PERMEABILITY PREDICTION OF NON-CRIMP FABRICS BASED ON A
GEOMETRIC MODEL

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ABSTRACT

A model to predict the permeability of Non-Crimp Fabrics is proposed. The model is based on the geometrical features of the fabric. The stitches penetrating the uni-directional plies of the NCF induce distortions in the plane of the fabric. The dimensions of these Stitch Yarn induced fibre Distortions (SYD) are analysed for different fabrics in relaxed and sheared configurations. The length and width of the SYDs are found to be distribution values. The averaged value and the distribution change as the fabric is sheared. The SYDs 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 modelled to account for the statistical variations in the dimensions of the SYDs. The flow resistance of a single channel is calculated using a multigrid solver. The global flow is calculated by solving the effective resistance of all flow channels. 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.

1. INTRODUCTION

Resin Transfer Moulding (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 this relatively low cost production process: the absence of undulation (or crimp) 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 behaviour.

Accurate flow simulations, which require detailed knowledge on the impregnation behaviour, are an essential tool in finding the optimal RTM process parameters. One of the most critical parameters in the mould filling simulations is the permeability of the fibre preform, which is in essence a geometric quantity. Geometrical changes, such as compaction and drape affect the permeability. This research aims to predict the permeability on a local level, as a function of the geometrical features of NCFs and the effects of fabric deformation on these features.

An NCF reinforcement is mainly deformed by shear during drape, due to the low friction forces between fibres. The pure shear may be accompanied in tri- and quadriaxial NCFs by fibre-tow slippage, as these fabrics resist pure shear sufficiently hard to overcome initial friction [1]. Here only biaxial NCFs are dealt with.

The geometric model itself is based on the distortions of the fibres due to the stitches penetrating the uni-directional fibre layers. Fibres are forced aside by the needle penetrating the individual layers. The fibres enclose the thread which is left behind by the needle, forming a double wedge shaped distortion in the plane of the fibres in each layer. The distortions, referred to as Stitch Yarn induced fibre Distortions (SYD), are defined in [2,3,4].

Investigations on different types of fabrics revealed that the dimensions of the SYDs are distributed values. It was also shown that the dimensions as well as the distributions change under deformation of the fabric [2,3]. The results of these investigations are presented here and a relation is proposed to model the dimensions of the SYDs under shear for general NCFs.
The distortions in each layer can be considered as oriented in the direction of the fibres and form flow channels which determine the permeability of the fabric. Flow channels in the different fabric layers are connected to each other in overlapping regions, creating a network of flow channels. The flow resistances in each channel are computed using a multigrid fluid flow solver. The global flow domain is then analysed as a linear network of these resistances. The low computational requirements allow a proper statistic analysis, with statistically distributed flow channel dimensions, within a reasonable amount of time.

2. STITCH YARN DISTORTION

Several definitions used are discussed here for convenience of the reader. A single layer of an NCF consists of a stack of uni-directional plies of fibres, see Fig 1. The orientation of the fibres is defined as the angle $\theta$ between the fibres and the manufacturing direction. The stack of fibre 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 and geometry is found in Lomov et al. [2].

![Fig. 1. Structure of a single biaxial ply of a Non-Crimp Fabric: two uni-directional layers which are stitched together.]

The bottom face of the fabric is the face which contains the stitch loops. The loops can be considered as oriented in the manufacturing direction, inherent to the stitching process. Possible tilts are an exception to this rule and are discussed in [2]. The top face is the face lying on top during manufacturing. Fig. 2 shows a scanned image of both sides of an NCF. The distortions induced by the stitches are clearly visible. The distortions are referred to as Stitch Yarn induced fibre Distortions (SYD). The length and width of an SYD ($l$ and $b$ respectively) are indicated in the enlarged areas.

![Fig. 2. Stitch Yarn 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 distortions depend on a number of parameters. Amongst these are the machine settings, the needle spacing, stitch yarn, stitch tension and fibre-tow treatments. It is not clear yet how these parameters influence the dimensions of the Stitch Yarn induce fibre Distortions. The dimensions of the SYDs are assumed to be proportional to the stitch thread...
diameter. An empirical relation was proposed by Lomov et al. [2]. Analysis of different NCFs revealed that these relations do not hold in general. An intolerable discrepancy between the measured widths on both faces of the fabric was found. Revised relations are presented in [4].

The empirical proportionality constant $\kappa$ between the width of the SYD and the stitch yarn diameter is defined separately for the top and the bottom face of the fabric (subscripts $f$ and $b$ respectively):

\[
\begin{align*}
\text{(top face SYD)} & : b = \kappa_f \times d_0 \\
\text{(bottom face SYD)} & : b = \kappa_b \times d_0 \\
\text{(inner SYD)} & : b = 2d_0
\end{align*}
\]

$d_0$ refers to the compacted diameter of the stitch yarn [2] and is calculated by:

\[
d_0 = \sqrt[4]{\frac{4\rho_L}{\pi\rho_s K}}
\]

with $\rho_L$ and $\rho_s$ the linear and volumetric density of the yarn respectively and $K$ the packing coefficient, which is equal to 0.907 for a hexagonal packing. A detailed description on the modelling of the stitch yarns and fibre bundles can be found in [2].

“Table 1. Material data from the studied Non-Crimp Fabrics.”

<table>
<thead>
<tr>
<th>Ply</th>
<th>B1 (kg m$^{-2}$)</th>
<th>B2 (kg m$^{-2}$)</th>
<th>B3 (kg m$^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fibre</td>
<td>Toray T700 50E</td>
<td>Toray T700 50E</td>
<td>Tenax HTS 5631</td>
</tr>
<tr>
<td>fibre count</td>
<td>12K</td>
<td>24K</td>
<td>12K</td>
</tr>
<tr>
<td>orientation</td>
<td>$\pm 45$</td>
<td>0/90</td>
<td>$\pm 45$</td>
</tr>
<tr>
<td>Stitch</td>
<td>PES</td>
<td>PES</td>
<td>PES</td>
</tr>
<tr>
<td>Linear density</td>
<td>7.6</td>
<td>7.6</td>
<td>5</td>
</tr>
<tr>
<td>$d_0$</td>
<td>0.088</td>
<td>0.088</td>
<td>0.071</td>
</tr>
<tr>
<td>Knit pattern</td>
<td>tricot</td>
<td>tricot/chain</td>
<td>chain</td>
</tr>
<tr>
<td>$D_s$</td>
<td>1.79</td>
<td>2.64</td>
<td>2.22</td>
</tr>
<tr>
<td>$D_n$</td>
<td>4.45</td>
<td>5.03</td>
<td>5.76</td>
</tr>
</tbody>
</table>

However, the influence of shear on the dimensions of the SYD is still not addressed. Various biaxial NCFs in relaxed and sheared configuration were analysed in order to extend (1) and formulate a relation between the dimensions of the SYDs and the deformation of the fabric.

“Table 2. Samples of each of the fabrics.”

<table>
<thead>
<tr>
<th>$\gamma$ [°]</th>
<th>0</th>
<th>15</th>
<th>30</th>
<th>45</th>
<th>60</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>B2</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>B3</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
</tbody>
</table>

The dimensions of the SYDs are measured by analysis of scanned images. Pixel coordinates of one hundred SYDs are collected, allowing statistical analysis of the dimensions. An averaged value and a distribution of the SYD dimensions are obtained. Three fabrics were evaluated. The fabric data is presented in Table 1. Fabric B1 and B2 are studied in unsheared configuration in reference [5], fabric B in reference [2] is the same fabric as B1 here (also
only unsheared configurations). Fabric B3 is from a different manufacturer and results on both relaxed and sheared configurations have been presented in [3,4].

Samples with shear angles up to 60° were analysed. Table 2 lists the samples of each of the NCFs. The fabric is sheared in a small trellis frame. The frame measures $150 \times 150 \text{ mm}^2$. Sicomet™ type 85 glue is applied near the edge of the sample to maintain the shear angle after releasing the fabric from the frame.

“Fig. 3. Measured values of top and bottom face $\kappa$ (a,b) and length $l$ (c,d) of fabric B1 for various shear angles. The error bars indicate the standard deviation of the measured values.”

“Fig. 4. Measured values of top and bottom face $\kappa$ (a,b) and length $l$ (c,d) of fabric B2 for various shear angles. The error bars indicate the standard deviation of the measured values.”

“Fig. 5. Measured values of top and bottom face $\kappa$ (a,b) and length $l$ (c,d) of fabric B3 for various shear angles. The error bars indicate the standard deviation of the measured values.”
Both the width $b$ and length $l$ of the SYD were analysed for sheared configurations. The width of the SYD is expressed in terms of the dimensionless proportionality factor $\kappa$. The measured $\kappa_f$ and $\kappa_b$ values for different shear angles and different materials are presented in Fig. 3 to Fig. 5.

Fabrics B1 and B2 show similar $\kappa$ values, although having different fibre orientation and tow size. A larger difference is observed between the fabrics B1 and B3 which both have a similar tow size and fibre orientation. The orientation of the stitches is different on both sides of the fabrics B1 and B2 (tricot and tricot/chain pattern), whereas it is the same on both sides for fabric B3 (chain pattern) (see Fig. 6). This indicates that the stitch pattern plays a more important role than the fibre tow size and orientation of the fibres with respect to the machine direction.

It is suggested that the value of $\kappa$ is mainly influenced by:

1. In-plane compaction of the fibrous plies during shear.
2. Number of stitch threads in the SYD.
3. Stitch tension.

The plies are compacted in-plane as the fabric is sheared. The fibres will fill the SYDs and the stitch thread is moved and compacted as a consequence. The width of the SYD will decrease gradually with increasing shear angle. The decrease of the width of the SYDs stops as the stitch yarn is compacted fully and, if more than one thread is present in the SYD, the threads are rearranged such that the most compacted position is reached. The value of $\kappa$ remains constant and the fibre bundles themselves will be compacted if the shear angle increases beyond this point. The shear angle at which the minimum width of the SYD is reached, is defined as the threshold angle $\gamma_{thr}$. A threshold angle of roughly 30° is observed for all fabrics and all faces.

"Fig. 6. Difference in stitch pattern and loop size on top and bottom faces of the three fabrics."
Finally, the stitch tension affects the value of $\kappa$. The stitches of the tricot knitted fabrics (B1 and B2) are elongated as the fabric is sheared [6]. It is shown that the elongation of the stitch thread is different when the fabric is sheared with a positive or with a negative shear angle. The stitch threads of the chain knitted fabric B3 are either compressed or tensioned when sheared. Consequently, the differences in stitch yarn elongation may cause differences in the value of $\kappa$ depending on the direction of the shear angle. Here, all the fabrics are sheared such that the loops on the bottom face are under compressive load during shear.

The difference in $\kappa_0$ of the fabrics B1 and B2 and fabric B3 may originate from a difference in stitch tension applied during manufacturing. Fig. 6b, d and f show the stitches on the bottom face of the three fabrics. The scaling of the images is equal. Clearly the loops of B1 and B2 are similar, but those of the B3 are much wider, indicating a lower stitch tension. The SYDs on the bottom face will be wider for a higher stitch tension, since the higher the stitch tension, the more the loops are forced in the SYD. The direction of the fibres with respect to the stitching does not seem to influence this process.

The behaviour of the coefficient $\kappa$ is described employing a stepwise function:

$$\kappa(\gamma) = \begin{cases} 
\kappa_{\text{min}} & \text{if } \gamma = 0° \\
\kappa_{\text{min}} - (\kappa_{\text{min}} - \kappa_0) \frac{\gamma - \gamma_{\text{thr}}}{\gamma_{\text{thr}}} & \text{if } \gamma > \gamma_{\text{thr}} 
\end{cases}$$

(3)

with $\kappa_0$ and $\kappa_{\text{min}}$ the values of $\kappa$ at $0°$ shear (initial value) and its minimum value. The values of $\kappa_0$ and $\kappa_{\text{min}}$ for the top and bottom face of the three fabrics are given in Table 3.

**Table 3.** The initial and minimal values for the empirical constant $\kappa$ and the measured length for top and bottom face of the three fabrics.

<table>
<thead>
<tr>
<th></th>
<th>top $\kappa_0$ [-]</th>
<th>top $\kappa_{\text{min}}$ [-]</th>
<th>top $l$ [mm]</th>
<th>bottom $\kappa_0$ [-]</th>
<th>bottom $\kappa_{\text{min}}$ [-]</th>
<th>bottom $l$ [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td>3.14</td>
<td>2.21</td>
<td>4.77</td>
<td>4.94</td>
<td>3.78</td>
<td>5.51</td>
</tr>
<tr>
<td>B2</td>
<td>1.93</td>
<td>1.93</td>
<td>4.89</td>
<td>4.35</td>
<td>3.79</td>
<td>4.64</td>
</tr>
<tr>
<td>B3</td>
<td>3.93</td>
<td>1.70</td>
<td>6.63</td>
<td>3.83</td>
<td>2.23</td>
<td>6.32</td>
</tr>
</tbody>
</table>

The length of the SYDs is analysed in a similar way. However, it is impossible to find a single formulation the SYD length as a function of the shear angle for all three fabrics, especially since a large amount of scatter is found on the measured data (see Fig. 3 to Fig. 5). A constant value of the length of the SYD will be assumed in the models, based on the averaged values (Table 3). The length of the SYDs is roughly equal on the top and bottom faces of each of the fabrics, but the SYDs of B3 are longer than those of B1 and B2, which may be caused by the larger needle spacing (Table 1).

![Fig. 7. Histograms of the width of the SYDs on the top face of fabric B3 in relaxed and 15° sheared configuration on a linear scale.](image-url)
The averaged values of the dimensions of the SYD may not be sufficient to formulate a comprehensive model of the NCFs. The large scatter on the results, as indicated by the error bars in Fig. 3 to Fig. 5, has to be taken into account. The distribution of the dimensions is analysed to this end.

Fig. 7 shows the histograms of the widths of the top face SYDs of fabric B3 in relaxed (a) and 15° sheared configuration (b). A normal distribution is plotted (solid line), based on the calculated average and standard deviation. The graphs show that a good agreement is found for the relaxed configuration. However, the agreement is less for the 15° sheared configuration: the distribution tends to a lognormal distribution, which is confirmed by Fig 8, which shows the histograms of the width of the top face SYDs of 15° to 60° sheared fabric (B3) on a logarithmic scale.

**Fig. 8.** Histograms of the width of the SYDs on the top face of fabric B3 in 15°, 30°, 45° and 60° sheared configuration on a logarithmic scale.

The distributions for the SYD dimensions of the back face and those for fabrics B1 and B2 show a similar behaviour: the distribution of the dimensions changes from normal to lognormal during shear deformation of the fabric between 0° and 30° shear.

### 3. FLOW NETWORK

The common way to predict the permeability of a fabric, is based on a superposition of permeabilities [7,8,9]. The permeability of a single layer, consisting of a transverse and longitudinal component, is averaged over the ply or preform thickness after rotation to a global coordinate system. The effect of shear on the permeability is accounted for by rotating the permeability tensors of the layers. However, these models are not capable to incorporate the distribution of the permeability as found by experiments [10].

The variations in the dimensions of the SYDs (see section 2) can be modelled explicitly, due to the more accurate representation of the geometry of the NCF. The drawback is the increase in computational effort to solve the flow equations.

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. 9. 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 fibres with respect to the machine direction. Note that they are affected on a local level by the distribution of the dimensions of the SYDs.

The dimensions of the SYDs have to be treated as statistically distributed values. This does not only affect the dimensions themselves, but also the number, location and size of the overlapping regions of SYDs of different layers of the NCF. It is believed that a single unit cell is not sufficient to model the possible configurations and interactions between SYDs. A network of SYDs is built in order to model these interaction phenomena.

Furthermore, it should be noted that interply flow also has to be accounted for, but currently only a single layer model is implemented. A multi layer model will be developed in a later stage.

The structure of the model implicitly allows the analysis of the permeability through the thickness of the fabric. No changes in the model are required apart from the application of different boundary conditions.

In- and outflow regions are found in overlapping regions as depicted in Fig. 9. The amount of these regions and their location depend on the length of the SYDs, the needle spacing, the
stitch distance in machine direction and the orientation $\theta$ of the fibres with respect to the machine direction. However, the number and locations of the overlapping regions are not affected by shearing the fabric, provided trellis shear is assumed. Possible locations of the overlapping regions are limited to integer multiplications of the projected distance $d_p$ of the needle spacing $D_n$ and stitch distance $D_s$ on the stitch yarn distortion (see Fig. 10).

It can be derived that the relations between the projected distances $d_p$ and $D_n$ and $D_s$ are:

$$
\begin{align*}
d_{p}^{n} &= \frac{D_{s}}{\cos{\theta}(\tan{\theta_1} + \tan{\theta_2})} \\
d_{p}^{s} &= \frac{D_{s} \sin{\theta_1} \tan{\theta_1} \tan{\theta_2}}{\tan{\theta_1} + \tan{\theta_2}}
\end{align*}
$$

A multigrid solver [11] is chosen to calculate the flow resistances between the interaction regions in the SYD unit cells. This method is adopted since it is a powerful method for fast flow calculations.

![Fig. 11. Example of transformation from network of SYDs to network of flow resistances.](image)

A network of flow resistances is constructed subsequently, 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 global system of flow resistances is solved analogously to the solution of the effective resistance of an electrical circuit with parallel and serial resistances (see Fig. 11), with the pressure gradient $\nabla p$ and the voltage drop $V$ and secondly the fluid velocity $u$ and the current $I$ as congruent variables. The ratio of the permeability $K$ and the viscosity $\mu$ is congruent with the inverse of the electrical resistance $R$:

$$
\frac{V}{R} = \frac{K}{\mu} \cdot \nabla p \leftrightarrow I = \frac{1}{R} V
$$

The complexity of the network and the current uncertainties concerning the minimum size of the network force the analysis of relative large networks. The model will require more CPU time than the currently available purely uni-directional models, but, in contrast to those, the network model is able to quantify the statistical distribution observed in experiments.
4. CONCLUSIONS
A model for the geometrical description of (un)sheared NCF is presented. Subsequently, a model for the prediction of the permeability of a single layer NCF is based on this geometrical model. The SYDs, or wedge shaped distortions induced by the stitches penetrating the fabric, form a network of flow domains. This network model describes the actual geometry of the NCF more detailed than purely uni-directional models and the statistical distribution of the SYD dimensions can be incorporated explicitly in the model, by creating a network of SYDs having a certain spatial distribution of dimensions.

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