Transverse permeability of woven fabrics

W.J.B. Grouve[1], R. Akkerman[1], R. Loendersloot[2], S. van den Berg[1]

[1]University of Twente - Enschede, the Netherlands
URL: www.pt.ctw.utwente.nl
e-mail: w.j.b.grouve@utwente.nl;
e-mail: r.akkerman@utwente.nl;

[2]Reden - Hengelo, the Netherlands
URL: www.reden.nl
e-mail: r.loendersloot@reden.nl;

ABSTRACT: The transverse permeability is an essential input in describing the consolidation process of CETEX® laminates. A two-dimensional, finite difference based, Stokes flow solver has been developed to determine the mesoscopic permeability of arbitrary fabric structures. The use of a multigrid solver dramatically decreases the cpu time required (less than one minute on a 512^2 grid). The permeability of a square packed bed of impenetrable cylinders is calculated and shows excellent agreement with values found in literature.

KEYWORDS: Transverse permeability, Stokes equation, Multigrid algorithm

1 INTRODUCTION

CETEX® fabric reinforced thermoplastic laminates, mainly used for aerospace applications, are produced by forcing thermoplastic films to infiltrate the fabric at high pressure and temperature. Currently, polyetherimide (PEI) and polyphenylenesulfide (PPS) are used as matrix material in CETEX® products. The use of alternative thermoplastic polymers potentially offers an increase in performance, e.g. strength or toughness, combined with a decrease in cost. A thorough understanding of the consolidation process is required to develop an optimal processing route for these new thermoplastic composites.

he aim of the consolidation phase is to fully impregnate the fabric reinforcement. Thermoplastic resin needs to infiltrate into the dry fabric during consolidation. This is a complex process with various interrelated phenomena. The applied pressure drives the resin through the fabric but simultaneously deforms the compliant fabric, thereby altering the infiltration kinetics. A strong coupling exists between reinforcement compaction and permeability. Michaud and Månson [5] described the one dimensional, isothermal, infiltration of a needled glass fibre mat. The model is based on Darcy's Law for conservation of momentum:

$$\mathbf{u} = -\frac{\mathbf{K}}{\mu}\nabla p, \tag{1}$$

where p and $\mathbf{u}$ denote, respectively, the pressure and velocity field, μ is the resin viscosity and $\mathbf{K}$ the permeability tensor. The transverse permeability, as a function of fibre volume fraction, is an essential parameter in describing the consolidation process. The aforementioned authors obtained this function by fitting experimental data with a power law [6]. However, since permeability experiments are generally laborious and suffer from significant experimental scatter a modelling approach is desired.

The permeability, as function of fibre volume faction, can be described by the Kozeny-Carman relation, which is based on flow through granular beds consisting of ellipsoids [2]:

$$K = \frac{R^2}{4k}\frac{(1-\nu_f)^3}{\nu_f^2} \tag{2}$$

In this relation, which was initially derived for isotropic homogeneous porous media, k is the so-called Kozeny constant. Several authors, e.g. Gutowski [4], have proposed to adapt (2) for anisotropic media by applying distinct Kozeny constants for flow perpendicular and parallel to the fibres. One of the main drawbacks of the Kozeny-Carman equation is that the Kozeny constant has to be determined experimentally. Significant discrepancies in the parameter k for given reinforcements have been reported in literature, which is a reflection of the large amount of variation in the experimental results.

More sophisticated methodologies aim to take into account the preform structure more accurately. The basis of these models lies in the assumption that the porous media can be divided into repetitive elements or unit cells. The fabric permeability is then determined by modelling the flow through these, more or less, idealised cells. The degree of structural detail taken into account in the unit cell ultimately determines the accuracy of the model. In general the reinforcing preform consists of woven or stitched bundles, which themselves are build up from small filaments. The geometric shape, weave pattern and packing characteristics of the fabric should all be included in the model. Besides, the preform heterogeneity, i.e. fluid flows both around and through the bundles, could be of importance.

Gebart [3] derived the permeability of an idealised unidirectional reinforcement consisting of regularly ordered impenetrable cylinders. A lubrication approximation was used to relate the fibre volume fraction to the transverse permeability. The results closely match the numerical results for higher volume fractions. Bruschke and Advani [1] used a similar approach in the high fibre volume fraction range but adopted an analytic cell model for lower fibre volume fractions. A closed form solution, over the full fibre volume fraction range, is obtained by matching both solutions asymptotically. The results were experimentally validated by Sadiq et al. [8]. Excellent agreement was found between the measured and predicted permeability for flow transversely to the impenetrable cylinders. Experiments using porous cylinders were performed as well. The measured permeability of the heterogeneous lattice was found to be up to 25% higher than the measured permeability of the corresponding lattice of impenetrable cylinders.

While the proposed analyses provide valuable fundamental understanding of permeability they show limited applicability in practise. This is partly caused by the fact that the heterogeneous character of the reinforcement is not taken into account. But more importantly, the bundle cross-sectional shape can generally not be described as circular. This problem can be circumvented by calculating the complete fluid flow in a unit cell around an arbitrary cross-sectional shape numerically. Subsequently, Darcy's Law (1) can be used to determine the unit cell permeability.

In this paper a finite difference based Stokes-Flow solver is presented to predict the meso-scopic permeability of textile reinforcements. The use of a multi-grid algorithm dramatically decreases the cpu time required. The solver is validated with experimental results found in literature [8] and compared to the solutions presented by Bruschke and Advani [1] and Gebart [3].

2 STOKES FLOW SOLVER

2.1 Governing equations

The solver is developed to calculate the fluid flow around an arbitrary geometry in a unit cell. Typically in flow problems regarding composite forming processes the inertial forces are small compared to the viscous forces, i.e. the Reynolds number is low ($Re << 1$). The impregnating fluid is, for now, assumed to be Newtonian. The Stokes equation can be used for conservation of momentum:

$$\nabla p - \mu \Delta \mathbf{u} = 0 \tag{3}$$

Conservation of mass reads:

$$\nabla \cdot \mathbf{u} = 0 \tag{4}$$

These equations are solved in a two dimensional flow domain. An analytical solution of these equations is only available for specific cases, therefore the partial system is solved numerically using a finite difference approach. The flow domain is covered with a fixed rectangular grid and the system variables are solved at the grid points only. The application of a so-called staggered grid is common in suchlike problems. Such a grid, for the two dimensional case, is outlined in figure 1.

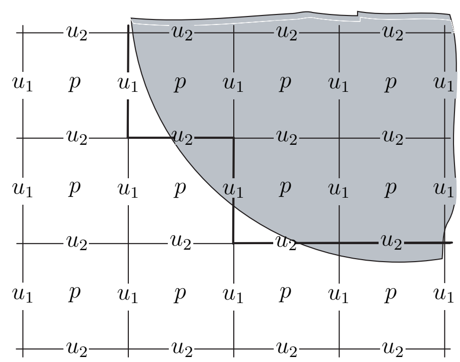

Figure 1: Part of the staggered grid; the gray section represents a part of the fibre bundle, the white section corresponds to the pore space.

The grid lines define the cells. The discrete pressure is defined at the cell centres. The discrete velocity u_1 is defined at the centres of the of the vertical links, and u_2 is defined at the centres of the horizontal links. The conservation of mass (4) is considered in every individual cell, whereas the conservation of momentum (3) should hold on the cell faces. Both equations are discretised using a central differences scheme. Dirichlet or Neumann boundary conditions can be applied on every cell face throughout the domain to define the domain boundaries and reinforcement geometry. The solution of the defined flow problem is then obtained by using a Jacobi relaxation method [9].

2.2 Multigrid algorithm

The convergence speed of these elliptical partial derivative equations is generally low. A multigrid solution technique has been employed to overcome this. A Full-Multigrid Algorithm, using five different grid sizes, has been implemented in Matlab. To further decrease the computational calculation time the solver will be implemented in C++.

3 SIMULATION

3.1 Square packed cylinders

The permeability of a square packed bed of impenetrable cylinders is determined to validate the developed solver. The obtained results are compared with the results obtained by Bruschke and Advani [1], Gebart [3] and Sadiq et al. [8]. The repetitive unit cell is depicted in figure 2. Using symmetry only the flow in a quarter of the unit cell is calculated. The figure shows that symmetry is applied on the upper and lower boundary. A pressure is applied on the left and right boundary. The velocity on the inlet and outlet is restricted to have no vertical component. The velocity on the cylinder surface is equal to zero. The calculated volume flow can, by applying Darcy's Law (1), be used to determine the permeability. The dimensionless permeability is determined by dividing the permeability by the squared radius of the cylinder. A single analysis of such a problem on a fine grid (256^2) takes approximately 30 seconds.
In figure 2 the dimensionless permeability for varying fibre volume fraction is compared to the values found in literature. The results show, for higher fibre volume fractions, excellent agreement to the results found in literature. For lower fibre volume fractions, however, the obtained permeability deviates. Finite element calculations, using Ansys CFX, have been performed to verify the results in the lower range. The CFX results virtually coincide with the multigrid solver results, as can be seen from the graph. For comparison, the finite element calculation takes approximately six minutes.

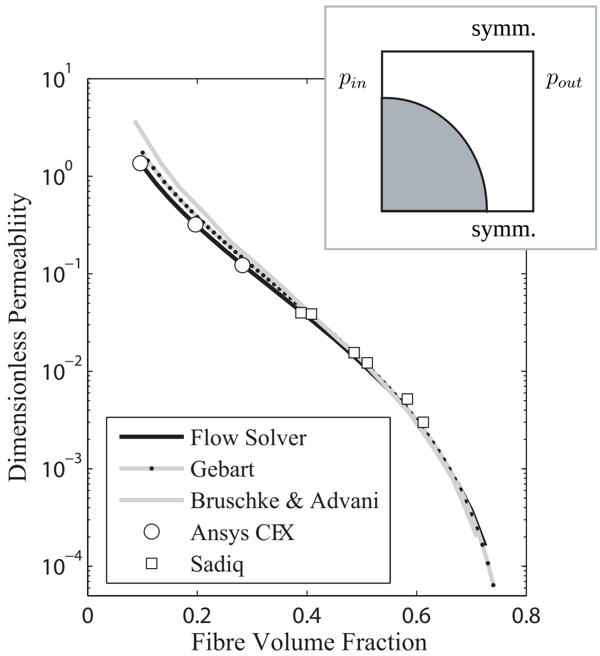

Figure 2: Comparison between results from MG solver and data from literature.

3.2 Square packed ellipses

The bundle cross-sectional area can, in general, better be represented by an ellipse than a perfect circle. The permeability of square packed ellipses can easily be investigated. Figure 3 shows the defined unit cell. The ellipse axes ratio equals the unit cell aspect ratio. The constant c is used to vary the fibre volume fraction of the reinforcement: $\nu_f = \pi c^2/4$. Symmetry is, as before, applied on the upper and lower boundary, while a pressure is enforced on the left and right boundary. The graph in figure 3 shows the dimensionless permeability, which is obtained by dividing the calculated permeability by product of ellipse radii, as function of the fibre volume fraction for three different cases. The obtained results show excellent agreement to Ansys CFX simulations.
Most of the flow resistance is caused by the narrow

gap between two adjacent bundles. In case the major axis of the ellipse is oriented parallel to the flow direction, i.e. $A/B = .5$, the gap through which the flow is forced is smaller than in case the major axis lies perpendicular to the flow direction. This also follows from the results shown in the graph, as the highest permeability values correspond to the domain with the largest gap ($A/B = 2$).

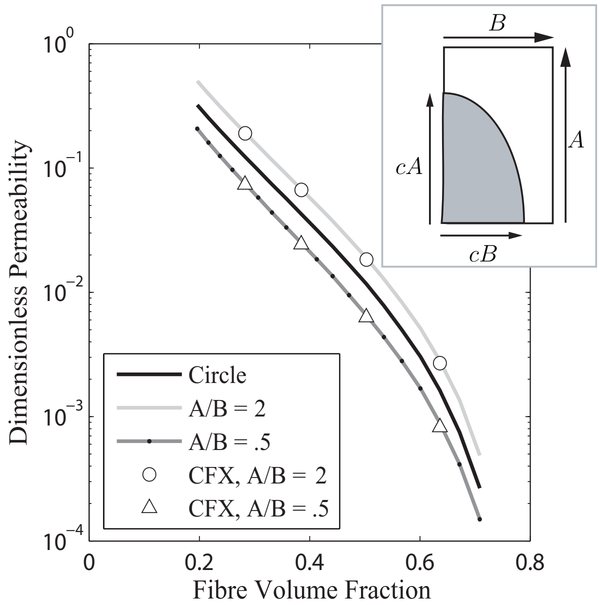

Figure 3: Dimensionless permeability for flow through a square packed bed of ellipses. Inset: defined unit cell.

4 CONCLUSIONS AND FUTURE WORK

The fabric permeability, as function of fibre volume fraction, is an essential input in describing the consolidation process of CETEX® laminates. During the consolidation process the applied pressure results in deformation of the compliant fabric, thereby altering the fabric structure and consequently the permeability. The existing permeability models pose severe restrictions on fabric geometry or require experimental data to fit the results. A fast and accurate permeability model is desired to describe the complicated consolidation process. A finite differences based Stokes solver has been developed to determine the permeability of arbitrary fabric geometries. A multigrid algorithm enables the use of fine grids to accurately represent the fabric geometry, while keeping the cpu time required to a minimum.

Future research activities will concentrate on extending the developed solver in order to improve its accuracy. First, additional rheological models, such as a power-law description, will be incorporated to accurately represent the thermoplastic films used in CETEX® laminates. Secondly, the heterogeneous character of the reinforcement will be addressed. This dual porosity can have a significant influence on the fabric permeability as was shown by Sadiq et al. [8] and Phelan and Wise [7].
An experimental set-up has been developed for validation purposes. The transverse permeability of distinct CETEX® fabrics will be measured and used as a reference.

ACKNOWLEDGEMENT

This work is performed with the support of from the Netherlands Agency for Aerospace Programmes (NIVR) and Ten Cate AC. This support is gratefully acknowledged by the authors.

REFERENCES

[1] M.V. Bruschke and S.G. Advani. Flow of generalized newtonian fluids across a periodic array of cylinders. *Journal of Rheology*, 37(3):479–496, May/June 1993.

[2] P.C. Carman. Fluid flow through granular beds. *Chemical Engineering Research and Design*, 15:150–166, 1937.

[3] B.R. Gebart. Permeability of unidirectional reinforcements for rtm. *Journal of Composite Materials*, 26(8):1100–1133, 1992.

[4] T.G. Gutowski, Z. Cai, and S. Bauer. The consolidation of laminate composites. *Journal of Composite Materials*, 21:172–188, 1987.

[5] V. Michaud and J.-A.E. Manson. Impregnation of compressible fiber mats with a thermoplastic resin. part i: Theory. *Journal of Composite Materials*, 35(13):1150–1173, 2001.

[6] V. Michaud and J.-A.E. Manson. Impregnation of compressible fiber mats with a thermoplastic resin. part ii: Experiments. *Journal of Composite Materials*, 35(13):1174–1200, 2001.

[7] F.R. Phelan Jr. and G. Wise. Analysis of transverse flow in aligned fibrous porous media. *Composites Part A*, 27A(1):25–34, 1995.

[8] T.A.K. Sadiq, S.G. Advani, and R.S. Parnas. Experimental investigation of transverse flow through aligned cylinders. *International Journal of Multiphase flow*, 21(5):755–774, 1995.

[9] C.H. Venner and A.A. Lubrecht. *Multilevel methods in lubrication, Tribology Series 37*. Elsevier, Amsterdam, 2000.