

## A PERMEABILITY PREDICTION FOR NON-CRIMP FABRICS

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**ABSTRACT:** A model is proposed to analyse the variation in the permeability of Non-Crimp Fabrics, originating from variations in the internal structure of the material. A geometrical description of the fabric based on the distortion induced by the stitch threads piercing through the fabric is employed. The distortions form channels which are mutually connected. It is assumed that these channels dominate the permeability of the fabric. A network of flow channels is subsequently defined, in which the variations, measured in the dimensions of the distortions, is explicitly accounted for. The variations in the internal structure of the fabric affect the averaged permeability significantly. Moreover, a network rather than a single unit cell is required to predict the averaged permeability and its variation properly. Finally, the spatial distribution of the randomly generated channel dimensions affects the permeability significantly.

**KEYWORDS:** composites, permeability, flow modelling, internal geometry, variability

### INTRODUCTION

The closed mould production technology Resin Transfer Moulding (RTM) is a cost-effective method to manufacture near net-shaped composite products. The resin is injected into a cavity at a pressure of typically 2 – 10 bars, while a preform, consisting of dry semi-continuous fibres, fills the cavity. One of the key problems to obtain a reproducible product quality is the impregnation behaviour of the fibrous reinforcement. The permeability of a textile structure is difficult to predict and a significant amount of variation is present in measured permeability values.

This work focusses on the variability in the permeability originating from variations in the internal geometry of a Non-Crimp Fabric (NCF). A network flow model is defined to predict the permeability and its variation based on the internal geometry of the fabric and its variations.

The geometrical model is based on the analysis of three different types of biaxial NCFs. The geometry of these fabrics was previously presented in [1].

## GEOMETRICAL MODEL

Non-Crimp Fabrics (NCF) are frequently applied as reinforcement material for RTM based composites. NCFs consist of a stack of uni-directional, but mutually differently oriented fibre mats. The stacks are stitched together by a relatively thin thread to obtain sufficient structural integrity of the fabric.

Multiple layers of fibres are spread on the machine bed during the manufacturing of NCF. The fibre bed moves in the longitudinal direction of the machine ('machine direction'). A bar of needles spans the width of the fabric and the needles penetrates the fabric, leaving the stitch thread behind. The needle spacing  $A$  and the distance between subsequent needle penetrations, the stitch distance  $B$ , remain constant during the manufacturing process. Different stitch patterns are formed by applying a additional movement of the needle bar in cross direction [2]. Three different warp knitted stitch patterns are depicted in figure 1.

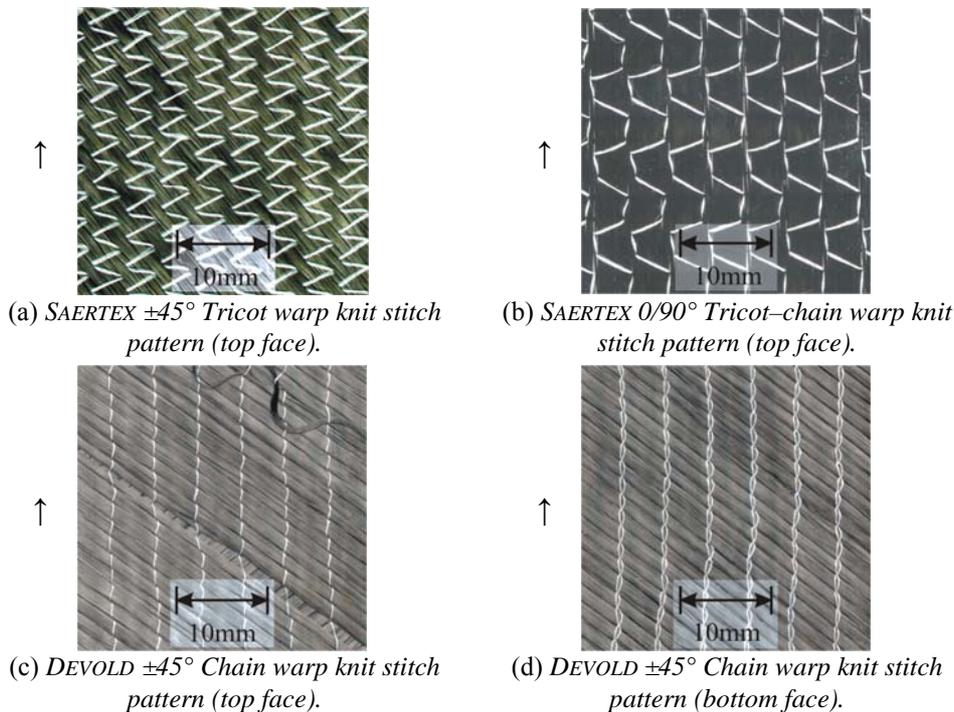


Fig 1: Three stitch patterns (a-c). The bottom face is similar for all fabrics (d). The arrow indicates the machine direction.

### Meso – Level Structure

The core of the geometrical model is the distortion of the fibre paths, induced by the stitch threads piercing through the fabric. A wedge shaped gap results, oriented in the direction of the fibres, as shown in the scanned image of a DEVOLD biaxial  $\pm 45^\circ$  NCF depicted in figure 1. The width and length of the distortion are indicated ( $b$  and  $l$  respectively).

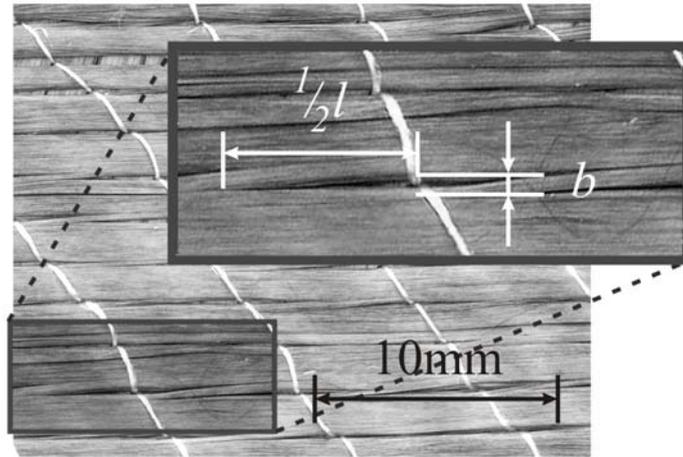


Fig.2: *Stitch Yarn induced fibre Distortions (SYD) of the top face of a DEVOLD biaxial  $\pm 45^\circ$  NCF (chain knit pattern), with  $b$  the width and  $l$  the length of the distortion.*

The definition of the distortions was first presented by Lomov et al. [2], who referred to them as ‘cracks’ and ‘channels’. Here the term ‘Stitch Yarn induced fibre Distortion’ (SYD) is used to comprise both these terms.

### SYD Shape

It is assumed that the distortion is wedge shaped and symmetric along its longitudinal axis (aligned in fibre direction) and its transverse axis (perpendicular to the fibre direction). A set of four needle penetrations and the accompanying SYDs of a  $\pm 45^\circ$  biaxial fabric is depicted in figure 3.

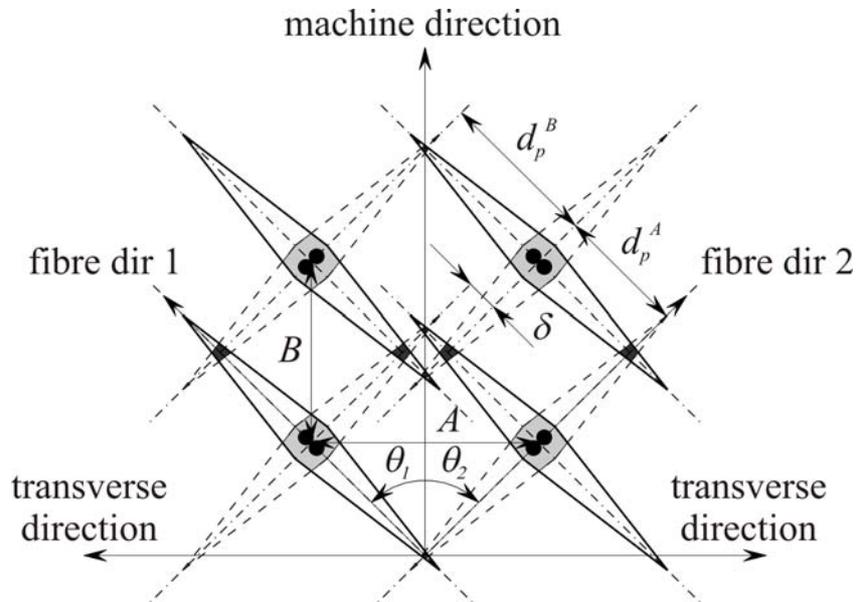


Fig. 3: *Schematic representation of the SYD configuration of a biaxial NCF. The light gray areas indicate the interaction regions between SYDs of top and bottom faces (solid and dashed lines respectively) in the centre of the SYD, the dark areas indicate the interaction regions in the tip. The dots indicate the stitch yarns piercing through the fabric.*

The stitch distances  $A$  and  $B$  are indicated, as are the fibre angles  $\theta_i$ , the distance  $\delta$  separating the tip of neighbouring SYDs and finally the projected stitch distances  $d_p^A$  and  $d_p^B$ . Moreover, it is assumed that the shape of the SYD is constant in the through–thickness direction of the fabric. The height of the SYD directly follows from the height of the cavity (which is constant in case of RTM) and the total number of plies. Dimensionless parameters were introduced for the width ( $\kappa$ ) and the length ( $\lambda$ ) [1].

### Statistical Distribution

The length and width of the SYDs were measured for the three different fabrics, shown in figure 1. The averaged width and length was measured for 100 SYDs on either side of the fabrics. The logarithmic values of the dimensions exhibit a normal distribution [1]. The length is assumed to be constant here. The fabric properties and measured widths  $b$  and standard deviations  $\sigma_{ln}$  of the  $\pm 45^\circ$  chain knit fabric (figure 1c–d) are presented in table 1. This fabric is used in the flow model.

Table 1: *Material properties and measured averaged width and standard deviation (averaged over both faces) of the DEVOLD biaxial  $\pm 45^\circ$  chain knit fabric.*

Parameter		value
Averaged width	$\bar{b}$ [mm]	0.28
Length	$l$ [mm]	3.89
Layer thickness	$h$ [mm]	0.5
Logarithmic standard deviation	$\sigma_{ln}$ [-]	0.33
Needle spacing	$A$ [mm]	5
Stitch distance	$B$ [mm]	2.5
Areal density	$\rho_A$ [kg·m <sup>-2</sup> ]	0.534
Fibre count	[-]	12K

### FLOW MODEL

The flow model is based on the assumption that the flow in the SYDs dominates the overall flow, since the SYDs are an order of magnitude larger in size than the space between the filaments of the fibre bundle. The SYDs are treated as channels and the fluid flows from a SYD in one ply to the SYD in an adjacent ply through the interactions regions. These regions are indicated by the gray areas in figure 3.

### Channel Flow Equations

The flow of resin through a fibrous reinforcement can be characterised as a laminar, viscous flow of an incompressible, Newtonian fluid. Hence the flow rate  $\Phi$  in a channel with radius  $r$  is related to the pressure gradient in longitudinal direction  $dp/ds$  as:

$$\Phi = \frac{\pi r^4}{8\mu} \frac{dp}{ds} = \frac{K}{\mu} \frac{dp}{ds} \equiv \frac{1}{\mathfrak{R}\mu} \frac{dp}{ds}, \quad (1)$$

with  $\mu$  the dynamic viscosity,  $K$  the permeability and  $\mathfrak{R}$  the flow resistance. However, the cross–sectional shape of the SYD is not circular and not constant over its length. Therefore

the hydraulic radius  $r_h$  is employed, defined as the twice the ratio of the cross-sectional area  $A_c$  over the perimeter  $P$ :

$$r_h = \frac{2A_c}{P}. \quad (2)$$

Subsequently the flow resistance  $R_i$  of the  $i^{\text{th}}$  channel is calculated by integration of the flow resistance  $\mathfrak{R}$ , given in equation (1), between the two points  $s_i$  and  $s_{i+1}$  (as indicated in figure 4):

$$R_i = \int_{s_i}^{s_{i+1}} \mathfrak{R}(s) ds = \frac{8}{\pi} \int_{s_i}^{s_{i+1}} (r_h(s))^{-4} ds. \quad (3)$$

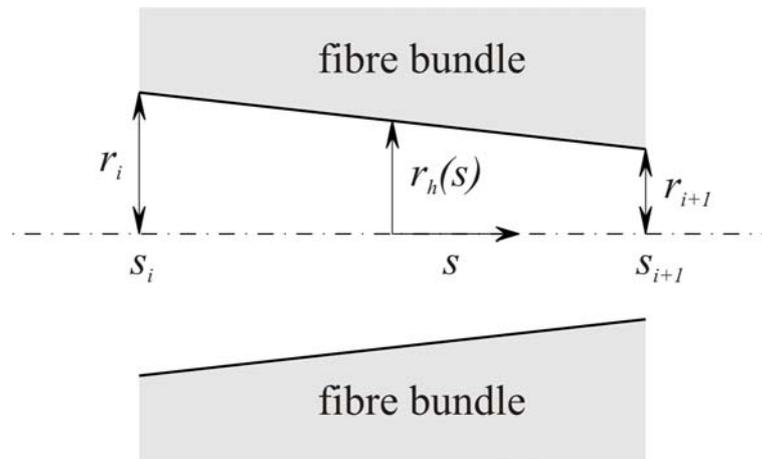


Fig. 4: Linearly decreasing channel radius  $r_h(s)$ :  $r_i$  maximum,  $r_{i+1}$  minimum radius,  $s$  longitudinal coordinate.

### Single SYD Unit Cell

A single SYD is subdivided into six channel sections, see figure 5. The  $a$  and  $b$  variants of the channels section  $I$ ,  $II$  and  $III$  are equal, based on the symmetrical shape of the SYD.

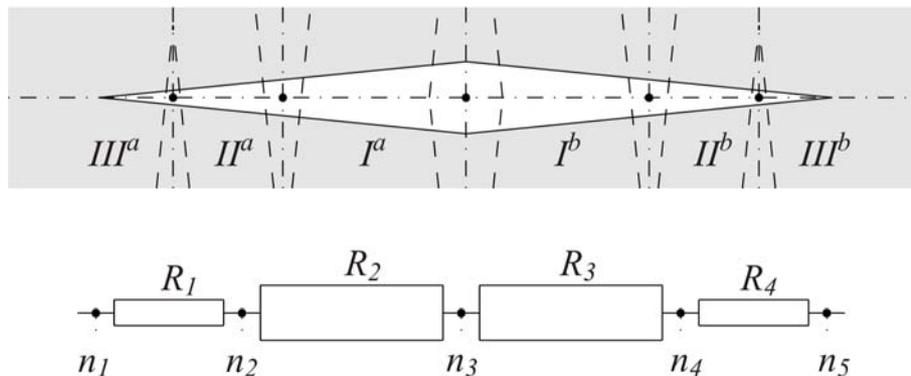


Fig. 5: SYD subdivided into two times three sections. The dashed lines indicate SYDs of the adjacent ply, the dots are the centres of the interaction regions. The channel sections  $I$  and  $II$  are represented by a channel with an effective resistance.

The dots ( $n_{1,2,3,4,5}$ ) indicate the centres of the interaction regions between the SYDs of adjacent plies. The sections  $III^{a,b}$  are dead ended sections and are discarded. The sections  $I^{a,b}$  and  $II^{a,b}$  are represented by channels with a flow resistances  $R_{1,2,3,4}$ .

### Network Formulation

The effect of the variability in the dimensions of the SYDs on the averaged value of the permeability and its variation cannot be estimated based on a single SYD unit cell. Hence, a network of SYDs is formed, as depicted in figure 6. The light gray resistances correspond to section *I*, the dark gray to section *II*.

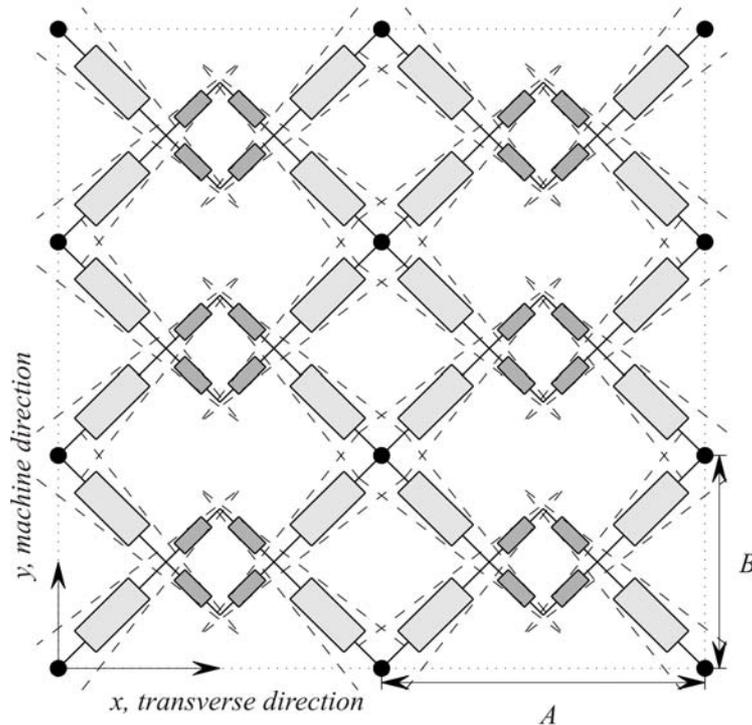


Fig. 6: A network of flow resistances, representing a flow domain. The dots indicate the stitch penetration locations.

The flow through a network is solved by employing a finite element discretisation. Pressure boundary conditions were used to apply a pressure gradient either in machine direction (*y* in figure 6) or in transverse direction (*x*).

A set of SYD widths was generated, based on the measured averaged width and its variation. The widths were assigned to the SYD of the network, either randomly or according to a predefined distribution. The permeability of the network was finally calculated by comparing the total volumetric flow rate with the pressure drop, see equation (1).

## RESULT & DISCUSSION

A number of networks were analysed, based on fabric 3. The permeabilities in machine direction and transverse direction (figure 6) of the analysed networks are normalised on the permeability of a network with equally sized SYDs (referred to as the ‘nominal permeability’).

### Amount of Variation

The amount of variation on the widths of the SYDs was varied between 0 and 150% of the measured standard deviation. The resulting normalised permeability  $K_N$  for a network of size  $40A \times 60B$  drops to roughly 85% of the nominal permeability for  $\sigma_{in} = \sigma_{meas}$  and to 70% for  $\sigma_{in} = \sigma_{meas} \times 150\%$  (see figure 7). Note that the normalised permeability is expected to be higher than 1 if the averaged permeability of a series of single SYD unit cells is determined. This corresponds to a system of parallelly connected flow resistances. A network approach results in a different prediction of the permeability compared to a unit cell approach.

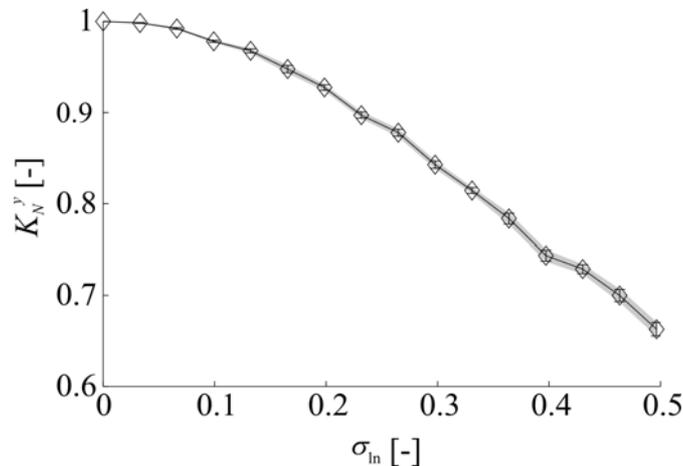


Fig. 7: Normalised permeability as a function of the amount of variation based on a logarithmic standard deviation (measured standard deviation:  $\sigma_{meas} = 0.33$ , network size:  $40A \times 60B$ ).

### Lower and Upper Bound

The lower and upper bounds of the permeability of the network are estimated by assuming that the widths either only vary in or perpendicular to the flow direction. The lower and upper bound (see figure 8) are found to be 40% below and 50% above the nominal permeability, irrespective of the flow direction.

This can result in a factor 3 difference between predicted – or measured – permeabilities for the given variation in the SYD dimensions.

## Influence of Spatial Distribution

The set of randomly generated SYD widths can either be distributed randomly, or according to a certain predefined spatial distribution. The normalised permeabilities for a flow in the machine direction are shown in figure 8. The spatial distribution causes the clustering of channels with comparable size. The type of distribution determines where the clustering occurs (for example: clustering of large SYD widths in the centre). The normalised permeabilities approach the upper or lower bounds, in which the amount of order is maximal. A similar behaviour is observed for a flow perpendicular to the machine direction. The permeabilities approach the opposite bound compared to a flow in the machine direction, in that case.

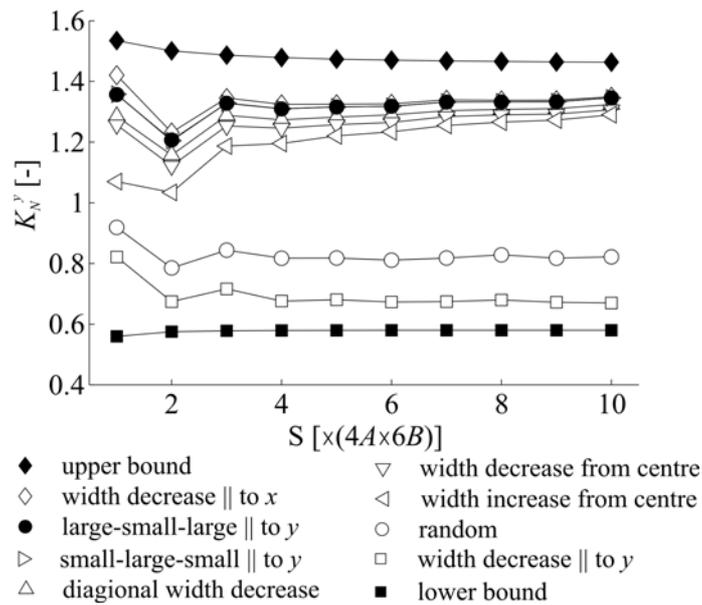


Fig. 8: Normalised permeability in machine direction for various spatial distributions ( $K_N^y$ ).

The predicted permeability of the network is essentially different from the predicted permeability if only individual SYD unit cells are analysed. The level of order in the spatial distribution has a significant effect on the predicted permeability. Hence, both the variation and the spatial distribution have to be taken into account in a network formulation to predict the permeability and its variation properly.

## CONCLUSIONS

The conclusions that can be drawn from the network approach, to predict the permeability of an NCF are:

- The variations in the internal structure of an Non-Crimp Fabrics have a significant effect on the macroscopic permeability of the fabric.
- It is not sufficient to average over a sufficiently large number of single SYD unit cells. A coupled network is required to obtain an accurate prediction of the permeability and its variation.
  - The spatial distribution of the dimensions of the SYDs in the network has a significant effect on the normalised permeability.

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