Computer Modeling for the Prediction of the In-Plane Permeability of Non-Crimp Stitch Bonded Fabrics

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SUMMARY: 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 fiber tows is considered as Stokes's flow and it generally progresses ahead the micro-flow. Darcy's law is employed to model micro-flow through each fiber 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 fiber 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.

KEYWORDS: Permeability, modeling, non-crimp, stitch-bonded, fabrics.

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 fibers, 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 costs reductions 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.

Regarding the prediction of the permeability of fabrics, the non-crimp fabrics have the advantage to have a simple design, where each layer may be possibly assumed as a unidirectional fiber layer.

Amico and Lekakou [2] developed a permeability model, implemented in a computer code, which allows the prediction of in-plane permeability parallel to the fibers for assemblies of fiber tows characterized by meso-channels, between the fiber tows, and micro-channels between the fibers within each tow. This computer model has been successfully validated with respect to both, advancing meso-flow and micro-flow. The computer model for the prediction of the in-plane permeability of non-crimp stitch bonded fabrics presented in this study is based on this meso-/micro-flow model.

PERMEABILITY MODEL

Each layer in the non-crimp stitch bonded fabric was considered as an array of parallel fiber 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 [2]. Axial Stokes's flow was considered in the meso-channels and Darcy's law was applied within the porous fiber tows, taking into account injection pressure and capillary pressure in both types of flow. Transverse flow transfer was modeled 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 flow through the multi-layer assembly was modeled as the total of parallel flows through each layer [3], in the direction of the total flow, so that the total permeability, K_{tot}, was given by the average of permeabilities if all layers were assumed to be of the same thickness:

$$K_{tot} = \frac{\Sigma K_{Li} H_{Li}}{\Sigma H_{Li}} \tag{1}$$

where K_{Li} and H_{Li} are the permeability and thickness of layer i.

If the fiber 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 [2]. If the fiber direction in layer i was at 90° with respect to the total flow direction, the permeability $K_{Li,T}$ is given by the relation

$$K_{Li,T} = \left[\frac{1}{L_{Tot}} \left(\Sigma \frac{L_{mes,i}}{K_{mes,i}} + \Sigma \frac{L_{micro,i}}{K_{micro,T}} \right) \right]^{-1} \tag{2}$$

where L_{Tot} is the total flow length, $L_{Tot} = \Sigma L_{mes,i} + \Sigma L_{micro,i}$, $K_{micro,T}$ is the transverse permeability of fiber tow and

$$K_{mes,i} = \frac{H^2_{mes,i}}{12} \tag{3}$$

where $H_{mes,I}$ is the height of the rectangular meso-channel in layer i.

EXPERIMENTS

The experiments included in-plane permeability measurements in an RTM mold with central injection (radial outward flow). Six layers of non-crimp stitch bonded fabrics were used in each permeability experiment and no central hole was cut for the injection. Silicone oil was used as the infiltrating liquid in each permeability experiment. After the permeability experiment, a curing Araldite epoxy was injected to make an RTM laminate which was used to measure total thickness, H, and fiber volume fraction, V_f, and geometrical parameters of the fibers, fiber tows and meso-channels in microstructural analyses of mosaics of micrographs.

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

Table 1: Non-crimp stitch bonded fabrics used in this study

Fabric Code	**Fibre Type**	**Percentage of Each Ply**				**Stitch Type**
		0°	90°	+45°	-45°	
EBX936	Glass	---	---	50_1	50_2	Chain
EBXhd936	Glass	---	---	50_1	50_2	Tricot
ELT850	Glass	50_2	50_1	---	---	Tricot

RESULTS AND DISCUSSION

Table 2 presents the results of the predicted and measured permeabilities, where 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. Starting with the $0^o/90^o$ biaxial fabric ELT850, one of the two layer directions (90^o) proved most appropriate for validating the permeability model, since it had regular and straight meso-channels (see Fig.1). Using an average meso-channel width, $w = 3.8 \text{x} 10^{-4}$ m, the predicted permeability agreed exactly with the measured permeability value.

However, the meso-channels of EBX936 and EBXhd936 were not at all straight, as shown in Fig.2 and Fig.3. When the maximum values of the measured meso-channel widths were used for EBX936, $w_{-45,max}=2.37 \text{x} 10^{-4}$ m and $w_{+45,max}=3.34 \text{x} 10^{-4}$ m, the predicted permeabilities varied significantly from the measured values, as presented in Table 2. By using the average measured values, $w_{-45,ave}=1.52 \text{x} 10^{-4}$ m and $w_{+45,ave}=1.68 \text{x} 10^{-4}$ m, excellent agreement was reached between predictions and experiment. The same occurred with EBXhd936, where

$w_{-45,max}=2.37 \text{x} 10^{-4}$ m and $w_{+45,max}=1.53 \text{x} 10^{-4}$ m and

$w_{-45,ave}=2.15 \text{x} 10^{-4}$ m and $w_{+45,max}=1.85 \text{x} 10^{-4}$ m.

Table 2: Results of the predicted and measured permeabilities of the tested non-crimp stitch bonded fabrics.

Fabric code	Predicted Permeability (m^2)	Measured Permeability (m^2)	Predicted Permeability (m^2)	Measured Permeability (m^2)
ELT850	$K_{90} = 1.48\text{x}10^{-11}$	$K_{90} = 1.48\text{x}10^{-11}$		
EBX936, $w_{meso,max}$	$K_{-45} = 1.14x10^{-11}$	$K_{-45} = 5.42\text{x}10^{-12}$	$K_{+45} = 2.41x10^{-11}$	$K_{+45} = 6.54\text{x}10^{-12}$
EBX936, $w_{meso,ave}$	$K_{-45} = 5.38\text{x}10^{-12}$	$K_{-45} = 5.42\text{x}10^{-12}$	$K_{+45} = 6.54\text{x}10^{-12}$	$K_{+45} = 6.54\text{x}10^{-12}$
EBXhd936 $W_{meso,max}$	$K_{-45} = 6.62x10^{-12}$	$K_{-45} = 5.52\text{x}10^{-12}$	$K_{+45} = 6.54x10^{-12}$	$K_{+45} = 3.02\text{x}10^{-12}$
EBXhd936 $W_{meso,ave}$	$K_{-45} = 5.51\text{x}10^{-12}$	$K_{-45} = 5.52\text{x}10^{-12}$	$K_{+45} = 3.02\text{x}10^{-12}$	$K_{+45} = 3.00\text{x}10^{-12}$

Fig.1. The 90° layer of ELT850.

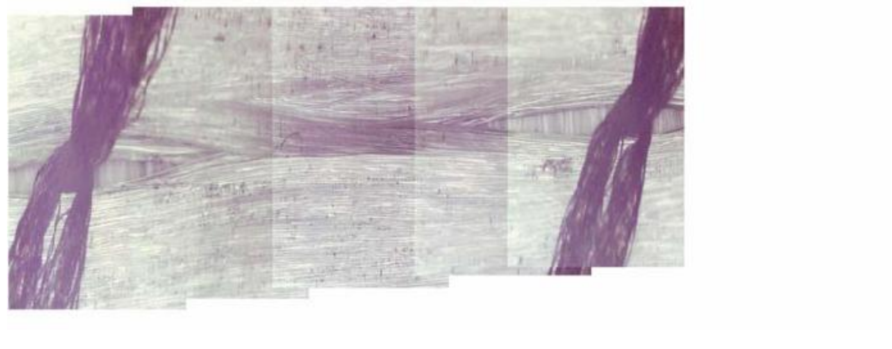

Fig.2. Fabric structure of EBX936.

Fig.3. Fabric structure of EBXhd936.

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 fiber direction is based on a meso-/micro-flow model [2]. Successful permeability predictions in comparison with experimental data were achieved for straight meso-channels as in 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 excellent agreement with experimental data.

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