EXPERIMENTAL VALIDATION OF NUMERICAL DUAL-SCALE PERMEABILITY PREDICTION

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Introduction

This study shows the experimental validation of numerical permeability prediction in endless fibre textiles using porous yarn simulations. Different scales of modelling will be analyzed and validated separately as well as in experiments. Permeability measurements and predictions are one of the most critical parameters for LCM simulation and have been subject of research for many years. Experimental permeability measurements are time and material consuming, but necessary for today's FEM simulation. Virtual permeability predictions are based on different models or analytical approaches but the validation with experimental results is insufficient. In Dittmann et al. [1] [2] the prediction of dual-scale permeability values with porous yarns in CFD simulations for the use in FEM filling simulations is already shown. In this study, based on multi-scale triaxial braid models created with TexGen, PAM-Crash and OpenFOAM, the validation of numerical predicted permeability values is addressed.

Simulation set-up

Microscopic approach

Microscopic simulations were performed to predict the yarn permeability. RVE's with random positioned filaments were built and flow parameters like velocity U, pressure p and permeability K were calculated in fibre direction ($K_{\parallel}$) and perpendicular to it ($K_{\perp}$). To validate these simulation results, a capillary rise test bench was built and tests were executed. The test fluid was Glycerol 85 % with a dynamic viscosity of η = 109 mPas, a static contact angle of θ = 52.96°, a surface tension of σ = 65.19 mN/m and capillary pressures of $p_{i\_cap\_\perp}$ = 8953.55 Pa and $p_{i\_cap\_\parallel}$ = 41038.08 Pa. Capillary pressure was calculated with the Young-Laplace equation, a form factor $F_{\parallel}$ = 4, $F_{\perp}$ = 2 and a filament diameter of d_f = 7 µm [3].

$$p_c = \frac{F}{d_f}\left(\frac{FVC}{1-FVC}\right)\sigma \cos\theta \tag{1}$$

To avoid evaporation the fluid reservoir and the cavity were capsuled. A measurement of fluid weight showed a reduction of 0.2 g after 96.5 hours, which caused a viscosity reduction of 0.86 %. The mean testing period was about 24 hours and therefore evaporation was neglected.

Mesoscopic approach

Mesoscopic numerical simulations at unit cell level were executed to predict the dual-scale effect in textile architectures. Therefore the predicted microscopic permeability values were transferred to the mesoscopic mesh by defining porous zones in OpenFOAM [1]. To validate the mesoscopic permeability values a test bench was built to analyze flow effects, monitor flow front development and void transport. Therefore glass fibre yarns were used to observe void transport and void entrapment. The used test fluid was Glycerol 85 % and the inlet pressure was p_{i_meso} = 2 bar.

Macroscopic approach

The predicted mesoscopic permeability values were used as input for the macroscopic FEM simulations, which were validated by radial permeability tests as well as analytical solutions, published by B. R. Gebart [4], A. C. Long [5] and T. G. Gutowski [6]. A preform was infiltrated with an infiltration pressure of p = 2 bar and a fibre volume content (FVC) of 36 %. The experimental tests were executed with 2 bar infiltration pressure and a FVC of 37.8 %. Analytical solutions used the Kozeny-Carman equation and a modified mixture rule for the prediction with the algorithm of A. C. Long.

Results

Experimental microscopic results in fibre direction showed good correlation with the predicted numerical values. Experiments perpendicular to the fibre direction showed inhomogeneous flow front development and therefore noticeable deviations (cf. Fig. 1, Tab. 1), provoked by stitching and yarn bending at sample borders induced by cutting. Some samples showed a faster impregnation of yarns at locations where yarns are in contact to each other and shifted flow front development from cross-yarn-impregnation to in-yarn impregnation. These tests weren't considered in this study.

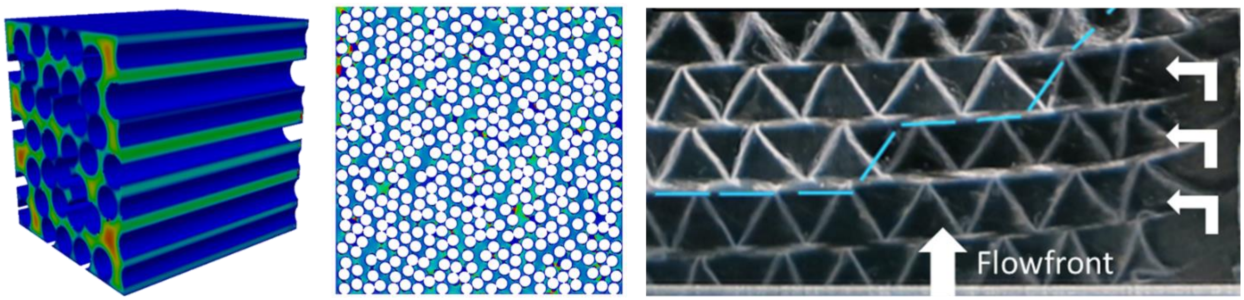

Fig. 1: *Microscopic flow simulation in filament direction and perpendicular, experimental mesoscopic impregnation characteristics in PX35 UD 300*

Tab. 1: *Permeability values*

	Numerical permeability values [m^2]	Analytical permeability values (Gebart) [m^2]	Experimental permeability measurement [m^2]
Microscopic ($K_{\parallel}$)	9.03e-13 (FVC = 54.23 %)	2.41e-12 (FVC = 54.23 %)	2.85e-13 (FVC = 55.5 %)
Microscopic ($K_{\perp}$)	2.09e-13 (FVC = 58.47 %)	3.37e-13 (FVC = 58.47 %)	3.48e-14 (FVC = 58.1 %)
Mesoscopic K_I (solid yarns)	8.39e-09 (FVC = 36 %)	-	-
Mesoscopic K_I (porous yarns)	8.51e-10 (FVC = 36 %)	9.94e-12 (FVC = 36 %)	-
Macroscopic K_I (radial test bench)	8.51e-10 (FEM mapped)	-	4.28e-10 (FVC = 37.8 %)

Discussion & Conclusion

Results show that a route for predicting permeability values without experimental tests exists and that subareas perform well, but also show that values still differ too much, which causes deviations in filling characteristics. Reasons for deviations are equal permeability values for different compacted yarns and poor modelling quality provoked by insufficient computational power. In addition experimental tests for validation are very sensitive (e.g. capillary rise tests perpendicular to filaments) and proper results are rare. Next step should be an international numerical/analytical permeability benchmark to collect the different approaches, solver and tools, validating predicted results.

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