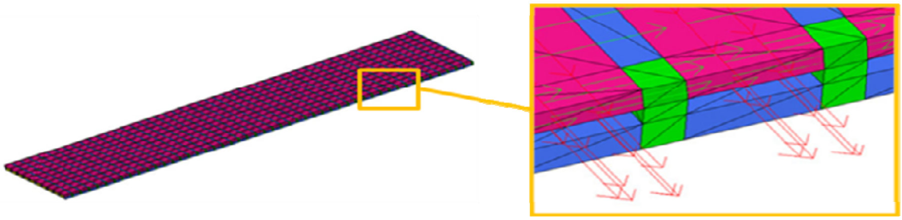
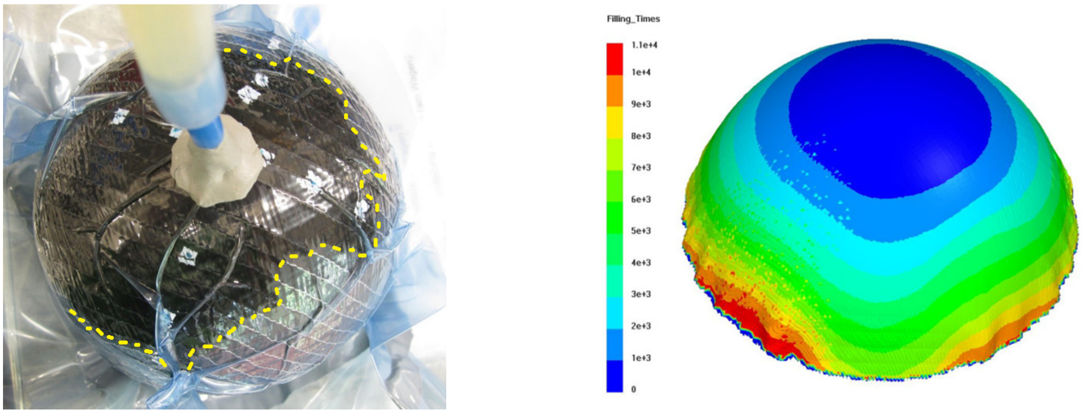


Figure 11. 'Gap' permeability estimation FE model

Final validation

Final validation was made by comparing VARI type draped hemisphere infusion tests results with the simulated model, figure 12. A point inlet was placed on top of the hemisphere with outlet vents around the base circumference. The general filling times and flow rates are in reasonable agreement with test measurements, but unfortunately wrinkles from the vacuum bag have caused certain discrepancies to the flow front due to race tracking.



(a) (b)

Figure 12. Hemisphere infusion test (a) and simulation (b)

Conclusions

The approach presented for meso-scale modeling of the biaxial NCF is able to account for all important deformation mechanisms of the selected bi-axial NCF. The model has been kept deliberately simple in order to allow drape simulation of relatively large structural components. Subsequent direct coupling of draping results with the infusion analysis have showed promising agreement with experimental measurements.

Acknowledgements

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