The influence of fabrics' design parameters on the 3D permeability tensor of quasi-unidirectional non-crimp fabrics

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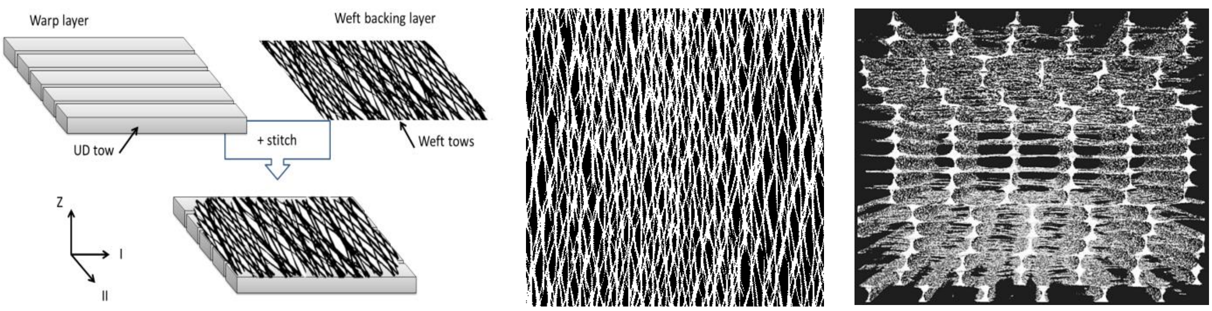
For long and thick part composite parts like spars, the knowledge of resin flow properties of the fibrous reinforcement is of prime interest to adjust resin infusion strategies. From the fabrics manufacturers' standpoint, they can modify various design parameters that will influence the final geometry and morphology of the tows and of the overall fabrics' properties. The study will focus on three of them: the stitch spacing (A), the stitch pattern (B) and the size of weft tows (C). The materials are quasi-UD NCF plies of total glass areal weight (A_w) of 1395 g/m² constituted of one layer of UD 0° glass tows and one weft backing glass layer at ± 80° orientation (Fig. 1a). All quasi-UD NCF fabrics (Owens Corning) are based on a reference material (REF). The four materials will induce very different microstructures over the range of fiber volume fraction of interest (*Vf*) along with their influence on the 3D permeability tensor.

Image analysis at the mesoscopic (tow) and the macroscopic (several plies) scales were used to characterize the morphology of the porous network in which the resin flows during composite manufacturing. Composites images were obtained using an X-ray tomographic device (XTC-400) with 17 μm^3 voxels on 20 mm × 20 mm × 16 mm composites samples. This resolution allows separating the main resin channels (between tows) from the tows. Thresholding on the volume is performed to only reveal the resin rich areas and meso channels (Fig. 1c). In parallel, the grayscale images of the weft backing layer have been acquired using a commercial 2D scanner. Since the NCF contain a visible stitch, a Matlab image processing program has been built to reconstruct the weft glass layer while removing the stitch yarn (Fig. 1b).



(a) NCF Construction (b) 2D view (I,II) plane (c) 3D view of meso channels

Fig. 1. Quasi-UD NCF fabric

In the present work, the aim is to extract the in-plane and out-of-plane (hydraulic) permeability components for a wide range of fiber volume fractions. Techniques based on unidirectional compression of saturated preforms are interesting because of their continuous feature but can only be used for in-plane isotropic materials. Therefore, an improved version of such techniques is presented here so as to continuously determine both in-plane permeability coefficients.

For compaction tests carried out on impregnated fabrics, the resulting total stress σ_{zz} under Terzaghi hypothesis is written as:

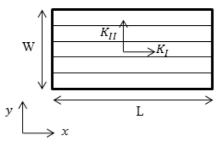
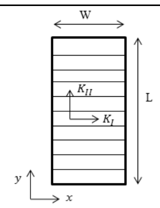
$$\sigma_{zz} = \sigma_{zz}^0 + p \tag{1}$$

where σ_{zz}^0 is the stress of the lubricated preform and p the hydrostatic pressure generated by the fluid flow. The consolidation equation (conservation of mass and Darcy's law) for top and bottom non-perforated compression platens is:

$$m\frac{\partial^2\hat{p}}{\partial\hat{x}^2}+\frac{\partial^2\hat{p}}{\partial\hat{y}^2}=-1 \qquad \textit{with} \qquad \hat{p}=\frac{p}{p_c}\ ;\ m=\frac{L_y^2K_x}{L_x^2K_y}\ \textit{and}\ \ p_c=-\frac{\mu\dot{\mathrm{h}}L_x^2}{\mathrm{h}K_x} \tag{2}$$

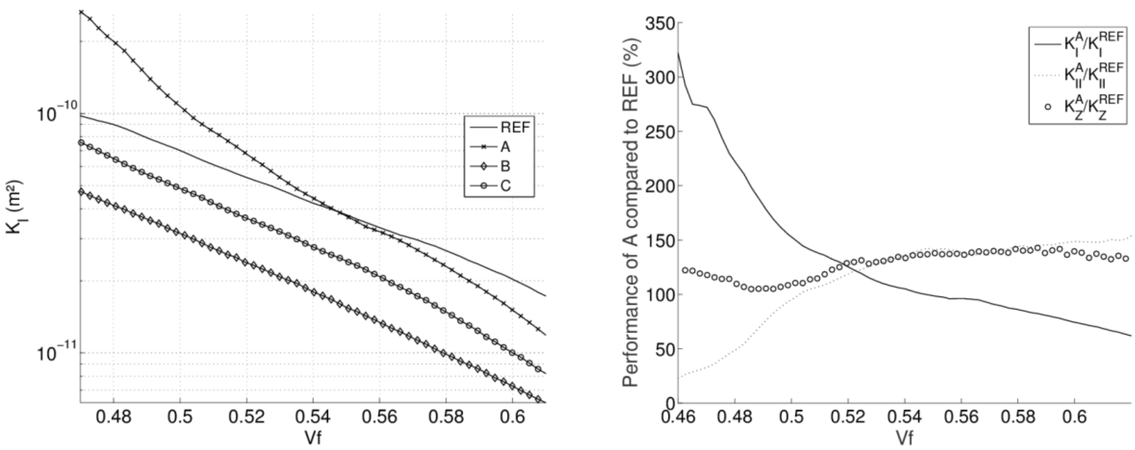
Equation 2 involves two unknown principal in-plane permeabilities. Therefore, two independent experiments should be carried. Two compression tests are performed using 2 distinct platen aspect ratios L_x/L_y of 2 and 0.5 (Tab. 1).

Tab. 1: Positioning of fabrics and parameters for the in-plane permeability tests.

Test α		***Test β***	
$\boldsymbol{m_a=\frac{L^2K_I}{W^2K_{II}}}\quad \boldsymbol{p_{ca}=-\frac{\mu\dot{h}L^2}{hK_I}}$		$\boldsymbol{m_b=\frac{W^2K_I}{L^2K_{II}}}\quad \boldsymbol{p_{cb}=-\frac{\mu\dot{h}W^2}{hK_I}}$	

The two experimental compression tests' forces are used in an inverse method algorithm that outputs both in-plane permeabilities once the numerically simulated forces (solving Eq. 1) match the experimental ones.

Trends of permeability as a function of the fiber volume fraction are depicted in Fig. 2. Since the measurement technique is continuous over Vf, permeability coefficients are presented for 47%<Vf<61%. Regarding the reduction of the stitch length (*A*), an increase in the K_I permeability for fiber volume fraction between 50% and 55% is noted (Fig. 2a). This can be correlated with the greater macro-pore volume available for the resin to flow (Fig. 1c). Using a more loose stitch (B) or increasing the weft tex reduces the K_I permeability. Figure 2b shows that for Vf>50% the A fabrics performs better in both II and Z permeabilities.



(a) In-plane permeability with various fabrics' design

(b) Performance of fabric A compared to fabric REF (baseline 100)

Fig. 2. Examples of results

In this study an innovative method has been proposed and used to continuously extract the in-plane permeability coefficients of various fabrics. The results allow to quantify very finely the performance (in gain or loss) of the fabrics with new fabric design parameter over the full range of Vf of interest.