Computer modelling for the prediction of the in-plane permeability of non-crimp stitch bonded fabrics

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Abstract

The purpose of this paper is to present and validate a model for the prediction of in-plane permeability in non-crimp stitch bonded fabrics. The model is based on the combined flow through the multi-layer assembly in each non-crimp fabric. The permeability of each layer of the assembly is predicted on the basis of a meso-/micro-flow computer model. In this the meso-flow between fibre tows is considered as Stokes’ flow and it generally progresses ahead of the micro-flow. Darcy’s law is employed to model micro-flow through each fibre tow, taking into account injection and capillary pressures in both types of flow. Transverse mass transfer is considered from the advancing meso-flow to the micro-flow through the permeable boundaries of fibre tows. The model is tested in biaxial non-crimp stitch bonded fabrics with either chain or tricot stitch. Excellent agreement exists between predictions and experiment when the meso-channels are straight of homogeneous cross-section. The permeability predictions are very sensitive to the dimensions of the meso-channel cross-section and require input data from a detailed microstructural analysis for meso-channels with varying cross-section.

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1. Introduction

Non-crimp stitch bonded fabrics are a later class of fabrics with some advantages over existing unidirectional prepregs and other fabrics, such as woven fabrics. The presence of stitch allows for multi-layer assemblies of unidirectional fibres, where each layer may be in a different specified orientation and where the stitched assembly is easy to handle. Hence, the purpose of the non-crimp stitch bonded fabrics has been to replace unidirectional prepregs aiming at cost reduction by shortening and automating the lay-up time. On the other hand, they have the benefit of reduced through-thickness crimp in comparison to woven fabrics leading to improvements in mechanical properties [1] although some in-plane crimp is present.

The stitch, and more specifically the type and tightness of stitch affect the drapeability/formability of the fabric. Two common types of stitch are the chain stitch and the tricot stitch, where the former is generally tight and restrictive in forming, whereas the latter is much more favoured for the manufacturing of formed products.

A considerable amount of past and present research has focused on the prediction of the permeability of textiles used in composite manufacturing. The first step has been to predict the permeability of homogeneous beds of unidirectional fibres, for which a plethora of empirical [2–4], analytical [5,6] or numerical models [6] have been tried in the past, demonstrating that detailed solutions are based on the geometrical arrangement of the fibres, i.e. whether they form square or hexagonal arrays for example [5,6], which applies only to an ideal model of fibre bed. Real aligned fibre beds for composite materials do not form any consistent geometrical arrangement and, hence, empirical models have been applied successfully (e.g. Amico and Lekakou [7] used such an empirical model for the prediction of the permeability of a fibre bundle).

Commercial textiles have the additional complication of incorporating at least two porosity scales. There have been several studies regarding the prediction of their permeability on the basis of phenomenological models [8], for example, dual Darcy’s flows for the dual-porosity regions [9–14],

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and a mixed flow model including a Stokes’ flow model in the meso-channels and Darcy’s flow within the porous fibre tows [15–19]. However, it has been realised that it may be very difficult to predict permeability values for textiles that agree well with experimental measurements for a variety of reasons. Experiments to measure in-plane permeability may involve well-documented process errors ranging from 8% [20] to 24% [21]. The permeability of textiles is greatly affected by their geometrical dimensions and architecture [22–24], which means the accurate measurement of the geometrical parameters associated with the textile microstructure and any spatial variations of such parameters in the same or different batches of textiles are expected to affect both predicted and measured permeability values. As a result, detailed CAD models of textile architectures have been generated by several groups [24,25]. However, only qualitative agreement between predictions and experiment has been reached to date for the permeability of textiles. A successful case involves the prediction of the in-plane permeability of textiles as a function of shear angle, for which good agreement has been achieved [26,27] between predictions and experimental data provided that the predictions are based on the measured permeability of the unsheared textile.

The present study focuses on the prediction of the in-plane permeability of the non-crimp fabrics as it has been thought that they have simpler design than other commercial textiles, where each layer may be possibly assumed as a unidirectional fibre layer. The stitching process creates meso-channels between the fibre tows yielding a dual-porosity fabric, overall. Amico and Lekakou [19] developed a permeability model, implemented in a computer code, which allows the prediction of in-plane permeability parallel to the fibres for assemblies of fibre tows characterised by meso-channels, between the fibre tows, and micro-channels between the fibres within each tow. This computer model has been successfully validated with respect to both, advancing meso-flow and micro-flow. This is particularly important since past studies, particularly focusing on non-crimp fabrics [28], have encountered specific problems in the experimental validation of model predictions attributed to insufficient characterisation and modelling of the structure of the porous medium [28].

The present study has extended this computer model [19], based on the combination of meso- and micro-flow, to multi-layer, non-crimp stitch bonded fabrics in order to predict their in-plane permeability. The predictions are compared with corresponding experimental in-plane permeability data for a 0°/90° biaxial fabric with tricot stitch and ±45° biaxial fabrics with either chain or tricot stitch.

2. Permeability model

Fig. 1 illustrates an example of the cross-section of a polymer composite with assemblies of a non-crimp ±45° fabric. Each layer in a non-crimp stitch bonded fabric was considered as an array of parallel fibre tows with meso-channels between the tows, where the meso-channels and the tows were assumed to be of rectangular and elliptical cross-section, respectively [19]. Axial Stokes’ flow was considered in the meso-channels and Darcy’s law was applied within the porous fibre tows, taking into account injection pressure and capillary pressure in both types of flow. Transverse flow transfer was modelled from the leading flow front to the lagging flow and a partial-slip boundary condition was applied at the permeable boundaries of meso-channels.

The Stokes’ flow model applied to the meso-flow is described by

\[ \nu^2 U + \frac{G}{\mu} = 0 \]  

(1)

Boundary conditions: \( U = 0 \) at \( z = \pm b \) and \( U = u_b \) at \( y = \pm b \)\( \alpha \) where \( U \) is the velocity in the \( x \) direction and \( G = -dP/dx \) is a constant pressure gradient in the direction of the positive \( x \)-axis, \( \mu \) is the viscosity of the filling Newtonian fluid, and \( \alpha \) and \( b \) are the meso-channel half-width and half-height, respectively. Eq. (1) was solved using an auxiliary function, separation of variables, Fourier analysis and the boundary conditions [19,29], yielding the following equation for the fluid velocity in the mesochannel

\[ U(y, z) = \frac{G}{2\mu} \left[ b^2 - z^2 \right] + \sum_{n=0}^{\infty} \left( \frac{2u_b \sin \beta_n b}{(2\pi)^2 b \beta_n^2} - \frac{4 \sin \beta_n b}{b \beta_n} \right) \times \frac{\cos h \beta_n y}{\cos h \beta_n \alpha} \cos \beta_n z \]  

(2)
where
\[ \beta_n = \frac{(2n+1)\pi}{2b} \]
and \( u_b \) is given by the partial slip boundary condition derived in [19], following theory and empirical relations presented by Beavers and Joseph [30] and Huang et al. [31].

The meso- and micro-flowrates, \( Q_{\text{me}} \) and \( Q_{\text{mi}} \), respectively, are given by
\[ Q_{\text{me}} = \int_{-a}^{a} \int_{-b}^{b} U(y, z) dz \ dy - Q_{\text{transfer}} \quad (4) \]
\[ Q_{\text{mi}} = \frac{\kappa_{\text{mi}} A_i (P_{c,\text{mia}} + P_{\text{inj}})}{\mu x_{\text{mia}}} + Q_{\text{transfer}} \quad (5) \]
where \( A_i \) is the cross-section of the elliptical tow, \( \kappa_{\text{mi}} \) is the axial micro-permeability in the fibre tow, \( P_{c,\text{mia}} \) is the axial capillary pressure in the fibre tow, \( P_{\text{inj}} \) is the injection pressure and \( x_{\text{mia}} \) is the progress of the micro-flow in the \( x \)-direction.

In this study, the meso-flow is assumed to lead the Darcy’s micro-flow and hence flow transfer is considered from the leading flow in the meso-channels to the micro-flow at the porous interface of each fibre tow, governed by Darcy’s law:
\[ Q_{\text{transfer}} = \frac{2\pi \sqrt{\frac{(R_o^2 + R_e^2)}{2} \kappa_{\text{mit}} (P_{c,\text{mit}} + P)(x_{\text{me}} - x_{\text{mia}})}}{0.5 \mu R_e} \quad (6) \]

where \( \pi((R_o^2 + R_e^2)/2)^{1/2} \) is half the perimeter of the elliptical tow, \( R_e \) is the radius of an equivalent cylindrical tow, \( \kappa_{\text{mit}} \) is the transverse micro-permeability of the fibre tow, \( P_{c,\text{mit}} \) is the transverse capillary pressure in the fibre tow and \( P \) is the local pressure (in the meso-channel if the meso-flow leads or in the micro-flow if the latter leads). Since the depth of tow impregnation varies from 0 at \( x_{\text{me}} \) (no tow impregnation) to \( R_e \) at \( x_{\text{mia}} \) (full tow impregnation), an approximate average depth of tow impregnation = 0.5 \( R_e \) has been assumed in Eq. (6).

The flow through the multi-layer assembly of the non-crimp fabric was modelled as the total of parallel flows through each layer [26], in the direction of the total flow (see Fig. 2), so that the total permeability, \( K_{\text{tot}} \), was given by the sum of permeabilities if all layers were assumed to be of the same thickness:
\[ K_{\text{tot}} = \frac{\sum K_{Li} H_{Li}}{\sum H_{Li}} \quad (7) \]
where \( K_{Li} \) and \( H_{Li} \) are the permeability and thickness of layer \( i \).

If the fibre direction in layer \( i \) was parallel to the total flow direction, the permeability \( K_{Li} \) was calculated on the basis of the computer model by Amico and Lekakou [19], represented by Eq. (1)–(6). If the fibre direction in layer \( i \) was at 90° with respect to the total flow direction, the permeability \( K_{Li} \) is given by the relation
\[ K_{Li,T} = \frac{1}{L_{\text{Tot}}} \left[ \frac{L_{\text{mes},i}}{K_{\text{mes},i}} + \frac{L_{\text{micro},i}}{K_{\text{mit}}} \right]^{-1} \quad (8) \]
where \( L_{\text{Tot}} \) is the total flow length, \( L_{\text{Tot}} = \sum L_{\text{mes},i} + \sum L_{\text{micro},i} \), \( K_{\text{mit}} \) is the transverse permeability of fibre tow and
\[ K_{\text{mes},i} = \frac{b^2}{3} \quad (9) \]
where \( 2b \) is the height of the rectangular meso-channel in layer \( i \).

3. Experiments

The experiments included in-plane permeability measurements in an RTM mould with central injection (radial outward flow) at a constant injection pressure of 0.2 MPa. The radial outward flow method was preferred for the measurement of the in-plane permeability as it is quick, leading to the determination of both principal in-plane permeabilities in a single flow experiment, and there are no risks of flow racing effects at the sides of the fabric assembly, as is sometimes the case in rectilinear flow with side injection. Six layers of non-crimp stitch bonded fabrics were used in each permeability experiment, and no central hole was cut for the injection so as not to disturb the continuity of the fabric microstructure. Silicone oil was used as the infiltrating liquid in each permeability experiment.

<table>
<thead>
<tr>
<th>Fabric code</th>
<th>Fibre type</th>
<th>Percentage of each ply</th>
<th>Stitch type</th>
</tr>
</thead>
<tbody>
<tr>
<td>EBX936</td>
<td>Glass</td>
<td>0° 90° +45° -45°</td>
<td>Chain</td>
</tr>
<tr>
<td>EBX936</td>
<td>Glass</td>
<td>0° 90° +45° -45°</td>
<td>Tricot</td>
</tr>
<tr>
<td>ELT850</td>
<td>Glass</td>
<td>0° 50° 50° 0°</td>
<td>Tricot</td>
</tr>
</tbody>
</table>
After the permeability experiment, a curing Araldite epoxy was injected to make an RTM laminate which was used to measure total thickness, $H$, fibre volume fraction, $V_f$, and geometrical parameters of the fibres, fibre tows and meso-channels in microstructural analyses of mosaics of micrographs using the UTHSCSA ImageTool. The measured $V_f$ for the various laminates was within the range of 54–56%.

Three types of non-crimp stitch bonded glass fibre fabrics were used as presented in Table 1. EBX936 and EBXhd936 were ±45° biaxial fabrics whereas ELT850 was a 0°/90° biaxial fabric. EBX936 had chain stitch whereas the other two fabrics had tricot stitch.

In-plane microstructural measurements for each fabric, on each side, included the meso-channel width, $2\alpha$, and were performed on dry, uncompressed samples of fabric of 50×50 mm. Past measurements on assemblies of a plain woven fabric [32] showed that the width of bundles does not change with compression up to a $V_f = 0.57$ and increases thereafter up to a maximum $V_f = 0.63$ (at a pressure of 1.77 MPa). Compression tests on assemblies of a non-crimp stitch bonded fabric [33] demonstrated that a $V_f = 0.55$ represents medium compression, whereas a maximum $V_f = 0.63$ is reached at a pressure of 1.77 MPa. Hence, in this study it is assumed that the width of meso-channels and bundles does not change up to the medium compression of $V_f = 0.55$, used in this study.

Figs. 3 and 4 demonstrate the in-plane microstructure of each side of ELT850 0°/90° non-crimp stitch bonded fabric. Continuous meso-channels were assumed in the microstructural analysis of each side of this fabric. In the digital image processing (using the UTHSCSA ImageTool), regular measurements of the meso-channel width, $2\alpha$, were made (about 10 such measurements along the meso-channel between consecutive stitches), and the total averaging yielded $2\alpha_{ave}$.

Figs. 5 and 6 demonstrate the in-plane microstructure of ±45° fabrics EBX936 and EBXhd936. It is clear that in both these fabrics the meso-channels are mainly discontinuous, consisting generally of ‘an eye’ around the needle point of the stitch. These ‘eyes’ have been approximated by elliptical meso-channel shapes, of major and minor axes $e_a$ and $e_b$, respectively, and have been considered to be at a distance $e_d$ on the same line (see Fig. 7). Hence, $e_a$, $e_b$ and $e_d$ have been measured for each ‘eye’ $i$, and for each eye an average meso-channel width is calculated as $e_{b,ave} = (\pi e_b)/4$ which is supposed to be homogeneous for a length $e_a$. The total average meso-channel width is then calculated as

$$2\alpha_{ave} = \frac{\sum_i e_{b,ave}, e_{a,i}}{\sum_i e_{a,i} + \sum_i e_{d,i}}$$

(10)
Table 2
Results of the predicted and measured permeabilities of the tested non-crimp stitch bonded fabrics

<table>
<thead>
<tr>
<th>Fabric code</th>
<th>Predicted permeability (m$^2$)</th>
<th>Measured permeability (m$^2$)</th>
<th>Predicted permeability (m$^2$)</th>
<th>Measured permeability (m$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ELT850</td>
<td>K$_{0}$ $= 1.48 \times 10^{-11}$</td>
<td>K$_{0}$ $= 1.48 \times 10^{-11}$</td>
<td>K$_{45}$ $= 2.41 \times 10^{-11}$</td>
<td>K$_{45}$ $= 6.54 \times 10^{-12}$</td>
</tr>
<tr>
<td>EBX936, $\alpha_{\text{max}}$</td>
<td>K$_{-45}$ $= 1.14 \times 10^{-11}$</td>
<td>K$_{-45}$ $= 5.42 \times 10^{-12}$</td>
<td>K$_{45}$ $= 6.54 \times 10^{-12}$</td>
<td>K$_{45}$ $= 6.54 \times 10^{-12}$</td>
</tr>
<tr>
<td>EBX936, $\alpha_{\text{ave}}$</td>
<td>K$_{-45}$ $= 5.38 \times 10^{-12}$</td>
<td>K$_{-45}$ $= 5.42 \times 10^{-12}$</td>
<td>K$_{45}$ $= 2.14 \times 10^{-12}$</td>
<td>K$_{45}$ $= 3.00 \times 10^{-12}$</td>
</tr>
<tr>
<td>EBXhd936 $\alpha_{\text{max}}$</td>
<td>K$_{-45}$ $= 6.62 \times 10^{-12}$</td>
<td>K$_{-45}$ $= 5.52 \times 10^{-12}$</td>
<td>K$_{45}$ $= 3.02 \times 10^{-12}$</td>
<td>K$_{45}$ $= 3.00 \times 10^{-12}$</td>
</tr>
<tr>
<td>EBXhd936 $\alpha_{\text{ave}}$</td>
<td>K$_{-45}$ $= 5.51 \times 10^{-12}$</td>
<td>K$_{-45}$ $= 5.52 \times 10^{-12}$</td>
<td>K$_{45}$ $= 3.02 \times 10^{-12}$</td>
<td>K$_{45}$ $= 3.00 \times 10^{-12}$</td>
</tr>
</tbody>
</table>

The height of meso-channels and fibre tows have been measured in cross-sections of the laminates obtained at each permeability measurement. Hence, these measurements include the compression effect ($V_f$ effect) in the permeability experiments for all fabrics.

4. Results and discussion

Table 2 presents the results of the predicted and measured permeabilities for the three fabrics, where for easy comparison all results have been extrapolated to the permeability corresponding to $V_f = 0.55$, using the Carman–Kozeny relationship. Parametric studies showed that the predicted permeabilities were very sensitive to the value of meso-channel width. Since each biaxial fabric was orthogonal, each fabric demonstrated two principal in-plane permeabilities in the two axial fabric directions. Each of the two principal in-plane permeabilities depended primarily on the geometrical parameters of the fabric layer with meso-channels and tows parallel to the direction of that principal permeability.

Starting with the $0^\circ/90^\circ$ biaxial fabric ELT850, one of the two layer directions ($90^\circ$) proved most appropriate for validating the permeability model, since it had regular and straight meso-channels (see Fig. 3). Using an average measured meso-channel width, $2\alpha = 3.8 \times 10^{-4}$ m, the predicted permeability, $K_{0}$, agreed exactly with the measured permeability value. No attempt was made to predict $K_{0}$ for ELT850, due to the most irregular structure and statistical variation in the geometrical parameters of the $0^\circ$ layer (see Fig. 4).

The meso-channels of EBX936 and EBXhd936 were not all straight, as shown in Figs. 5 and 6, although the in-plane permeability model used continuous meso-channels of constant width and height (see Section 2). When representative maximum values of the measured minor axes of the meso-channel ‘eyes’ were used in the permeability model for EBX936, $2\alpha_{-45,\text{max}} = 2.37 \times 10^{-4}$ m and $2\alpha_{+45,\text{max}} = 3.34 \times 10^{-4}$ m, the predicted permeabilities varied significantly from the measured values, as presented in Table 2. By using the average measured values given by Eq. (10), $2\alpha_{-45,\text{ave}} = 1.68 \times 10^{-4}$ m and $2\alpha_{+45,\text{ave}} = 1.88 \times 10^{-4}$ m, excellent agreement was reached between predictions and experiment. The same occurred with EBXhd936, where

$2\alpha_{-45,\text{max}} = 2.37 \times 10^{-4}$ m and $2\alpha_{+45,\text{max}} = 1.53 \times 10^{-4}$ m and $2\alpha_{-45,\text{ave}} = 2.15 \times 10^{-4}$ m and $2\alpha_{+45,\text{ave}} = 1.85 \times 10^{-4}$ m.

Hence, it was concluded that the in-plane permeabilities of each fabric were very sensitive to the magnitude of the meso-channel cross-section, especially the meso-channel width which would vary significantly along the length of the meso-channel, due to the periodic presence of the stitch. Fig. 8 shows an example of a parametric study regarding the variation of the predicted in-plane principal permeabilities as a function of the input value for the meso-channel width of the fabric EBX936.
5. Conclusions

A model has been presented for the prediction of the in-plane permeability of biaxial non-crimp stitch bonded fabrics based on the assembly of flow units in parallel (for different layers) or in series, whereas the prediction of the permeability of each layer along the fibre direction is based on a meso-/micro-flow model [19]. Successful permeability predictions in comparison with experimental data were achieved for straight meso-channels as in the 90° direction of fabric ELT850.

However, several stitched fabrics display a large extent of in-plane waviness and the width of their meso-channel has a large effect on their permeability. As a result, detailed microstructural analysis is required to determine average meso-channel dimensions, which when inputted in the computer model yielded in-plane permeability predictions in good agreement with experimental data for a Vf around 55%. This represents a medium degree of compression. Much lower Vf values due to low compression might result in interlayer meso-channels, which have not been taken into account in the permeability model in this study. Much higher Vf values, around 60%, might involve change of in-plane geometric parameters in the fabric architecture (meso-channel width, for example) as a function of compression, and hence they would require measurement of in-plane geometric parameters in compressed fabric samples.

References


