THE EFFECT OF GEOMETRICAL FEATURES OF NON-CRIMP FABRICS ON THE PERMEABILITY

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ABSTRACT

Non-crimp stitched fabrics (NCF) are often used as reinforcing material in high performance composite materials. Prediction models of the processing stage of the manufacturing are highly desirable in order to enhance the control of the process and enable the production of higher quality materials. In the present paper, different geometrical features are studied in order to investigate their influence on the permeability. This work proves that the thread and the crossings as well as the variations of the width and height of the inter-bundle channels have great influence on the permeability of a fabric. Prediction models therefore have to take these features as well as their statistical variations into account in order to be able to perform accurate predictions of the permeability.

INTRODUCTION

In order to produce high quality fibre reinforced composite materials, it is crucial that the amount of defects introduced during impregnation of the reinforcing fibres is minimised. New and improved models of this stage of the process are therefore highly desirable. It is well known that the flow through a fabric of a thermosetting resin follows Darcy's law [1]. Hence, a linear relationship between the flow rate and the pressure gradient is anticipated according to:

$$v_i = -\frac{K_{ij}}{\mu} p_{,j} \ . \tag{1}$$

Here v_i is the superficial velocity vector, K_{ij} the permeability tensor, μ the viscosity and p the pressure. Knowledge of the permeability of a fabric is therefore indispensable when the impregnation process is to be predicted. The permeability can be determined by measurements but these are often time-consuming and it is therefore of relevance to develop models based on the geometry of the fabric. In the latter case, the necessity of experimental measurements can diminish and a higher level of control of the process will be possible. Optimizations of the fabric geometry as to the impregnation process will also be facilitated with a proper model.

The focus in this paper is on non-crimp fabrics (NCFs). The geometry of this reinforcing material is built up by layers of fibre bundles that are stitched together. The stitching results in formation of channels between the fibre bundles and since the fibre bundles consist of a large number of fibres the fabric has dual scale porosity. Two types of flow can therefore be identified, micro scale flow within the bundles and meso scale flow between them. Typical length scales for these two types of flow are <10 μm and >100 μm, respectively. It is important to notice that the overall flow rate through the material, to a large extent, is set by the meso scale flow [2, 3].

Numerous models of the permeability of different porous materials have been developed that work for certain classes of geometries but that fails to quantitatively predict the permeability of fabrics used in composite material. For such fabrics the focus on the modelling has during the last years shifted from micro- [4, 5, 6] to meso scale modelling. Modelling of the inter-bundle channels as capillaries with rectangular areas [6] is one example of the latter. In this case good agreement with experimental data was obtained for some fabrics but the discrepancy was large for other types. Extending the models to more realistic cross-sections can improve the results [7] but the analytical expressions for the permeability become very complex even for relatively simple geometries. A few other attempts to model the permeability of repeatable unit cells in clustered fibre networks have been undertaken. For instance, a permeability model for woven fabrics was developed by [8] where the Stokes and Darcy flows were assumed for the resin channels and the weft and warp bundles respectively. In [9], conceptual models were proposed for four representative fibre reinforcements. For the unidirectional model of non-crimp fabrics, a medium sized pore parallel to a smaller pore are modelled and represents the flow in the inter-bundle channels and within the fibre bundles, respectively. This model was validated but showed a quantitative disagreement with the experiments.

One way to increase the exactness of the modelling is to improve the description of the meso geometry of the fabric. This can be realized by usage of Computer Aided Design, CAD, tools combined with a Computational Fluid Dynamics, CFD, code [10]. This technique is by definition approximate and must therefore be verified before being used. Although this was carefully done in [10] a unit cell model of a biaxial NCF strongly over-predicted the permeability compared to experimental data. This shows that additional features of the fabric must be accounted for such as the stitching [10] also stated in [11], fibres crossing the inter-bundle channels and variation in geometry between unit cells [7].

In the present paper a study of how different geometrical features of a biaxial NCF influence the permeability is performed. The features which come from the stitching process are analysed together with variations of various geometrical parameters and dimensions. Unit cells similar to those in [10] with different geometries are used in order to study the different features and at the same time reduce the computational load and time. A complementary study on the numerical accuracy is also performed to enhance the quality and trust.

STRUCTURE OF NCFS

Non-crimp fabrics consist of layers of fibre bundles stitched together in different directions. A consequence of the stitching is that channels are formed between the fibre bundles. In addition to the channels, the stitching process gives rise to two other major geometrical features of the fabric. The first is the penetration of the inter-bundle channels by the thread where the fabric is stitched, Figure 1a, and the second is the crossing of fibres between two neighbouring fibre bundles, Figure 1b.

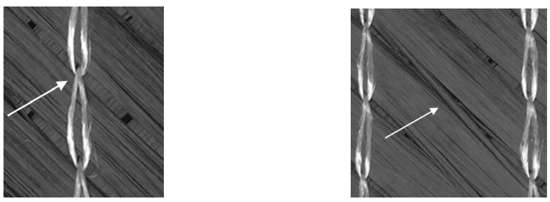


Figure 1. Top view of a [-45/+45] NCF showing a) the thread and b) the crossings.

The geometrical features are somewhat repeatable in a fabric due to the periodicity of the stitching process and their distribution is therefore dependent on the stitching pattern. A typical distribution of the different features in a material is visualised in Figure 2a.

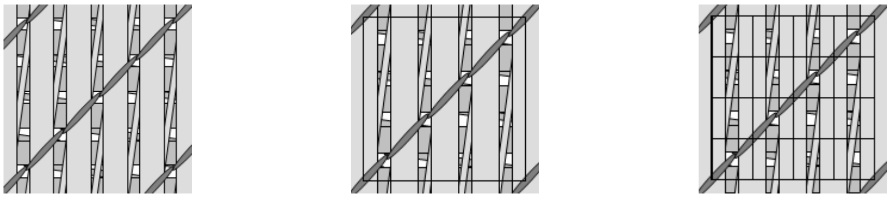


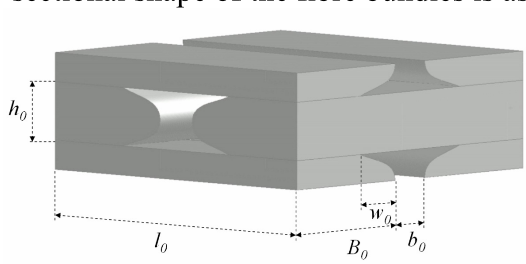
Figure 2. a) Typical distribution of the different features from the stitching process in a biaxial [-45/+45] NCF. b) Representative part of the unit cell including all the features which arise from the stitching process. c) Unit cell distribution of the biaxial fabric.

The repeatability of the stitching makes it possible to determine a representative volume of the fabric. This quantity should be repeatable throughout the fabric and can be considered as a large unit cell including all the features from the stitching process: cf. Figure 2a and 2b. The indicated volume is, however, too large if a detailed simulation is to be carried out with CFD. Resolving the geometry and flow to get a close to grid independent solution is extremely important in CFD- simulations for reliable results [12]. A way to overcome this problem is to perform simulations on smaller unit cells as was done in [10]. These unit cells can thereafter be used to build up the representative part of the fabric as outlined in [7]: see Figure 2c. Another advantage with the unit cells, except from being small, is that the different features such as the stitching are isolated and can therefore be evaluated separately. Finally, in real fabrics there are always statistical deviations from the average geometry present. Perturbations of the channel widths and heights as well as deviations from the average thread and crossing dimensions must therefore be considered.

MODELLING

The fabric used for this analysis is a biaxial non-crimp stitched fabric with a [-45°/+45°] lay-up from Devold AMT. The inter-bundle channels of a unit cell are built up by the fibre bundles with the shape defined by the dimensions b_0, h_0, B_0, l_0 and w_0, cf. Figure 3. To determine a unit cell for this type of fabric the following assumptions are introduced:

1) The unit cells are assumed to be repeatable in all directions of the fabric.
2) The flow is assumed not to travel between different layers.
3) The cross-sectional shape of the fibre bundles is assumed to be symmetric.



b_0 = 0.2316e-3 m
h_0 = 0.3100e-3 m
B_0 = 0.7622e-3 m
l_0 = 1.7560e-3 m
w_0 = 0.2702e-3 m

Figure 3. The dimensions of the average basic unit cell, the plain unit cell.

The Basic Cells

To represent the features of the fabric three basic unit cells are defined: *the plain unit cell*, *the tread unit cell* and the *crossing unit cell*. For the *plain unit cell* the geometry is exclusively determined by the fibre bundles, Figure 4a. I.e. the fibre bundles are treated as solids and only the inter-bundle channels are included in the fluid domain. For typical dimensions of the actual unit cell see Figure 3.

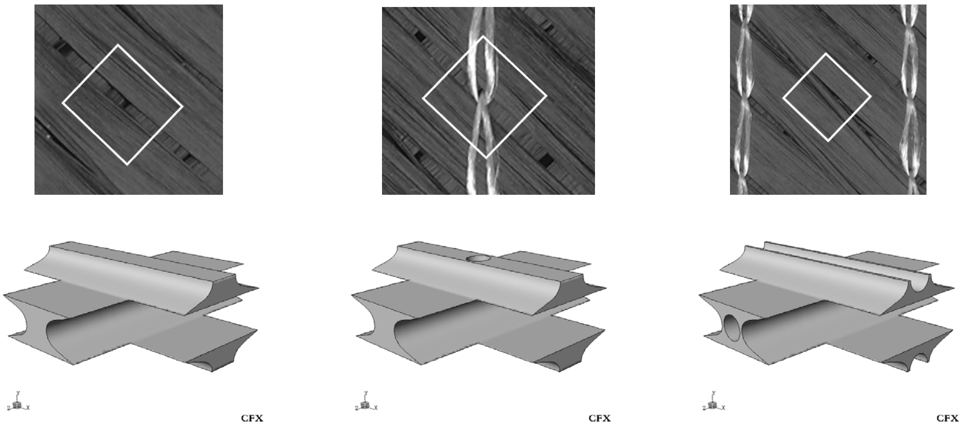


Figure 4. a) The basic geometry of a fabric with a [-45°/+45°] lay-up together with its corresponding fluid domain. b) The thread in a fabric with a [-45°/+45°] lay-up together with its corresponding fluid domain. c) The crossings in a fabric with a [-45°/+45°] lay-up together with its corresponding fluid domain.

The *thread unit cell* has the same geometry as the *plain unit cell* but with the extension that it contains a representation of the thread. In real fabrics, the thread has a relatively complex shape as it penetrates the inter-bundle channels, Figure 4b. To facilitate the numerical simulation the thread is in this stage modelled as a vertical solid cylinder.

In the final basic unit cell the crossings are represented. The crossings are a consequence of the stitching process and consist of fibres going from one bundle to another crossing the inter-bundle channels, Figure 4c. The cross-sectional shapes of the crossings vary, but a reasonable assumption based on their formation and from observations of micrographs is that the crossings have elliptical cross-sections. The crossings are usually longer than a basic unit cell and consequently a much larger cell is required to exactly describe their behaviour. However, a first assumption is to let the crossings be represented by elliptical cylinders placed symmetrically within a *plain unit cell*, see Figure 4c. This rather crude model of the crossings can still be seen to represent the main feature of the crossings, the filling of the inter-bundle channels.

Variations in geometry of the basic unit cells

As explained in the introduction it is of interest to study the influence on the permeability from variations of the geometry of the basic unit cells. For *the plain unit cell* the variations in height and width are carried out according to Figure 5a and 5b. For the variations of the width the two directions of the inter-bundle channels are varied independently and simultaneously in order to reveal the most significant parameters, Figure 5c. The variations of the height are performed on both channels simultaneously. During the variations of the channel height the ratio *w/h* is held constant to ensure the same curvature of the fibre bundles.

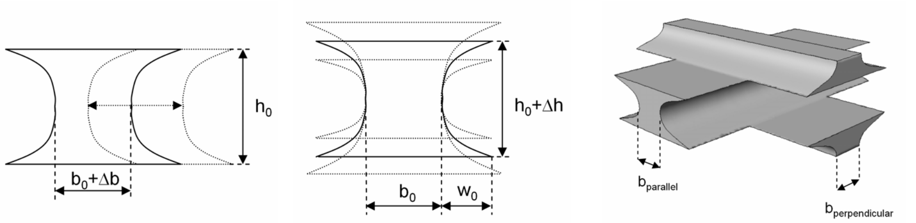


Figure 5. a) Variations of the channel shape by varying the channel width. b) Variations of the channel shape by varying the channel height. c) Variations in different channel directions of a unit cell.

For the *thread unit cell* the diameter of the thread, b_t, is varied as percentages of the channel width for three different width to height ratios of the channels, Figure 6.

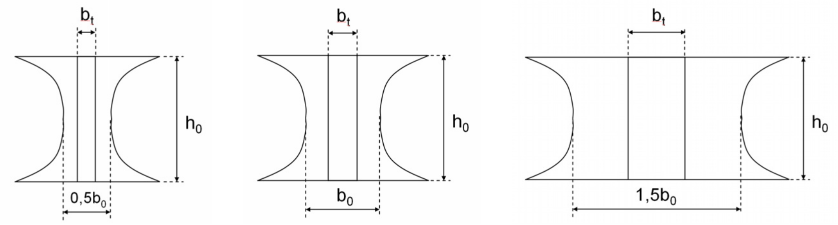


Figure 6. Definition of the variations of the thread for three different channel shapes: narrow, average and wide.

In the *crossing unit cell* the crossings are modelled as elliptical cylinders as previously described. Similar to the thread the parameters b_c and h_c are varied as percentages of the channel width and height respectively. This is done for three different width to height ratios of the channels, Figure 7. The variations of the parameters, b_c and h_c, are coupled in the way that the ratios b_c/b and h_c/h are held equal throughout the variations. The reason for not letting the parameters vary freely is that the elliptical shapes of the crossings are only approximate descriptions of the real shapes of the crossings. Hence, a more developed study of the variations would be an over-elaboration.

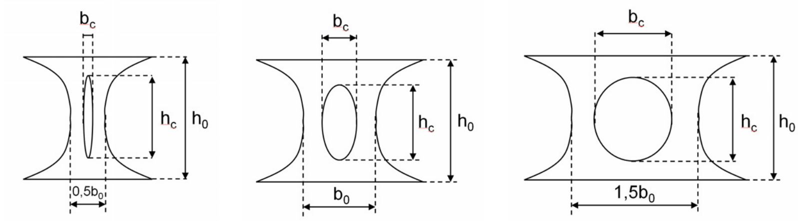


Figure 7. Definition of the variations of the crossings for three different channel shapes: narrow, average and wide.

Finally, the influence from changes of the bundle shape on the permeability is studied. Average bundle shapes can be determined by analysis of micrographs of cross-sections of manufactured composites. A different bundle shape modify the channel geometry and therefore also the permeability. Two types of variations are studied. The first is the shift of the centre line of the bundle curvature, s_w, Figure 8a, and the second is the amount of curvature of the bundle, w/h, Figure 8b. The variations are performed for all the bundles in the unit cells to maintain symmetry wherever possible.

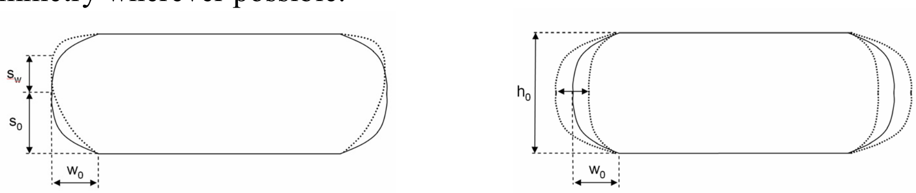


Figure 8. a) Warp of the bundle shape, s_w. b) Curvature variation of the bundle, w.

NUMERICAL SIMULATIONS

The commercial CFD code CFX5.6 from ANSYS Inc. is used to simulate steady, incompressible laminar flow through the unit cells. The code is based on a finite volume method and uses a non-structured solver [13]. Since the flow is laminar and the fluid treated as Newtonian the governing equations describing the flow are [1]:

$$U_i \partial_j U_i = -\frac{1}{\rho} \partial_i P + \nu \cdot \nabla^2 U_i \,, \tag{2}$$

$$\partial_i U_i = 0 \,, \tag{3}$$

where U_i is the local mean velocity vector, ρ is the fluid density, P is the local pressure and ν is the kinematic viscosity. To drive the flow a pressure gradient is added to the momentum equation as a momentum source. Knowing that the Reynolds number is low, Re<<1, in the simulations the term on the left-hand side of (2) could have been excluded. Including it facilitates, however, studies on higher Reynolds number flows in the future. The differencing schemes used to solve (2) and (3) in CFX5.6 are high resolution schemes, which gives a close to second order accurate solution as recommended in [14].

Symmetry is applied to the fluid domains in order to reduce the computational load of the simulations. The fluid domains used in the simulations are therefore, with one exception, one fourth of the domains of the unit cells: cf. Figure 9. The exception is when the channel geometry is asymmetric: cf. Figure 8a. In this case the fluid domain is half of the unit cell.

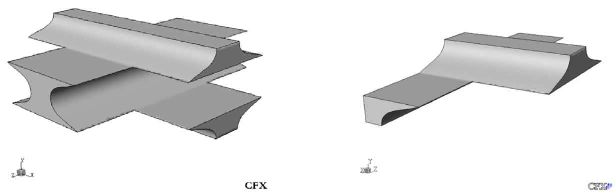


Figure 9. Entirety fluid domain for the plain unit cell (left) and the adapted fluid domain (right), used by the solver.

Since the bundles, threads and crossings are treated as solids no-slip boundary conditions are applied on these quantities. By definition of the unit cell, periodic boundary conditions are set at the inlet and outlet of the fluid domain and symmetry boundary conditions are set on the rest of the fluid boundaries.

The unstructured grids consisting of tetrahedral elements, used in the simulations, are generated by the CFX5.6 meshing tools [13]. The appropriate mesh for the fluid domains are determined by a grid convergence study performed on the fluid domain of the *plain unit cell* as in [10]. The grid resolution is thereafter held constant throughout the simulations so that the grid convergence error is about 3%.

RESULTS AND DISCUSSION

Having control of the numerical errors and knowing from previous studies that numerical results correspond to analytical ditto [10] enable deeper studies of the variations of the meso scale geometry. To start with, variations of the width of the channel parallel to the pressure gradient give large variations in the permeability, while variations of the channel perpendicular to the pressure gradient give marginal influence on the permeability: cf. Figure 10a. The coupled variations, where both channels are varied equally, show almost the same permeability variation as for the variations of the channel parallel to the pressure gradient alone. Hence, most of the contribution to the permeability variation comes from the variations of the channel parallel to the pressure gradient.

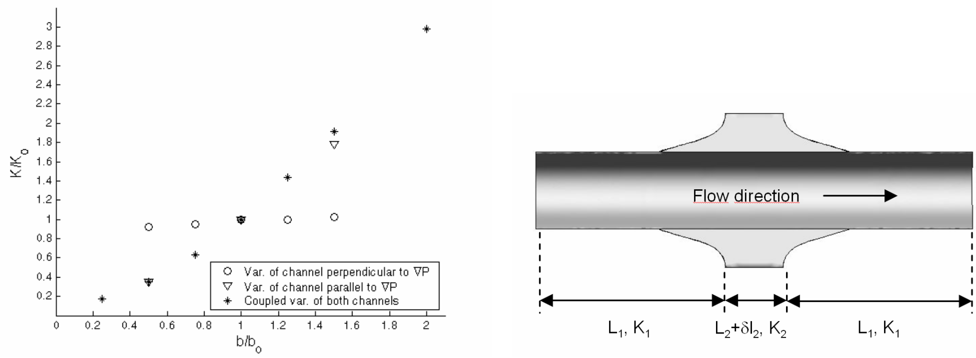


Figure 10. a) The influence on the permeability for different variations of the widths of the channels of a plain unit cell. b) Side view of the fluid domain and the different regions with different permeability.

The same result is obtained by analysing three regions with different permeability coupled in series, Figure 10b. The total permeability of the system can be calculated by [15]:

$$\frac{L_{total}}{K_{total}} = \sum_{i=1}^{m} \frac{L_i}{K_i} \quad . \tag{4}$$

The fact that the permeability of the middle region, K_2, is large gives:

$$K_{total} = \left(1 + \frac{(L_2 + \delta l_2)}{L_1}\right) K_1 . \tag{5}$$

On the first hand variations of the channel width perpendicular to the flow, δl_2, result in small changes of the total permeability, Equation (5). On the other hand a variation of the channel width parallel to the flow direction substantially changes K_1, and therefore gives a greater change in K_{total}. The variations of the width can therefore be performed simultaneously in both directions to reduce the degree of freedom without violating the resulting permeability. This will greatly reduce the number of simulations required to determine the permeability for a large set of variations.

A detail in Figure 10a is that the gradient of an imaginary curve through the star-like points tends towards zero as the channel becomes narrow. This is due to the fact that the unmodified slit region takes up a considerable part of the channel cross-section for narrow channels, Figure 11a, while for wider channels the slit region is small compared to the variable bulk region, Figure 11b. The slit region therefore has a great influence on the permeability for narrow channels while it has less influence for wider channels. To exemplify, the permeability for a unit cell with a width two times the average, is 198% larger than the average permeability while a decrease of the width to half of the average reduces the permeability by 83%. Variations of the channel widths are therefore a very important factor to take into account for prediction models.

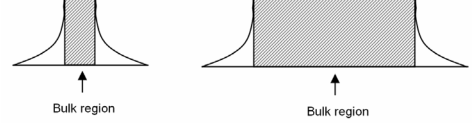


Figure 11. Regions of a cross-section of a a) narrow channel b) wide channel.

Having studied the influence from the width on the permeability it is natural to also find out how the variations of the height of the channels affect the permeability. In this case the relation is nearly linear, with a slightly non-linear behaviour, i.e. a steeper gradient for smaller heights, Figure 12. Larger heights of the channels give larger cross-sectional areas, which naturally result in higher permeability while lower heights result in lower permeability as indicated by Figure 12. The steeper gradient for the small heights of the channels originate from the fact that the channels are wide and therefore the bulk region dominates over the slit region, see Figure 11b. An increase of the height of the channels two times the average gives an increase of the permeability by 36%. A decrease of the heights of the channels to half of the average heights, results in a decrease of the permeability by 24% of the average. Hence, the variations of the height have large influence on the permeability but the influence is significantly smaller than for the variations of the width.

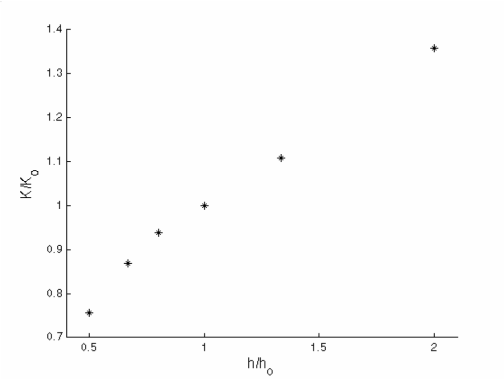


Figure 12. The influence of variations of the channel height on the permeability for a plain unit cell.

Moving over to the *thread unit cell* it is found that the variations of the diameter of the thread for cells with narrow channels give small variations of the permeability compared to unit cells with wider channels, Figure 13a. For unit cells with narrow channels, the permeability decreases about 5.4% when the diameter of the thread is 80% of the channel width while for unit cells with wide channels the decrease is about 28%. This difference is due to the fact that for narrow channels a large part of the cross-sectional area consists of the slit region, Figure 11a, and variations of the thread only takes place in the bulk region. A large part of the flow is therefore not influenced by the variations for unit cells with narrow channels. For wide channels where the bulk region dominates, Figure 11b, the variation in the thread dimensions therefore modifies the permeability more.

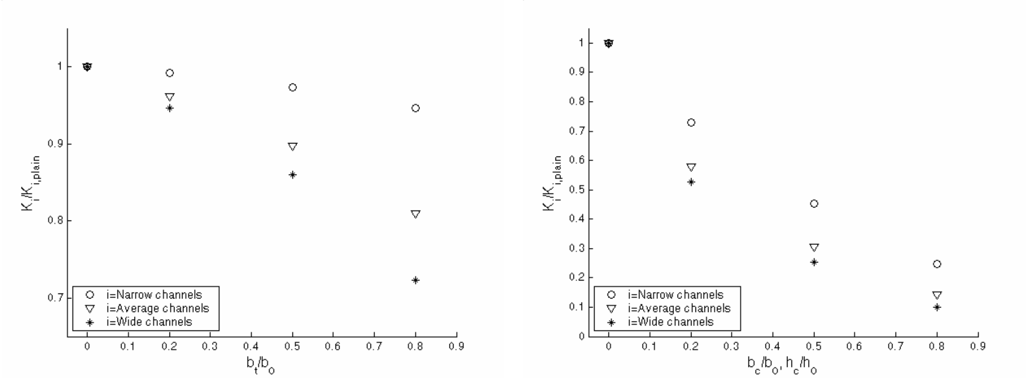


Figure 13. a) The influence of variations of the thread on the permeability for different channel shapes. b) The influence of variations of the crossings on the permeability for different channel shapes.

The influence from the crossings is similar to that of the thread, Figure 13b. *Crossing unit cells* with narrow channels are less affected by the crossings than those with wide channels due to the same argument as for the thread. For unit cells with narrow channels the permeability decreases about 75%, compared to the *plain unit cell*, when the width and height of the crossings are 80% of the channel width and height respectively. For unit cells with wider channels the permeability is decreased by 90% for the same case. As the results indicate the crossings have much more influence on the permeability than the thread. This is not surprising since the thread only appears at one location while the crossings are present throughout the geometry of a unit cell. The location of the thread is also at the place where the fluid domain is most voluminous: cf. Figure 4b.

The permeability for the variations of the bundle shapes, Table 1, shows that when the curvature of the bundles is varied, the permeability is only slightly affected. An increase of the curvature of the bundle, w/h, by 20% from the average gives a 5.4% higher permeability than for the average curvature. A 20% reduction of the bundle curvature, w/h, from the average gives 6.2% lower permeability. For the simulation of the unit cell where the centre line of the bundle curvature is shifted and the bundle shape therefore is warped by 20% of the parameter s_0, Figure 8a, the permeability is only increased by 0.98%. This indicates that possible asymmetries of the bundle curvatures are not that important to the permeability and unit cells can instead be modelled by symmetric curvatures. The influence of the variations of the bundle shapes is therefore small compared to other variations such as the width where an increase of the width by 25% gives 47.6% higher permeability. The curvature of the bundle is obviously more important for narrow channels where the slit region takes up a larger part of the fluid domain than for wide channels where the bulk region dominates.

Table 1. Permeability for the bundle shape variations.

Variation	Permeability, K [m^2]	K/K$_{average}$
Warp of curvature (s_w=0.2·s_0)	3.007E-10	0.97%
Curvature 1.2·w/h	3.138E-10	5.4%
Curvature 0.8·w/h	2.793E-10	-6.2%

CONCLUSIONS

A study of how different geometrical features of biaxial NCFs and their variations influence the permeability has been performed. Unit cells with different geometries have been used to describe different features that arise from the stitching process as well as variations of a number of geometrical parameters such as the width and height of the inter-bundle channels. CFD has been used to simulate the flow through the unit cells in order to determine the permeability.

The numerical errors are controlled in the same way as in [10] and together with a previous verification of the unit cells [10] the quality and trust of the simulations are ensured. The simulations in the work show that some features originating from the stitching process, i.e. the thread and the crossings, have significant influence on the permeability of a fabric. The significance of the two features is dependent of the width to height ratio of the channels in the unit cell. In the unit cells with narrow channels the thread can reduce the permeability by about 5.5% and the crossings by as much as 75% compared to unit cells without these features for the cases investigated. In the wider channels the effects of the thread and crossings are even larger. The reductions of the permeability are as much as 28 and 90% for the respective feature for the cases studied. Hence, generally the thread and the crossings do not influence the permeability as much in unit cells with narrow channels as they do in unit cells with wider channels but they are still of great importance for the permeability independently of the channel shapes.

It has also been shown that variations to the width of the channels parallel to the pressure gradient alone, give large influence on the permeability while the effect of variations of the perpendicular channel alone is very small. Regarding the channels parallel to the pressure gradient, a width two times the average width, result in an increase of the permeability of about 200% while an increase of the height two times the average height, gives an increase of about 35%. A feature of the unit cell that has a very small effect on the permeability is the bundle shape. It is only for unit cells with very narrow channels, where a large part of the flow goes in the slit region of the channels, that the bundle shape variations have a noticeable influence on the permeability.

To summarize, this study has pointed out what geometrical features and variations that have the greatest effect on the permeability. An interesting outcome of this is that a prediction model of the permeability of non-crimp fabrics has to include the effects from the stitching process, the thread and the crossings, as well as statistical variations of the channel dimensions in order to get realistic predictions.

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