A Permeability Prediction for (Un)Sheared Non-Crimp Fabrics

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SUMMARY: A permeability prediction model for relaxed and sheared Non-Crimp Fabrics is proposed. The model is based on geometrical features of the fabric. The stitches penetrating the uni-directional plies of the NCF induce distortions of the fibers in the plane of the fabric. These Stitch Yarn induced fiber Distortions (SYD) form flow channels, which determine the permeability of the NCF. The channels are connected to each other in overlap regions, allowing the fluid to flow from one channel to another and finally to impregnate the entire preform. A network of SYD flow channels is created to account for the statistical variations in the dimensions of the SYDs. The system of flow resistances is solved analogously to the solution of the effective resistance of an electrical circuit with parallel and serial resistances. The flow in each of the SYD domains is calculated employing an energy minimisation method. Analysis of different networks, with varying spatial distribution of the dimensions of the flow channels, allows the prediction of the variation in the permeability of an NCF.

KEYWORDS: Non-Crimp Fabric, Resin Transfer Molding, Permeability, Network, Shear

INTRODUCTION

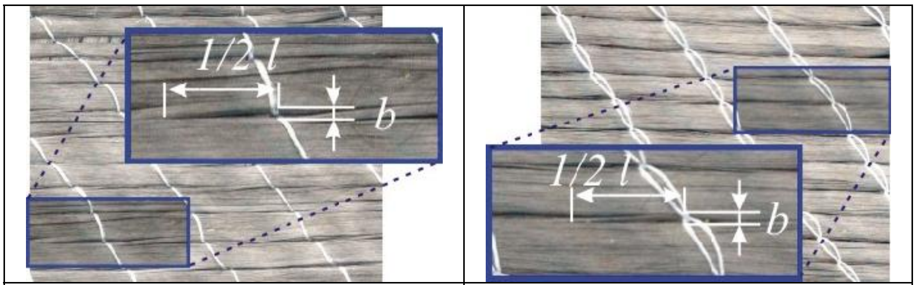
Resin Transfer Molding (RTM) has proven to be a cost effective production method for near-net shaped products with a high accuracy and a high reproducibility. The application of Non-Crimp Fabrics (NCF) in RTM combines improved properties with relatively low production costs. The absence of undulation (or crimp) of the fiber bundles of an NCF improves the in-plane properties relative to woven fabric composites, whereas the stitches in the material prevent a significant drop of the through thickness properties. The growing application of NCFs in complex shaped structural components increases the urge for models predicting the drape properties of the material and the resulting impregnation behavior.

Accurate flow simulations, which require detailed knowledge on the impregnation behavior, are an essential tool in finding the optimal RTM process parameters. One of the most critical parameters in the mold filling simulations is the permeability of the fibrous preform, which is in essence a geometric quantity.

This research aims to predict the permeability of NCFs based on a network of flow channels, which dimensions depend on geometrical features of the fabric and the fabric deformation. The analysis of a network of flow channels allows the incorporation of statistical variations of the channel dimensions, in the permeability prediction. These variations were observed during analysis of different types of NCFs [1-4].

GEOMETRY OF A NON-CRIMP FABRIC

A single layer of a Non-Crimp Fabric (NCF) consists of a stack of uni-directional plies of fibers. The stack of plies is stitched by the warp knitting process, according to a certain pattern (e.g. chain or tricot). A more detailed description of the stitching process is found in Lomov *et al.* [1]. The stitches induce fiber distortions in the plane of the fabric when penetrating the NCF, as clearly shown in Fig. 1.



(a) (b)

Fig. 1. Stitch Yarn induced fiber Distortions on the top and the bottom face of a ±45° biaxial Non-Crimp Fabric, with a chain knit pattern. *b* is the width and *l* the length of the SYD.

The dimensions of the Stitch Yarn induced fiber Distortions (SYD) and the effects of shear are discussed in [2-4]. A distribution of the dimensions of the SYDs is found. This distribution is explicitly incorporated in the permeability prediction model.

PERMEABILITY NETWORK MODEL

Unit Cell and Interaction Regions

The proposed permeability model is based on a unit cell approach. The unit cell is the flow domain formed by the SYD. In- and outflow regions of the SYD unit cells, which connect the unit cells and allow the fluid to flow through the reinforcement, are found in overlapping regions as depicted in Fig. 2. The amount of these regions and their locations depend on the dimensions of the SYDs, the needle spacing, the stitch distance in machine direction and the orientation of the fibers with respect to the machine direction. Note that they are affected on a local level by the distribution of the dimensions of the SYDs.

Possible locations of the overlapping regions are limited to integer multiplications of the projected distances d_p of the needle spacing D_n and stitch distance D_s in the fiber direction (Fig. 2).

It can be derived that:

$$d_p^n = \frac{D_n}{\cos\theta_1(\tan\theta_1 + \tan\theta_2)}$$
$$d_p^s = \frac{D_s \sin\theta_1 \tan\theta_1 \tan\theta_2}{\tan\theta_1 + \tan\theta_1} \quad (1)$$

with θ_1 and θ_2 as defined in Fig. 2. Note that the fiber angles may be different from 45° (in triaxial and quadriaxial NCFs), but shear does not affect the distances d_p, provided a trellis frame shear is assumed.

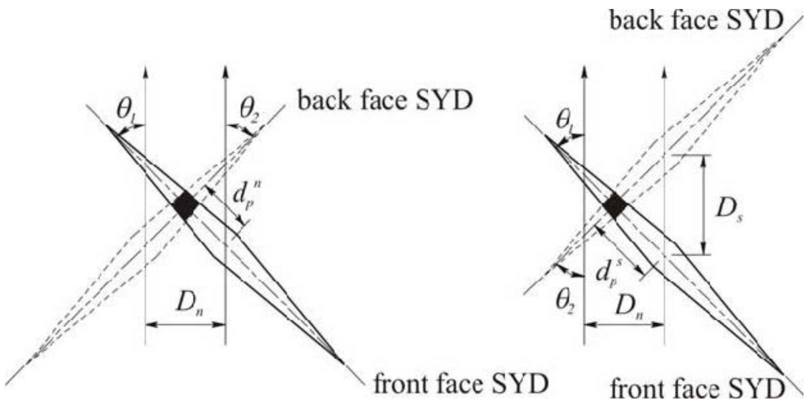


Fig. 2 Locations of overlap regions (dark areas) depend on integer multiplications of the projected distance d_p^n and d_p^s on the SYD. θ_1 is the fiber angle of the upper layer, θ_2 the fiber angle of the bottom layer.

Unit Cell Flow Solution

The flow resistance of the each of the unit cells is computed with a multigrid flow solver [5]. A 3D Stokes' flow is assumed in the unit cell:

$$\underline{\nabla} p - \mu \underline{\nabla}^2 \cdot \underline{u} = \underline{0} \quad (2)$$

The solution is obtained by solving Eqn. 2 on a staggered grid and using a bipolar mapping routine. The shape of a single SYD is assumed to be perfectly bipolar.

The fiber bundles, forming the boundaries of the SYD unit cell, can either be assumed to be solid or to be permeable. In the latter case, Brinkmans' equation is solved in the fiber bundle:

$$\mu \underline{\nabla}^2 \cdot \underline{u} - \mu \underline{\underline{K}}_{tow}^{-1} \underline{\nabla} \cdot \underline{u} = \underline{\nabla} p \quad (3)$$

with $\underline{\underline{K}}_{tow}$ the intra-bundle permeability. The permeability of the fabric will be overestimated in case the yarns are assumed to be solid, especially for reinforcements with a high fiber content [6]. However, incorporation of Eqn. 3 in the computations may increase the required CPU time to calculate the flow drastically.

SYD Network Solution

A network of flow resistances is constructed using the coordinates of the interaction regions and the calculated unit cell flow resistances between the interaction regions. The network domain has to be large enough to represent a continuous, possibly deformed reinforcement. The dimensions of the flow domains, and as a consequent those of the interaction regions, are assigned randomly, but in correspondence with the averaged value and distribution determined from the geometrical analysis of the preform. The system of flow resistances is solved analogously to the solution of the effective resistance of an electrical circuit with parallel and serial resistances, with the pressure gradient $\underline{\nabla p}$ and the voltage drop V and secondly the fluid velocity $\underline{u}$ and the current I as congruent variables. The ratio of the permeability $\underline{\underline{K}}$ and the viscosity μ is congruent with the inverse of the electrical resistance R:

$$\underline{u} = \frac{\underline{\underline{K}}}{\mu} \cdot \underline{\nabla p} \leftrightarrow I = \frac{1}{R} V \quad (4)$$

The principle permeabilities and the orientation of the principle axes are found iteratively. The principle of minimised work in the system is employed to solve the flows in each of the domains for given boundary conditions. The work $W^{(i)}$ in SYD domain i is defined as the product of the pressure gradient and the fluid velocity:

$$W^{(i)} = \underline{\nabla p}^{(i)} \cdot \underline{u}^{(i)} = \mu \left(\underline{\underline{K}}^{-1} \cdot \underline{u}^{(i)} \right) \cdot \underline{u}^{(i)} \quad (5)$$

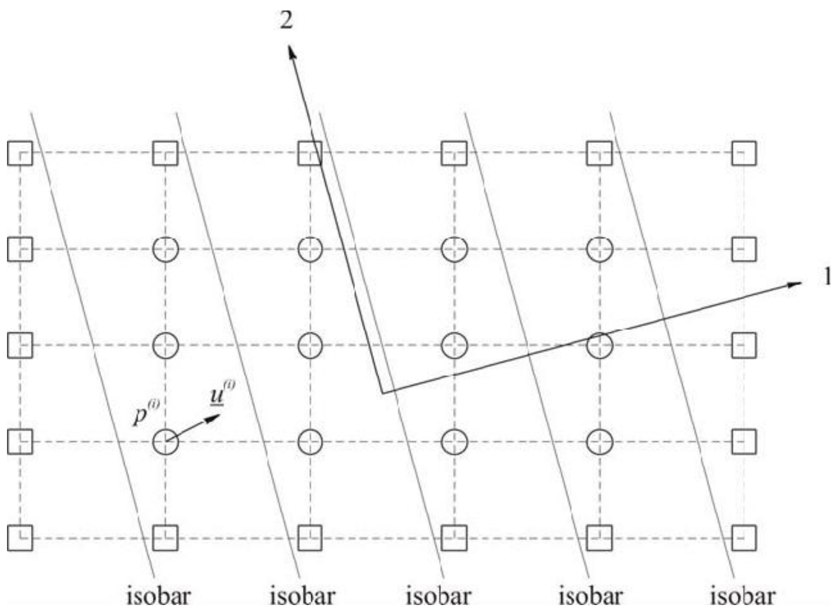


Fig. 3. Grid of interaction points (circles: inner points, squares: outer points at which the boundary conditions are applied). 1 and 2 refer to the principal directions, the pressure p and fluid velocity $\underline{u}$ at point i are indicated. Isobars visualise the assumed linear pressure gradient.

Subsequently, an initial guess of the principal directions is made and a linear pressure gradient in one of the principal directions is applied on the boundaries of the network domain (Fig. 5):

	$\underline{\nabla p}^{(i)}_{BC} = \mu \underline{\underline{K}}^{-1} \cdot \underline{u}^{(i)}$	(6)

with $\underline{\nabla p}^{(i)}_{BC}$ the pressure gradient on boundary point i and $\underline{u}^{(i)}$ the corresponding fluid velocity. The work W and the boundary conditions are combined in the objective function Φ:

	$\Phi = \sum_{i=1}^{N} \left(\mu \left(\underline{\underline{K}}^{-1} \cdot \underline{u}^{(i)} \right) \cdot \underline{u}^{(i)} \right)^2 + \psi \sum_{i=1}^{M} \left(\underline{\nabla p}^{(i)}_{BC} - \mu \underline{\underline{K}}^{-1} \cdot \underline{u}^{(i)} \right)^2$	(7)

with N the number of interaction points in the network, M the number of boundary points and ψ a weight factor for the boundary conditions: the higher its value, the better the boundary conditions are satisfied. Minimisation of the objective function Φ yields the fluid velocities in the SYD unit cell. The direction of the average fluid velocity should correspond with the principal direction in which the pressure gradient is applied. The initial guess of the principal directions is updated and the system is solved again. This procedure is repeated until convergence is reached. The effective permeability of the system can be calculated, once the local fluid velocities are determined. The effective permeability corresponds with the principal permeability in the direction in which the pressure gradient is applied.

CONCLUSIONS

A permeability prediction model for Non-Crimp Fabrics is proposed. The model is based on the geometry of the fabric. The distortions induced by the stitching form a network of flow channels. Statistical distributions in the dimensions of the flow channels is accounted for by analysis of a network of these flow channels. The model will require more CPU time than the currently available purely uni-directional models, but, in contrast to those models, the network model is able to quantify the statistical distribution observed in experiments.

FUTURE WORK

Experiments are being analysed currently to validate the model. The experiments are performed on single layer undeformed and sheared Non-Crimp Fabrics of different manufacturers.
Secondly, the model does not yet account for the interaction occuring between different layers of NCF. This has to be addressed in order to analyse realistic preforms.

ACKNOWLEDGEMENTS

This work was performed with the support from the National Aerospace Laboratory (NLR) and the European Commission, by means of the FALCOM project (GRD1-2001-40184), the TECABS Brite-Euram project and the Marie Curie Fellowship program. This support is gratefully acknowledged by the authors.

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