# APPLICATION OF PERMEABILITY NETWORK MODEL TO NON-CRIMP FABRICS*

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**SUMMARY:** We will here combine previous studies to yield a model that can predict the true permeability of NCFs. The model includes the geometrical features from the stitching process as well as statistical variations. A correlated randomisation is performed by the use of Monte Carlo simulations in order to mimic the global geometry of the fabric. The permeability for the unit cells, which describes the local geometry of the fabric, are thereafter determined by CFD-simulations. The permeability model for a biaxial fabric including the features from the stitching process proves that the correlation distance together with the amount of irregularity have only slight influences on the global permeability, while the presence of crossings and the average channel width are extremely important for the total permeability.

**KEYWORDS:** Permability, Network model, Unit cell, Monte Carlo, CFD, Stitch, Crossing.

## INTRODUCTION

In previous work we have developed a general statistical permeability network model [1,2] and a CFD-unit cell model for the permeability of Non-Crimp Fabrics, NCFs [3]. We will here combine these studies to yield a model that can predict the true permeability of NCFs.

The NCFs consists of layers of parallel fibre bundles stitched to other layers preferable laid in other directions. This results in formation of channels between the bundles which consists of a large amount of fibres. The two scale porosity implies that there will be two types of flow during impregnation i.e. within and between the bundles where the second kind is likely to be of highest importance for the overall flow rate and thus the permeability [4]. The possible location of the bundles is limited to a certain volume but their actual position within this volume can vary [1]. The stitching and fibres going from one bundle to another add to the complexity. The implication of this is that there will be easy and less easy paths for the fluid to penetrate the fibre network. The flow through fabrics used in composite manufacturing is usually modelled with Darcy's law, which in its general form is written as:

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$$v_i = -\frac{\mathbf{K}_{ij}}{\mu} p,_j , \qquad (1)$$

where $v$ is the superficial velocity, **K** the permeability tensor $\mu$ the dynamic viscosity and $p$ the pressure. On the first hand, the permeability of perfect geometries of different types is well known, see for instance: [5] regular packing of cylinders. On the second hand there is a lack of knowledge of systems having detailed geometrical description of the features from the stitching process and irregularities in the geometry. Alterations to perfect geometries have been considered in a few cases. It has, for instance, been shown that perturbations to the fibre pattern and radii can give remarkable changes to the permeability [6].

## BASIC APPROACH

The bundles and the inter-bundle channels are direct consequences of the stitching. The stitching process also gives rise to two other major geometrical features of the fabric, namely the penetration of the channels by the thread where the fabric is stitched, Fig. 1a, and the crossing of fibres between two neighbouring fibre bundles, Fig. 1b.

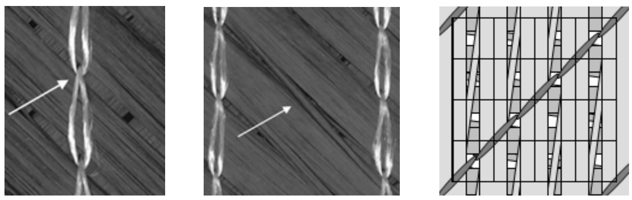

*Fig. 1. Top view of a biaxial NCF showing a) the thread and b) the crossings. c) Typical distribution of the different features from the stitching process in a biaxial NCF and its unit cell distribution.*

Due to the periodicity of the stitching process, the geometrical features are repeatable in a fabric and their distributions are hence dependent on the stitching pattern. Profound CFD-simulations of the whole fabric are to date impossible due to the enormous amount of volume elements required to fully resolve the geometry and flow. The fabric can instead be divided in unit cells, cf. Fig. 1c, which facilitates the simulations.

In order to develop a global permeability model for a biaxial fabric, which takes into account the effects from the stitching process and statistical variations, the work in three previous studies [1,2,3] will be combined. The global permeability of a fabric can be calculated by the use of a network model as was done in [1,2]. The tactic with the network model is to connect a number of unit cells with different permeability and thereafter calculate the overall permeability of the fabric. The unit cells in the network are connected to each other by the fluxes through the cell faces, see Fig. 2a.

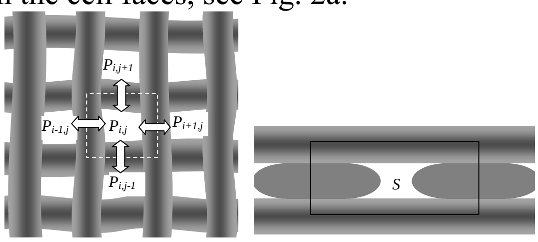


*Fig. 2. a) Placement of bundles in layers for biaxial fabric building a framework for network model. b) Side view of a unit cell in one layer.*

The total fluxes through the unit cell faces are obliged to satisfy mass conservation for incompressible fluid [2]:

$$\int v^x_{i-\frac{1}{2},j}\,dS + \int v^y_{i,j-\frac{1}{2}}\,dS + \int v^x_{i+\frac{1}{2},j}\,dS + \int v^y_{i,j+\frac{1}{2}}\,dS = 0. \qquad (2)$$

The boundaries parallel to the pressure gradient are set to be periodic, while pressure boundary conditions are set on the boundaries perpendicular to the pressure gradient. In real fabrics there will also be alterations of the geometry along the inter-bundle channels which is implemented in the network model so that the geometry and consequently the permeability can vary freely with spatial coordinate. The randomisation of the geometry is correlated i.e. adjacent unit cells are coupled to each other and their geometry and spatial coordinate can be determined by the use of a Monte Carlo method as in [1]. The two global parameters used in the Monte Carlo method are: the amount of irregularity in the system, $\tau$, and what kind of irregularities that dominates, shift or inclination, $\gamma$ [1]. Application of the network model and generation of channel gap distribution by the Monte Carlo method is performed on a biaxial fabric with a structure as the one in Fig. 1c, where every fourth cell contains the thread and the middle cell between these thread cells contains a crossing. Having the network, it must be filled with permeability values. This is done by usage of CFD-simulations on three types of cells: *the plain unit cell*, *the thread unit cell* and *the crossing unit cell* [3]. The discrete permeability values from the CFD-simulations, from variations of the geometries of the three cells, are fitted to analytical functions in order to obtain a permeability function for an arbitrary unit cell:

$$K_{cell}(b,h,c,t) = T(b,h,t)\cdot C(b,h,c)\cdot K_{plain}(b,h), \qquad (3)$$

where the function *T(b,h,t)* is the contribution from the thread, *C(b,h,c)* from the crossings, $K_{plain}$ is the permeability for a plain unit cell and *c* and *t* determines the extent of the crossings and thread in the channels with width, *b*, and height, *h*, respectively. As indicated in Fig. 1c, the thread and the crossing cannot exist in the same unit cell.

## RESULTS

The permeability of the unit cells is strongly dependent of the channel width and the size of the crossing, see Fig. 3a,c. It is also obvious that a thread unit cell has a lower permeability than a plain unit cell, see Fig. 3b. When the unit cell permeability data are put into the network model the influence from the global parameters may be studied.

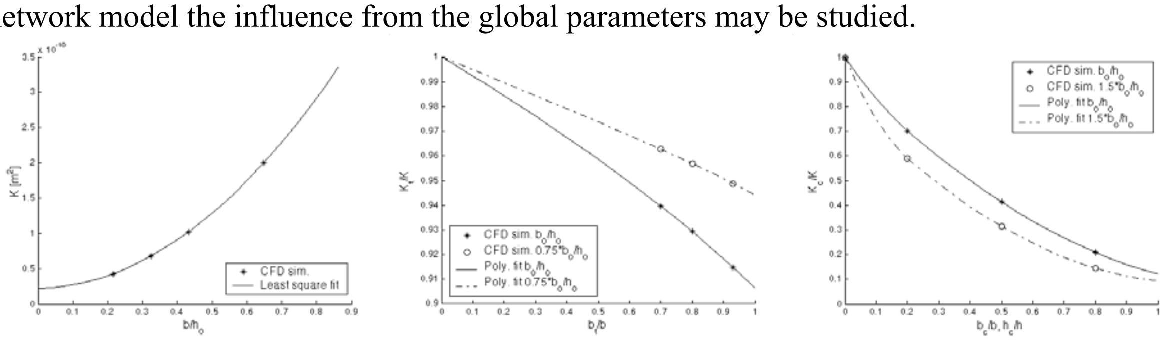


*Fig. 3. a) Permeability for variation of the channel width. Influence of b) the thread, T(b,h,t), c) the crossings, C(b,h,c), on the permeability for two channel shapes, b/h.*

At a given $\gamma$, the total permeability of a system with the size of 100×100 cells first increases with the irregularity $\tau$, but afterwards it decreases as described in [1], see Fig. 4a. The change of the global permeability is smaller than for a structure without the thread or crossings [1], since the local permeability for the unit cells including the thread or the crossings have weaker dependence on the channel parameter, *b/h*, than the plain unit cell. Naturally, the standard deviation of the channel width increases monotonously with $\tau$ since an increased irregularity results in greater variations of the channel width, cf. Fig. 4a. Fig. 4b shows that the permeability increases with the characteristic correlation distance, $l_0$, along the bundles as the wide gaps gets longer. This is especially true for higher standard deviations, $\sigma$. In comparison, the permeability for a regular structure without the thread and the crossings is $1.0224 \cdot 10^{-10}$ m$^2$, which indicates that the thread and crossings are very important for the permeability.

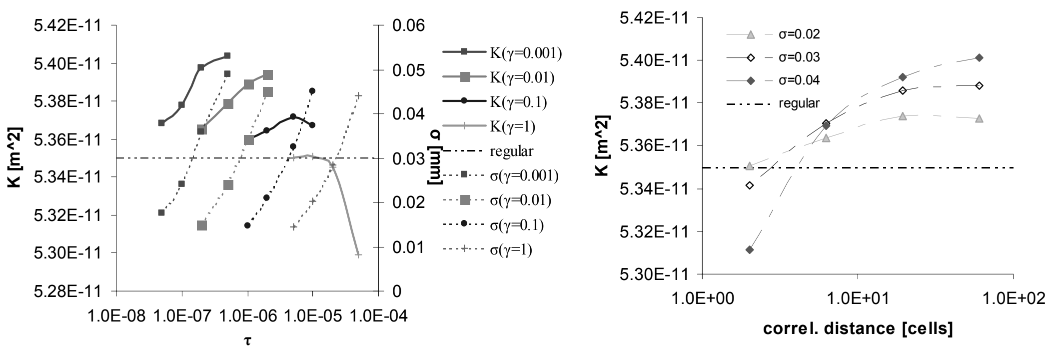


*Fig. 4. The influence of a) the Monte Carlo parameters $\tau$ (bottom axis), $\gamma$ (in legend) and b) the correlation distance on the global permeability for different standard deviations for a network structure including the thread and the crossings as in Fig. 1c.*

Fig. 5a shows that the average channel width also considerably influences the global permeability, while the standard deviation of the channel width at the same Monte Carlo parameters $\tau=10^{-6}$, $\gamma=10^{-2}$ only changes slightly. Fig. 5b shows that the influence of the crossing width is extremely important, while there is only a weak dependence of the global permeability on the size of the thread. Thus all the deviations from regular structures involving changes of *c* or changes in spatial placement of the crossings in the structure leads to significant changes of the total permeability.

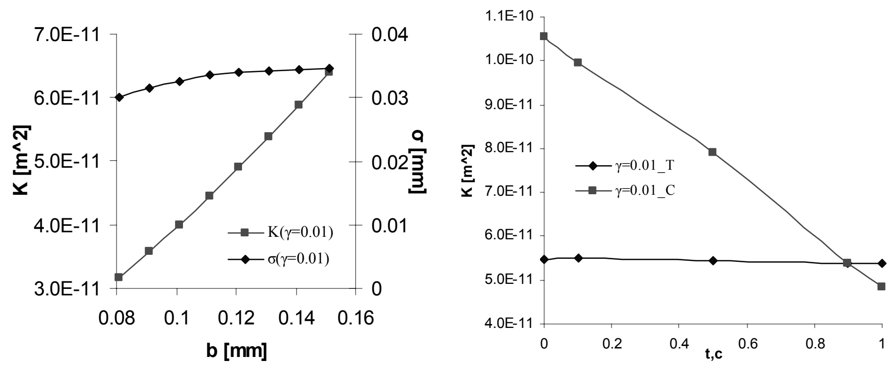


*Fig. 5. The influence of a) average channel width and standard deviations and b) the sizes of the thread and the crossings on the permeability for $\gamma$=0.01.*

The permeability from the global network model can be validated to experimental data on the permeability for a real fabric with similar geometrical dimensions. The measurements provided by SICOMP AB give permeability data between $2.49 \cdot 10^{-11}$ and $4.82 \cdot 10^{-11}$ $m^2$. The inclusion of the thread and crossings greatly improve the prediction of the permeability, about $1 \cdot 10^{-10}$ $m^2$ without to about $4\text{-}5 \cdot 10^{-11}$ $m^2$ with thread and crossings.

## CONCLUSIONS

A global permeability network model for real NCFs has been developed. The model is based on a network of unit cells including the features from the stitching process as well as statistical variations of the geometry. The model shows that the global permeability only varies slightly with the Monte Carlo parameters, which set the irregularity of the network of unit cells. The global permeability also shows a weak dependence on the correlation distance between adjacent cells. The largest influences on the global permeability are from the presence of fibres crossing the inter-bundle channels and the average channel gap width. The standard deviation of the gap width and the presence of the thread have less effect on the global permeability. Validation shows that the model is greatly improved when including effects from the stitching process.

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