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Compaction, Nesting and Image based Permeability Analysis of Multi-layer Dry Preforms by Computed Tomography (CT)

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Abstract

Textile preforms have a multi-scale hierarchy of fibres, tows and plies; geometry at each scale influences the manufacturing processes, the permeability of the textile to resin as well as the mechanical properties of the finished laminate. High-fidelity structural models for textile composites require accurate non-idealised tow geometry as well as changes to this geometry during processing. This paper presents a CT-based experimental technique for capturing the realistic meso-scale geometry of individual tows in a 2D fabric layer and the nesting or ply shifting between fabric layers in a multi-layer stack during a simulated consolidation process. In-situ compression loading mechanism has been implemented in order to capture multi-layer preform geometry under loading conditions to simulate the vacuum infusion process (up to 1 bar pressure). Inter-tow and inter-ply void geometry has been captured in 3D due to high x-ray contrast between the fibres and the air. Degree of ply nesting and the connectivity between adjacent voids have been assessed at each stage of the compaction process. An image-based flow analysis has been performed on the extracted 3D realistic void geometry and effect of layer nesting on resin flow has been evaluated. Image-based prediction of permeability values have been in good agreement with experimental values found in the literature when normalised as a function of fibre volume fractions.

Keywords: Tow, CT analysis, Nesting, Permeability

1. Introduction

Liquid infusion technologies in conjunction with textile preforming have the potential to meet the volume and cost targets of the high-volume automotive composites market as well as the rapidly growing civil airframes market. In these processes, several fabric plies are usually draped and preformed (on a preforming tool) before transferring to an infusion tool. During the infusion process, fabric plies are subjected to transverse compression; the level of compression depends on the manufacturing process. The compaction of dry fabrics changes the tow geometry and inter-tow voids. The compaction behaviour of the dry fibre assemblies also has a significant influence on permeability and the fibre volume fraction [1]. As a result
it is important to characterise the compaction behaviour during the composite manufacturing process [2].

Since several layers of fabric are used in most applications, shifting and nesting of adjacent layers affect the resin flow, laminate thickness and hence the laminate mechanical properties [3]. Nesting of fabrics has been studied by a number of researchers [3-5], including its relation to the permeability of the woven fabrics [4]. It was shown by Hoes et al. [4] that nesting is a major source of variation in experimentally determined permeability values. Unlike idealised geometries, textile structures have large variability at meso-scale.

Desplentere et al.[6] employed computed tomography to capture variability in textile structures and reported 16% scatter in geometrical parameters. These geometrical variations along with shifting and nesting of layers effect the inter-tow voids and consequently resin flow. Permeability of textile structures has been investigated by several researchers using experimental methods [2, 4, 7-17], numerical approaches [18-24], geometrical models [25-31] and post-processing methods based on textile models [32, 33]. Computed tomography (CT) has also been employed to calculate resin flow in textile composite [28, 34-36].

In previous work, mainly idealised geometries have been employed to calculate the permeability of textile structures e.g. [23, 32]. As discussed earlier, textiles structures have large scatter at tow level and also shifting and nesting of layers influence the inter-two voids/resin channels so idealised geometries may not capture the variations due to these factors and hence are inadequate for textiles [37]. Attempts have been made to employ the realistic textile geometry obtained by computed tomography, e.g. [15, 38, 39]. These studies have mainly focused on 3D fabrics. Some researchers have investigated permeability of 2D fabrics by employing geometries obtained from cured laminates [28, 34, 35]. There is limitation with cured laminates in that they do not precisely represent the dry fabrics [40] and same specimens cannot be used again and again under different loadings. Using different
laminate samples at different compaction level will lead to sample to sample variation due to inherent variability of textiles [6]. Also these studies have not investigated layer nesting which is a key feature of 2D fabric stacks and can significantly influence the resin flow [4]. Therefore, in the present paper we focus on capturing realistic geometry of 2D dry preform stacks with the aid of computed tomography (CT) under in-situ compaction. We study the layer nesting by computing single layer thickness from unit-cell thickness measurements from CT images. We also quantify the inter-tow voids and analyse the effect of nesting on these voids. We subsequently perform flow simulations on dry fabric geometry.

Furthermore, we study the effect of layer nesting on resin flow at unit cell levels. This technique enables us to study the tow geometry, nesting of layers, inter-tow voids and subsequently resin flow on the same dry fabric specimen under different pressures. Using the same dry fabric specimen for all volume fractions avoids unnecessary sample to sample variations. High fidelity images of individual tows have been obtained due to the fact that the X-ray contrast between fibres and air is significantly better than the contrast between fibres and resin due to higher density difference between glass fibres (2.6 g/cm$^3$) and air (1.22x10^{-3} g/cm$^3$) in comparison to glass fibres(2.6 g/cm$^3$) and resin (1.14 g/cm$^3$).

**Nomenclature**

- NF: nesting factor
- a: tow width/major diameter
- b: tow thickness /minor diameter
- H: ply thickness
- h/2: half of the crimp amplitude
- L: crimped yarn length
- P: original yarn length without crimp
- C%: crimp percentage
- Δ: Divergence operator
2. Material and mechanical testing

2.1 Material

E-glass plain woven fabric with a warp density of 4.8 ends/cm and weft density 4.4 picks/cm has been used in this study. A 600 Tex glass tow (fibre density 2.60 g/cm³) has been used in the warp and weft directions.

2.2 Mechanical testing

Compression tests on single and multilayer fabrics were conducted on an Instron 5569 universal testing machine equipped with a 5kN load-cell. The fabric samples (5cm x 5cm) were subjected to compression loading between flat plattens at the rate of 1mm/min. As the fabric thickness is small in comparison to the machine stroke, machine compliance as a function of the applied load was measured and accounted for in the fabric strain calculations in order to minimise errors due to machine compliance (machine compliance is small but significant in comparison to fabric deformation). Mechanical testing was conducted by step compaction method. In step compaction method, the machine cross-head was moved to a specific pressure and stopped at that pressure for five minutes before moving to new pressure.
level. This five minutes time was given to allow fibre assemblies to relax. In this way, the initial and final thicknesses of fabric samples were recorded.

2.3 Tomography and in-situ compression set up

In the present work, an in-situ loading rig has been developed (Fig. 1) in order to support the dry fabric as well as to apply known compressive loads (strains). The rig comprises of two 60 mm x 35 mm x 12 mm clear polycarbonate plates. Two thickness (or slip) gauges were placed between the two plates on either side of the sample in order to control the degree of compression. CT scans were conducted at different compression pressures (~100 kPa).

![Compression Rig](image)

Fig.1. Compression Rig (a) Compression rig fixed on the tomography stage, (b) close-up of the rig.

The fabric specimens were scanned on a Nikon Metrology 225/320 kV Custom Bay system at the Henry Moseley X-ray Imaging Facility, University of Manchester. Scanning was performed using a silver target, a voltage of 80 kV and a current of 110 μA. The number of projections was set to 3142 acquired over 360°. The 3D data set was reconstructed at full resolution with a voxel size of 18.6 μm. Image analysis was performed using Avizo® Fire.
version 7.0.1 software. The dataset were filtered using a non-local mean filter [41] in order to remove noise from the data. Fig. 2 shows a 3D reconstruction of the six-layer stack studied in the present work.

![3D reconstruction of the six layer dry preform.](image)

The segmentation, i.e. separation of the pore space and fibres, was achieved using a global thresholding approach based on seed region growing algorithms [42]. Seed region growing is a function that works on seeds that are selected and grow the region from the seed by adding neighbouring seeds that are similar to the already selected seeds [42, 43]. Fig. 3 depicts the 3D segmented tows isolated from a tomogram.

![Tows isolated from the tomograph showing both warp (green) and weft (gold) tows](image)
3. Results and discussion

3.1 Macroscopic deformation

Fig. 4 shows the method adopted for step compaction and pressure-thickness curves for single-layer and multi-layer (six) fabric specimens conducted in two different modes a) compressed at a constant rate of 1 mm/min, b) test stopped at each pressure (4kPa, 45kPa, 100kPa and up to 600kPa) for 5 minutes to record stabilised fabric thickness. The duration of 5 minutes has been recommended by previous research [44, 45] but authors observed that the thickness stabilises after one minute. The average thickness per layer of the six-layer stack is lower than the single layer at the same pressures due to nesting. It is observed that there is a quantifiable reduction in thickness when a sample is held under constant pressure. This behaviour is due to the viscoelastic nature of the fibre tows [46, 47]. Data points on the relaxed pressure-thickness curves (Fig. 4) were used in setting the sample thickness in micro-CT experiments.

![Fig. 4. a) Step compaction method and b,c) variation in per layer thickness as a function of pressure for 1 and 6 layer systems respectively](image)

3.2 Meso-structural analysis

Fig. 5 shows important meso-scale geometrical parameters calculated from CT images. Percentage crimp (C%) was calculated by using the equation 1.
Fig. 5. Tow geometry parameters calculated during meso-scale analysis.

Fig. 6 shows typical cross-sectional views obtained from the 3D CT images at different pressure levels. Meso-scale geometrical parameters have been computed at several locations in the 3D volume and presented as mean values with error bars (Fig. 7). There are significant inter-tow voids at the nominal pressure (4kPa) with adjacent plies in contact at few locations and exhibiting random phase shift between the layers. At 45kPa, nesting between layers can be clearly observed with the extent of nesting varied at different slices within the stack. When the pressure level was increased to 45kPa, there was a decrease in the warp crimp % and the crimp amplitude whereas there was a slight increase in weft crimp % and crimp amplitude. This type of crimp interchange between the layers was observed by Lomov et al.[48]. There was no significant change in the warp and weft tow cross-sectional geometry at this stage. At 100 kPa, tow thickness and tow cross-sectional area decreased; warp crimp amplitude decreased further with a slight increase in weft crimp. Warp and weft tow widths remained unchanged during the compression loading while thickness reduction was the primary reason for increased packing factor.
Fig. 6. Tomographic sections through the stack of six layers at different pressures (a) 4 kPa, (b) 45 kPa, and (c) 100 kPa.
**Fig. 7.** Tow geometry parameters quantified from the X-ray tomographs a) tow width, b) tow thickness, c) tow area, d) tow crimp %, e) crimp amplitude.
Extracted 3D tows from the tomograph are presented in Figure 8 which shows higher crimp in warp tows compared to weft tows that can be attributed to different warp/weft tensions during fabric manufacturing.

Fig. 8. 3D reconstructed warp and weft tows.

3.3 Nesting factor analysis

The nesting between layers affect laminate thickness (hence fibre volume fraction) as well as resin flow during processing [3]. Nesting happens when individual layers in a multilayer stack shift relative to each other and embed into adjacent layers as shown in Figure 9.

Fig. 9. Multilayer fabric plies without shifting and nesting (left) and with shifting and nesting (right) developed using TexGen

The nesting is defined in terms of nesting factor (NF) [49], which can be calculated by:

\[ NF = \frac{T}{\sum_{i=1}^{n} T_i} \]  

The nesting factor (NF) will be 1 if the plies sit exactly on top of each other without nesting (Fig. 10a) and thickness of the stack in this case will be the sum of the thickness of the individual plies. The nesting factor (NF) will be less than 1 if the plies shift and nest with each other (Fig.10b). Smaller the nesting factor better the nesting efficiency is.
The nesting factors are traditionally computed from thickness results of single and multi-layer preforms measured separately at different pressure levels (using equation 1). In this work, an additional method of calculating the nesting factors from the tomographic images of multi-layer preforms has been employed. In this method (labelled in Fig. 12 as tomographic analysis) single layer thickness, in equation 1, has been computed from the unit-cell measurements from a multi-layer image (instead of conducting a single layer compression test).

Fig. 11 presents per layer thickness of single layer and multi-layer preforms under different pressures; single layer thickness was also computed from the tomographic images. Nesting factors (ratio of thickness of multi-layer stack and sum of thickness of single layers (Eq.1)) at three different pressures have been presented in fig.12. It can be seen from the Fig. 11 that the thickness of single layer extracted from CT images of a six-layer stack is higher than the single layer thickness obtained from pressure-thickness curve. Compression of a single layer between rigid platens results in higher contact pressure at the peaks (in a unit-cell) in comparison to a more uniformly distributed pressure on layers inside a multilayer stack. So due to different boundary conditions, we get different layer thickness from pressure-thickness curve and CT images.
Fig. 11. Average layer thickness from pressure-thickness curve and CT images

Fig. 12 presents nesting factors (ratio of thickness of multi-layer stack and sum of thickness of single layers (Eq.1)) calculated at different pressures. It can be seen that nesting factors decreased for incremental pressures showing that increase in pressure improve the nesting efficiency of multilayer stacks. It can also be seen from Fig. 12 that nesting factors calculated from tomographic images are smaller (hence more efficient nesting) than the nesting factors calculated from pressure thickness curves obtained from compression tests. This is due to fact that thickness of single layer extracted from the CT image a multilayer stack is higher than that obtained through compression testing between two rigid platens. This is due to fact that rigid platens apply higher contact pressure at the peaks (in a unit-cell) in comparison to a
more uniformly distributed pressure on individual layers inside a multilayer stack. We believe that nesting factor computed from individual layer thickness obtained from tomographic images are more representative of the realistic boundary conditions.

![Nesting factors at different compaction pressures](image)

**Fig.12.** Nesting factors at different compaction pressures

### 3.4 Quantification of inter-tow voids

Due to the meso-scale architecture and imperfect nesting between the layers, permeability of multi-layer preforms is mainly dictated by inter-tow voids and relatively small contribution from intra-tow voids [27]. In this paper, permeability analysis has been conducted on inter-tow and inter-ply voids.
Fig. 13. Inter-tow voids at (a) 4 kPa, (b) 45 kPa, and (c) 100 kPa under step compaction.

Fig. 13 shows the presence of flow channels/inter-tow voids (weft cross-section) in between the tows at pressure levels of 4 kPa (Fig. 13 a), 45 kPa (Fig. 13 b) and 100 kPa (Fig. 13 c). From these images it can be seen that the voids get constricted especially in the regions of nesting (Fig. 14). Fig.14 shows that the regions of least nesting have the highest void area (0.23 mm²) and the regions of highest nesting have smallest void (0.1mm² or less). It can be seen from the cross-sectional images (in Fig.13) that the inter-tow voids become disconnected in the 2D plane and hence the resin has to follow tortuous paths through adjacent channels, where possible. However, it is not possible to judge from 2D images if the adjacent inter-tow voids are connected or not.
Fig. 14 Tomographic weft cross section showing smallest inter-tow voids with highest layer nesting and vice versa at 45 kPa.

Fig. 15. 3D representation of inter-tow voids at (a) 4 kPa, (b) 45 kPa, and (c) 100 kPa under step compaction.

Fig. 15 shows 3D inter-tow void geometry segmented from the tomographic images of fabric samples. It can be seen that inter-tow voids/flow channels become narrower with increasing transverse pressure levels from 4 kPa to 45 kPa and 100 kPa. The inter-tow voids were quantified both for the 3D structure as well as by studying 2D slices of the preform (Fig. 16). Almost a 60 to 70% decrease in inter-tow voids was observed when pressure was
increased from 4 kPa to 100 kPa. It was also seen that voids were higher in the area between the two tows and less in the centre of the tow intersection when these voids were checked along slices (Fig. 16). In Fig. 16, the inter-tow voids along slices follows a sinusoidal pattern, similar to the interlacement pattern (1/1); the slices in the centre of the intersections have the lowest inter-tow voids while the slices in between two tows have the highest inter-tow voids giving rise to a sinusoidal behaviour along the slices.

Fig.16. Inter-tow voids (%) along slices and average inter-tow voids (%) at (a) 4 kPa, (b) 45 kPa and (c) 100 kPa

3.5 CT assisted permeability simulations

Permeability simulations are sensitive to the accuracy of tow geometry in a unit-cell and how the unit-cells nest with each other at macro-level. Idealised tow geometry (e.g. Texgen, WiseTex) has been previously used by many researchers for modelling of permeability [23, 32]. It has been reported that resin flow through the woven fabrics is mainly through inter-tows as the inter-tow flow is relatively small. Delerue et al.[28] observed that, for woven fabrics, the intra-tow permeability is lower than fabric permeability by two order of magnitude. It was concluded that neglecting intra-tow permeability is a reasonable assumption [27, 28]. The absolute permeability experimental simulation (APES) available in Avizo software based on 3D CT images was previously employed for modelling flow through porous rock structures, catalyst and bioscaffolds e.g. [50]. The authors have utilised this feature of APES in the CT analysis software (XLab Hydro) to study flow through fibre
assemblies. This software simulates the permeability of realistic geometry obtained from computed tomography (CT) by hermetically closing the sample on four faces while applying the experimental setups on two opposite faces of the sample. In the XLab Hydro module, flow simulations are based on solving the Stokes equations for the velocity and the pressure fields using finite volume method [66]. The Stokes equations are given by

\[ \begin{cases} \Delta \vec{V} = 0 \\ \mu \Delta \vec{V} - \vec{v} P = 0 \end{cases} \]  \hspace{1cm} (3)

where \( P \) is the pressure of the fluid in Pascal, \( V \) is the velocity of the fluid in \( \text{ms}^{-1} \) and \( \mu \) is the viscosity of the fluid in Pascal seconds. In this study, the resin was considered as an incompressible fluid which exhibit Newtonian behaviour and follows a steady and laminar flow. The pressure difference was maintained at \( 10^5 \) Pascals and a representative resin viscosity of 0.25 Pascal seconds was used throughout this study. Permeability simulations were performed in all three directions (along warp tows, along weft tows and through thickness direction as shown in Fig. 17.

![Fig.17. Principal directions for permeability calculations](image)

The boundary conditions for permeability simulation are specified as:
a no-slip condition is imposed at interfaces between fluid and fibre tows as fibre tows are considered impermeable

a 1-pixel wide plane of solid phase (with no-slip condition) is added to the sides of the sample parallel to the flow (top and bottom sides of sample) in order to prevent the loss of the fluid through the adjacent faces. Instead of using periodic boundaries as discussed earlier, experimental setups are added on the faces of the image that are perpendicular to the main flow direction. These experimental setups create a stabilization zone where pressure is quasi-static and the fluid can freely spread on the input face of the sample

the input pressure and output pressure are kept constant and are imposed on the entrance and outlet

During post processing, the volumetric flux $Q$ ($m^3 s^{-1}$) across the end faces is computed and an application of Darcy’s law yields the permeability $k$ (m$^2$)

$$k = \frac{-Q \mu L}{\Delta P A} \quad (4)$$

Schematic of a virtual permeability experimental set up is shown Fig. 18.

Fig.18. (a) Schematic diagram of a virtual permeability experiment set up. P is pressure; L is the length of the sample and hash marks indicates impermeable boundaries, (b) flow field of a
virtual fluid displayed as stream lines representing velocity field along with weft cross section

Permeability values were calculated as a function of pressure along warp and weft tows and through thickness directions (Fig. 19). The permeability values in all three directions decreased with an increase in compaction pressure due to a corresponding reduction in inter-tow voids. Through thickness permeability values for the multi-layer stack are significantly lower than the in-plane permeability. Similar trends were reported by Weitzenbock et al. and Nedanov et al. [18, 51] for permeability values of 2D woven fabrics, by Ngo and Tamma [52] on 3D orthogonal fabrics and by Song et al.[53] on 3D braided textiles in through thickness directions in comparison to in-plane permeabilities. To study the effect of layer nesting, permeabilities of the fabric stack were calculated at highest and lowest nested regions. The calculated permeabilities for different nesting levels are presented in Fig.20.

![Permeability Chart](image)

**Fig.19.** Permeability of fabric as function of pressure (note different scales for in-plane and through-thickness permeabilities)
As can be seen from Fig. 20 the tomographic slice on LHS was in the region where the permeability values were highest as tows were sitting on top of each other giving rise to bigger resin channels whereas the slice on RHS was in the region which gave least permeability values, as a result of smaller resin channels due to better nesting of tows. The nesting of the layers increased the local fibre volume fractions but at the cost of decreased permeability. These observations are in agreement with the previous research work [4, 54]. The effect of nesting on permeability was highlighted by Grujicic et al. [54] as they observed decrease in permeability values with the fabric nesting. In the experimental work of Hoes et al. [4], the permeability results of layered reinforcement fabrics showed that nesting has a major effect on variation of permeability and bigger channels gave rise to higher permeability values. Similar explanation about effect of tow nesting on permeability values was given by Pavel et al. [18]. In literature, the permeability has been reported as a function of fibre volume fraction [2, 29, 55], so in the present work the permeability values have also been calculated and presented as a function of fibre volume fraction (Fig. 21). The magnitude of the obtained permeability results in the present study are comparable to the experimental permeability results in the literature (10^{-10} \text{m}^2) on the woven fabrics [2, 4, 9, 11, 12, 18, 27,
The obtained permeability values in the present study were also compared with the permeability values obtained by Kozeny-Carman model (Fig. 21). Permeabilities by Kozeny-Carman model were computed by employing equation 5.

\[
K = \frac{D^2 (1-V_f)^3}{16 k_o V_f^2}
\]  

(5) 

Where, \(K\) is the permeability by Kozeny model, \(D\) is the fibre diameter, \(V_f\) is fibre volume fraction and \(k_o\) is Kozeny constant. Kozeny constant needs to be determined experimentally and in the literature different values of \(k_o\) have been reported, e.g. 0.0018–0.04 \([56]\), 0.02–0.1 \([57]\). It was shown that the value of \(k_o\) varies with different fibre volume fractions for the same fabric \([57]\). In the present study, it was observed that the CT based permeability values obtained for FVF of 40% and 50% fitted well with Kozeny model with a Kozeny constant of 0.1.

**Fig. 21.** Comparison of permeability as function of FVF with literature (K1 and K2 are permeabilities along weft and warp tows) and Kozeny model (shown by dash lines)
Conclusions

Degree of nesting and meso-scale tow geometry changes have a significant influence on the resin permeability during the infusion process as well as the fibre volume fraction and the resulting mechanical properties of the composite laminates. High-fidelity structural models for textile composites require accurate non-idealised tow geometry as well as changes to this geometry during processing. In this work, an in-situ set up was developed to measure the realistic meso-scale geometry of the dry fabrics under transverse compaction using CT. Taking advantage of the high x-ray contrast between glass fibres and the air, high fidelity images of glass tows and inter-tow voids were captured under different levels of loading. These 3D images enabled us to capture spatial variability of degree of nesting, its influence on inter-tow void geometry and subsequently on resin flow. With the help of the existing in-situ compression mechanism, we were able to access nesting and permeability of the same dry fabric utilising computed tomography.

Inter-tow void geometry has a significant influence on resin flow. For example, at certain transverse loading, these inter-tow voids become disconnected islands and hence making the resin flow much harder. These types of subtle changes are difficult to capture in idealised tow geometry models. In this work, image-based resin flow simulations were developed with the aid of a feature in commercial software, Avizo. While this software was previously employed in flow through porous rocks, we have utilised the features in this software to simulate the permeability of dry textiles. Predicted permeability values as a function of volume fraction were compared with the results found in literature. Considering the general difficulty in accurately measuring and predicting permeability constants, this image-based prediction techniques shows a good agreement between the predictions and experimental results.

Additionally, following specific observations could be made from the CT based imaging of multi-layer fabric stack under transverse compression:

1. There is a degree of shifting and nesting between 2D fabric layers even at small transverse pressure. Degree of nesting improves (corresponding reduction in nesting factor) with transverse pressure.
2. Tow thickness decreased with transverse pressure primarily due to improved intra-tow fibre packing; change is tow width is negligible; tow crimp or waviness reduces with pressure.

3. Inter-tow voids reduced sharply with increase in transverse pressure (~ 70% decrease in inter-tow/inter ply voids at 1 bar pressure). Nesting of plies improved the fibre volume fraction but at the cost of reduced inter-tow/ inter-pl ply voids with adverse effect on fabric permeability (40-50 % reduction in permeability values observed at 1 bar pressure in highly nested regions).

4. At higher pressures, inter-tow voids become discontinuous islands. At this stage, the flow is primarily intra-tow.

5. Local permeability variations were predicted using image-based analysis technique described in the paper. These types of predictions are not possible with idealised tow geometry models as well as flow measurement techniques.

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References

[1] Robitaille F, Gauvin R. Compaction of textile reinforcements for composites manufacturing. I: Review of experimental results. Polymer Composites. 1998;19:198-216.

[2] Arbter R, Beraud JM, Binetruy C, Bizet L, Bréard J, Comas-Cardona S, et al. Experimental determination of the permeability of textiles: A benchmark exercise. Composites Part A: Applied Science and Manufacturing. 2011;42:1157-68.

[3] Lomov SV, Verpoest I, Peeters T, Roose D, Zako M. Nesting in textile laminates: geometrical modelling of the laminate. Composites Science and Technology. 2003;63:993-1007.

[4] Hoes K, Dinescu D, Sol H, Parnas RS, Lomov S. Study of nesting induced scatter of permeability values in layered reinforcement fabrics. Composites Part A: Applied Science and Manufacturing. 2004;35:1407-18.
[5] Chen B, Chou T-W. Compaction of woven-fabric preforms: nesting and multi-layer deformation. Composites Science and Technology. 2000;60:2223-31.

[6] Desplentere F, Lomov SV, Woerdeman DL, Verpoest I, Wevers M, Bogdanovich A. Micro-CT characterization of variability in 3D textile architecture. Composites Science and Technology. 2005;65:1920-30.

[7] Lekakou C, Johari MAK, Norman D, Bader MG. Measurement techniques and effects on in-plane permeability of woven cloths in resin transfer moulding. Composites Part A: Applied Science and Manufacturing. 1996;27:401-8.

[8] Stadtfeld HC, Erminger M, Bickerton S, Advani SG. An Experimental Method to Continuously Measure Permeability of Fiber Preforms as a Function of Fiber Volume Fraction. Journal of Reinforced Plastics and Composites. 2002;21:879-99.

[9] Luo Y, Verpoest I, Hoes K, Vanheule M, Sol H, Cardon A. Permeability measurement of textile reinforcements with several test fluids. Composites Part A: Applied Science and Manufacturing. 2001;32:1497-504.

[10] Amico S, Lekakou C. An experimental study of the permeability and capillary pressure in resin-transfer moulding. Composites Science and Technology. 2001;61:1945-59.

[11] Endruweit A, Ermanni P. The in-plane permeability of sheared textiles: Experimental observations and a predictive conversion model. Composites Part A: Applied Science and Manufacturing. 2004;35:439-51.

[12] Endruweit A, McGregor P, Long AC, Johnson MS. Influence of the fabric architecture on the variations in experimentally determined in-plane permeability values. Composites Science and Technology. 2006;66:1778-92.

[13] Mogavero J, Advani SG. Experimental investigation of flow through multi-layered preforms. Polymer Composites. 1997;18:649-55.

[14] Bickerton S, Sozer EM, Graham PJ, Advani SG. Fabric structure and mold curvature effects on preform permeability and mold filling in the RTM process. Part I. Experiments. Composites Part A: Applied Science and Manufacturing. 2000;31:423-38.

[15] Alhussein H, Umer R, Rao S, Swery E, Bickerton S, Cantwell WJ. Characterization of 3D woven reinforcements for liquid composite molding processes. Journal of Materials Science. 2016;51:3277-88.

[16] Vernet N, Ruiz E, Advani S, Alms JB, Aubert M, Barburski M, et al. Experimental determination of the permeability of engineering textiles: Benchmark II. Composites Part A: Applied Science and Manufacturing. 2014;61:172-84.

[17] Kabachi MA, Danzi M, Arreguin S, Ermanni P. Experimental study on the influence of cyclic compaction on the fiber-bed permeability, quasi-static and dynamic compaction responses. Composites Part A: Applied Science and Manufacturing. 2019;125:105559.

[18] Nedanov PB, Advani SG. Numerical computation of the fiber preform permeability tensor by the homogenization method. Polymer Composites. 2002;23:758-70.

[19] Loix F, Badel P, Orgéas L, Geindreau C, Boisse P. Woven fabric permeability: From textile deformation to fluid flow mesoscale simulations. Composites Science and Technology. 2008;68:1624-30.

[20] Simacek P, Advani SG. Permeability model for a woven fabric. Polymer Composites. 1996;17:887-99.

[21] Tahir MW, Stig F, Åkermo M, Hallström S. A numerical study of the influence from architecture on the permeability of 3D-woven fibre reinforcement. Composites Part A: Applied Science and Manufacturing. 2015;74:18-25.

[22] Bickerton S, Sozer EM, Šimáček P, Advani SG. Fabric structure and mold curvature effects on preform permeability and mold filling in the RTM process. Part II. Predictions and comparisons with experiments. Composites Part A: Applied Science and Manufacturing. 2000;31:439-58.
[23] Wong CC, Long AC, Sherburn M, Robitaille F, Harrison P, Rudd CD. Comparisons of novel and efficient approaches for permeability prediction based on the fabric architecture. Composites Part A: Applied Science and Manufacturing. 2006;37:847-57.

[24] Kim J-I, Hwang Y-T, Choi K-H, Kim H-J, Kim H-S. Prediction of the vacuum assisted resin transfer molding (VARTM) process considering the directional permeability of sheared woven fabric. Composite Structures. 2019;211:236-43.

[25] Hivet G, Wendling A, Vidal-Salle E, Laine B, Boisse P. Modeling strategies for fabrics unit cell geometry application to permeability simulations. International Journal of Material Forming. 2010;3:727-30.

[26] Laine B HG, Boisse P, Boust F, Lomov S, Badel S. Permeability of the woven fabrics. The 8th International Conference on Flow Processes in Composite Materials (FPCM8). 11-13 July 2006; Douai, France.

[27] Yu B, James Lee L. A simplified in-plane permeability model for textile fabrics. Polymer Composites. 2000;21:660-85.

[28] Delerue JF, Lomov SV, Parnas RS, Verpoest I, Wevers M. Pore network modeling of permeability for textile reinforcements. Polymer Composites. 2003;24:344-57.

[29] Zeng X, Brown LP, Endruweit A, Matveev M, Long AC. Geometrical modelling of 3D woven reinforcements for polymer composites: Prediction of fabric permeability and composite mechanical properties. Composites Part A: Applied Science and Manufacturing. 2014;56:150-60.

[30] Xiao Z, Liu X, Harper LT, Endruweit A, Warrior NA. Modelling the permeability of random discontinuous carbon fibre preforms. Journal of Composite Materials. 2020;54:2739-51.

[31] Endruweit A, Harper LT, Turner TA, Warrior NA, Long AC. Random discontinuous carbon fibre preforms: Permeability modelling and resin injection simulation. Composites Part A: Applied Science and Manufacturing. 2008;39:1660-9.

[32] Verpoest I, Lomov SV. Virtual textile composites software WiseTex: Integration with micro-mechanical, permeability and structural analysis. Composites Science and Technology. 2005;65:2563-74.

[33] Lomov SV, Mikolanda T, Kosek M, Verpoest I. Model of internal geometry of textile fabrics: Data structure and virtual reality implementation. The Journal of The Textile Institute. 2007;98:1-13.

[34] Straunit I, Lomov SV, Wevers M, Quoc NN, Martine W. From a micro-CT image to model of internal geometry, defects, micromechanics and permeability of textile composites-VoxTex Software, ECCM-17. 2016.

[35] Straunit I, Hahn C, Winterstein E, Plank B, Lomov SV, Wevers M. Computation of permeability of a non-crimp carbon textile reinforcement based on X-ray computed tomography images. Composites Part A: Applied Science and Manufacturing. 2016;81:289-95.

[36] Vilà J, Sket F, Wilde F, Requena G, González C, Llorca J. An in situ investigation of microscopic infusion and void transport during vacuum-assisted infiltration by means of X-ray computed tomography. Composites Science and Technology. 2015;119:12-9.

[37] Green SD, Matveev MY, Long AC, Ivanov D, Hallett SR. Mechanical modelling of 3D woven composites considering realistic unit cell geometry. Composite Structures. 2014;118:284-93.

[38] Ali MA, Umer R, Khan KA, Cantwell WJ. In-plane virtual permeability characterization of 3D woven fabrics using a hybrid experimental and numerical approach. Composites Science and Technology. 2019;173:99-109.
[39] Alhussein H, Umer R, Swery E, Rao S, Cantwell W, Bickerton S. In-plane and through-thickness permeability characterization of 3D woven reinforcements. 20th International conference on composite materials. 19-24 July 2015.

[40] Schell JSU, Renggli M, Van Lenthe GH, Müller R, Ermanni P. Micro-computed tomography determination of glass fibre reinforced polymer meso-structure. Composites Science and Technology. 2006;66:2016-22.

[41] Buades A, Coll B, Morel JM. A non-local algorithm for image denoising. Computer Vision and Pattern Recognition, 2005 CVPR 2005 IEEE Computer Society Conference on 2005. p. 60-5 vol. 2.

[42] L. ARB. Seed region growing. IEEE Transactions on pattern analysis and machine intelligence. 1994;16:641-7.

[43] Scott AE, Mavrogordato M, Wright P, Sinclair I, Spearing SM. In situ fibre fracture measurement in carbon–epoxy laminates using high resolution computed tomography. Composites Science and Technology. 2011;71:1471-7.

[44] Kruckenberg T, Ye L, Paton R. Static and vibration compaction and microstructure analysis on plain-woven textile fabrics. Composites Part A: Applied Science and Manufacturing. 2008;39:488-502.

[45] Robitaille F, Gauvin R. Compaction of textile reinforcements for composites manufacturing. II: Compaction and relaxation of dry and H2O-saturated woven reinforcements. Polymer Composites. 1998;19:543-57.

[46] Bickerton S, Buntain MJ, Somashekar AA. The viscoelastic compression behavior of liquid composite molding preforms. Composites Part A: Applied Science and Manufacturing. 2003;34:431-44.

[47] Somashekar AA, Bickerton S, Bhattacharyya D. Modelling the viscoelastic stress relaxation of glass fibre reinforcements under constant compaction strain during composites manufacturing. Composites Part A: Applied Science and Manufacturing. 2012;43:1044-52.

[48] Lomov SV, Verpoest I. Compression of woven reinforcements: A mathematical model. Journal of Reinforced Plastics and Composites. 2000;19:1329-50.

[49] Potluri P, Sagar TV. Compaction modelling of textile preforms for composite structures. Composite Structures. 2008;86:177-85.

[50] Miller KJ, Zhu W-l, Montési LGJ, Gaetani GA. Experimental quantification of permeability of partially molten mantle rock. Earth and Planetary Science Letters. 2014;388:273-82.

[51] Weitzenböck JR, Shenoi RA, Wilson PA. Measurement of three-dimensional permeability. Composites Part A: Applied Science and Manufacturing. 1998;29:159-69.

[52] Ngo ND, Tamma KK. Complex three-dimensional microstructural permeability prediction of porous fibrous media with and without compaction. International Journal for Numerical Methods in Engineering. 2004;60:1741-57.

[53] Song YS, Chung K, Kang TJ, Youn JR. Prediction of permeability tensor for three dimensional circular braided preform by applying a finite volume method to a unit cell. Composites Science and Technology. 2004;64:1629-36.

[54] Grujicic M, Chittajallu KM, Walsh S. Effect of shear, compaction and nesting on permeability of the orthogonal plain-weave fabric preforms. Materials Chemistry and Physics. 2004;86:358-69.

[55] Verleye B, Lomov SV, Long A, Verpoest I, Roose D. Permeability prediction for the meso-macro coupling in the simulation of the impregnation stage of Resin Transfer Moulding. Composites Part A: Applied Science and Manufacturing. 2010;41:29-35.

[56] Smith P, Rudd CD, Long AC. The effect of shear deformation on the processing and mechanical properties of aligned reinforcements. Composites Science and Technology. 1997;57:327-44.
[57] Liu HL, Hwang WR. Permeability prediction of fibrous porous media with complex 3D architectures. Composites Part A: Applied Science and Manufacturing, 2012;43:2030-8.

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: