

MULTI-SCALE STUDY OF RTM PROCESS MODELLING IN THE MANUFACTURING OF AEROSPACE COMPOSITES

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Abstract

Resin Transfer Moulding (RTM) is an advanced manufacturing process for composite components, and is widely applied in industries such as aerospace. A full resin impregnation during RTM is essential to obtain a high-quality component with reduced defects content. To reduce the level of experimental work as well as the cost for optimizing processing parameters, numerical simulation tools are widely used nowadays.

The work presented in this thesis is based on one work package from a company sponsored project, focused mainly on research in permeability characterisation and defects generation during the RTM process. From another point of view, this research can be considered as a multi-scale study of RTM process modelling, which consists of a micro-scale study of the fluid-porous interface to determine fibre tow boundary conditions for permeability modelling, a meso-scale study of textiles permeability based on unit cell modelling, and a macro-scale study of RTM process modelling to characterize void formation. Furthermore, experimental work is also included for validation against simulation results.

As a key input for RTM process modelling, permeability prediction based on meso-scale unit cell is studied in this research. Micro-CT technology is employed to characterize the internal geometry of 3D woven fabric, which is the input for the generation of unit cell. Besides, geometrical variability is studied for its influence on the permeability prediction results. Due to the dual flow characteristic within 3D woven fabric, proper fibre yarn boundary conditions are developed for permeability modelling with unit cell. Fibre yarn with random fibre distribution models are generated. Flow transverse with the fibre yarn is studied and it's found that no-slip boundary condition can be applied in the present research. Considering the geometric variability inherent with fabrics, permeability variability study is also conducted in this research. The geometric variability characterization methods are introduced and based on that, the influence of geometric variability on the permeability prediction is studied. Regarding with macro-scale RTM process modelling, parametric study of injection conditions are conducted to investigate its effect on voids formation.

Furthermore, permeability experiment of 3D woven fabrics with different fibre volume fraction, as well as parametric study of RTM experiments for voids formation are also included in this research. Comparison of permeability measurement value and modelling results are made, with which the unit cell model is optimized.

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Nomenclature

K	Textiles' permeability (m ²)
μ	Fluid viscosity (Pa.s)
P	Pressure (Pa)
∇P	Pressure gradient
Q	Volume flow rate (m ³ /s)
Re	Reynolds number
ρ	Fluid density (kg/m ³)
u	Fluid velocity (m/s)
u_x	x component of Fluid velocity (m/s)
u_y	y component of Fluid velocity (m/s)
u_z	z component of Fluid velocity (m/s)
K_{ij}	Components of textiles' permeability (m ²)
$\frac{dp}{dx}$	Pressure gradient in x direction
$\frac{dp}{dy}$	Pressure gradient in y direction
$\frac{dp}{dz}$	Pressure gradient in z direction
M_s	Unit volume of solid (m ³)
M	Unit volume of porous medium (m ³)
$K_{ }$	Permeability along with fibre arrays (m ²)
$K_{\perp}$	Permeability transverse with fibre arrays (m ²)
V_{fmax}	Max fibre volume fraction within fibre tow
R_f	Fibre Radius (m)
V_f	Fibre volume fraction
$\frac{dp}{dx}$	Pressure gradient in x direction
ϕ	Porosity of porous medium
c_0	Kozeny's constant
C_a^*	Capillary number
ρ_s	Areal density of dry fabric (g/cm ²)
ρ_g	Fibre density (g/cm ³)
γ	Surface tension of liquid
α	Slip coefficient
u_b	Slip velocity (m/s)

1. Introduction

1.1 The application of composites in aerospace industry

Fibre-reinforced composites (FRC) are composed of fibres with specific mechanical properties and a polymeric matrix. The fibres within composites serve as a load-carrying medium and provide structural properties such as stiffness and strength. The matrix mainly binds the fibres together and transfers the load to the fibre reinforcement [1].

According to the required mechanical properties and manufacturing characteristics, the fibre reinforcements can be prepared in a wide range of forms, including individual filaments, mats, woven or non-woven fabrics. Generally, laminates are the common form used in structural applications [2]. They are formed by stacking a number of layers of fabric with matrix to a desired thickness. Various physical and mechanical properties can be achieved by designing the fibre orientations and stacking sequence in the laminate. However, due to the lack of fibre reinforcements in the through-thickness direction, the major disadvantage of 2-dimensional (2D) laminates lies in their low through-thickness mechanical properties and poor impact damage resistance [3].

Thus, a variety of three-dimensional (3D) fibre composites have been introduced to overcome the disadvantages of 2D laminates. With the inclusion of fibre reinforcements in the through-thickness (or z-) direction, higher delamination fracture toughness and impact damage tolerance can be found in 3D composites than the conventional laminates. In addition, the preform can be produced with near-net shape. [4] Based on different fabrication processes such as stitching, weaving, braiding and knitting techniques, the most common types of 3D preforms include 3D woven composites, stitched composites, 3D braided composites and multi-layer non-crimp knitted composites.

Due to its low density, high specific strength and modulus, FRC are being considered as a substitution for metallic materials in aerospace, automotive and other industries. Composites were originally introduced to military aircraft in the 1960s for secondary structures such as wing extensions, nose cones or helicopter bodies. [1] Their adoption in civil aircraft started in the 1980s and gained wide applications at the beginning of the 21st century. For example, a composite material called Glare, which is a laminate of glass reinforced epoxy resin and aluminium sheets, was developed by Airbus to make the upper fuselage and the leading edges of the vertical and horizontal stabilizers of its superjumbo A380. The application of Glare leads to a weight reduction as high as 25%

compared with the traditional materials. [5] The application of composite materials in the Boeing 787 has reached as high as 50% by mass, including an all-composite fuselage, as is shown in Figure 1.1. The expanded use of composite materials in its frame and primary structure greatly reduces both the overall airplane weight and maintenance cost [6]. Similarly, 52% of the newly launched Airbus A350XWB is fabricated with composite materials, such as the fuselage as well as wings and empennage.[7]

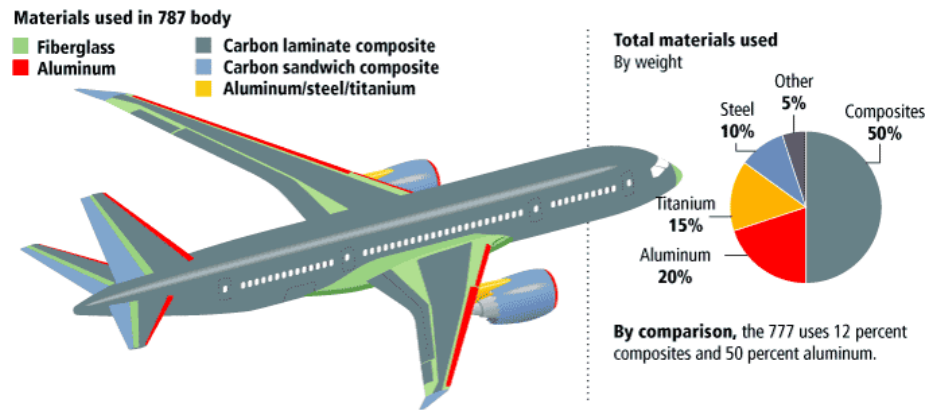


Figure 1.1 The materials used to construct the Boeing 787 [8]

In addition to airframes, the potential adoption of advanced composites in commercial aero-engines is also attracting manufactures' attention. In 1980s, General Electric's (GE) CF6-80C2 came into the market with outlet guide vanes and shrouds made from unidirectional preregs and chopped carbon fibre in glass-fibre reinforcing matrix respectively. Since then, subsequent uses extended to new structures such as nacelles, thrust reversers, and even fan blades in the latest engines.

With the development of weaving technology, 3D woven composite parts are successfully applied in the LEAP engine series produced by CFM international. The 18 composite fan blades are fabricated with 3D woven textiles and processed with Resin Transfer Moulding (RTM). Figure 1.2 presents an example of a composite fan blade manufactured with 3D woven composites. Compared with the conventional hand-layup of multiple-ply and autoclave-curing process of the composite fan blades in the GE90 and GEnx engines [9], the use of 3D woven preform and RTM drives down the manufacturing cost and provides superior damage tolerance, resulting in thinner and more curved blades with additional aerodynamic benefits. [10]



Figure 1.2 Fan blade produced with 3D woven composites [11]

The application of composite fan blades in aero-engines makes it possible to produce the fan containment case with composites in substitution for metallic materials (or over-wrapped with dry aramid fibres), as the fan containment case must be able to contain a released fan blade under a fan blade-out event to prevent further damage to the airframe, and also maintain structural integrity before full engine shutdown according to Federal Aviation Regulations [12]. The first whole composite fan containment case was introduced in GENx engine by GE Aviation. It is fabricated with a weave of biaxial and tri-axial carbon-epoxy braids around a fan case tool [9]. For the LEAP composite fan case, the near-net-shape preforms are produced by 3-D weaving technology called contour weaving and RTM is applied to obtain the final shape. [13] With this weaving technique, the previous fan containment case used in GE90 which requires separate manufacture and assembly of a metallic ring with an aramid fibre wrap is substituted. Figure 1.3 presents the composite fan modules from the GENx engine and LEAP-1A engine respectively.



Fig 1.3 Composite fan module (comprised of fan blades, platforms, and fan case):
GE9X-1B (left) [14] and LEAP-1A (right) [15]

It can be seen that the application of FRC materials in the aerospace industry will increase steadily with the continuous demand for fuel-efficient and economic commercial flights from customers. Specifically, the advantages of 3D composites, such as improvements in damage tolerance, durability and the resultant maintenance cost, makes them a more promising choice over conventional 2D composites. Besides, the manufacturing cost of these 3D composite components can be lowered with the more efficient processing technology via RTM.

1.2 Resin transfer moulding and process modelling

The Resin Transfer Moulding process consists of placing a dry preform in a rigid and closed mould, injecting resin into the mould with a positive pressure, curing and demoulding, as shown in Figure 1.4. As a variation of liquid composite moulding (LCM), which features injecting resin through a fibrous reinforcement, RTM is capable of making large 3D complex parts with high fibre volume fraction [16]. Thus, compared with other composites manufacturing processes such as hand lay-up, autoclave and filament winding, RTM shows its advantages in producing three-dimensional near-net-shape components with good mechanical properties.

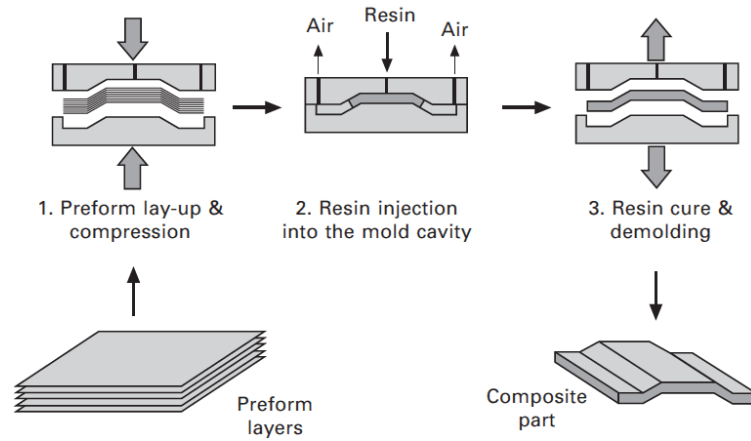


Fig 1.4 Resin transfer moulding process [17]

With RTM, the final quality of the moulded component depends mainly on the mould filling process during resin injection stage. The preform within the rigid mould should be fully impregnated to avoid the generation of manufacturing defects such as dry spots and or micro-voids, as these defects will cause deterioration in mechanical behaviour of the moulded component. This essential mould filling process during RTM is controlled by a multitude of parameters, such as the injection pressure, mould temperature, resin viscosity, the preform's permeability and the mould design [18]. All of these parameters should be considered mutually to accomplish a complete filling of the mould. For example, the locations of injection gates and vents within the mould must be carefully designed to prevent air entrapment, as well as to obtain a shorter mould filling time.

RTM process modelling and numerical simulation provides an important tool to avoid the traditional costly trial and error method for designing the mould [19]. Resin flow front location or flow pattern during the mould filling phase can be predicted, and the processing parameters mentioned above can be optimized to achieve the appropriate flow pattern to avoid the potential defects generation [20]. The relevant processing parameters and their mutual relations are presented in Figure 1.5.

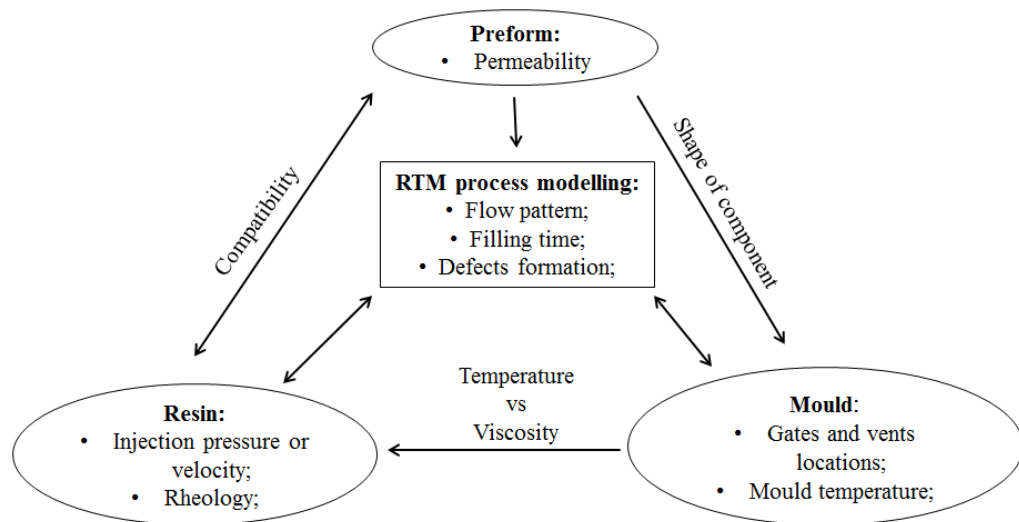


Fig 1.5 Influencing factors of RTM process simulation and their relations

1.3 Objectives of this thesis and outline of chapters

This present work is one work package from the cooperative project ‘*Simulation Methodology for Impact Damage in Composite Components of Aero-Engines - Theoretical Models and Experimental Validation Strategy*’, between ACAE (AVIC Commercial Aircraft Engine. Co., ltd) and the University of Nottingham, which aims to develop a theoretical modelling capability for designing and manufacturing composite components used in modern commercial aero-engines, such as fan blades and containment casing. Based on that, the objectives of this present work consist of predicting the effective permeability of textile preforms and the formation of defects in the RTM process with an efficient numerical tool, followed by experimental validation by permeability measurement and the inspection of the internal defects within components.

This thesis is outlined as follows:

Chapter 2 presents a literature review of general concepts related to the RTM process; in particular, the existing numerical and experimental characterisation of textile preform permeability and the variability of textile’s internal geometry are reviewed; also, the state-of-the-art in focus of mechanisms of defect generation is discussed. Chapter 3 describes the geometric characterisation of a 3D angle interlock preform; the related geometric variability is also studied. Chapter 4 studies the influence of boundary conditions at the tow interface on prediction of permeability with unit cell model. Chapter 5 describes permeability prediction based on a meso-scale unit cell generated from the geometric characterisation of the 3D preform; the influence of geometric

variability on the permeability prediction is also investigated; in addition, validation against experimental measurements is provided. Chapter 6 describes defects formation based on numerical and experimental parametric studies of the RTM process. Chapter 7 presents a discussion related with RTM process modelling from an overall perspective.

2. Literature review

2.1 Introduction

For the resin transfer moulding (RTM) process, there are a number of variables and processing parameters, including the preparation of preform, the resin injection and curing stage, as well as the de-moulding process. All these factors need to be considered properly in order to manufacture composite parts with high quality. Besides, cycle time is another topic which relates with the manufacturing cost. Composites manufacturing starts with production and handling of the preform, and lasts until the composite parts are ready to be applied in industry. Hence, to achieve its advantages of high performance and low cost, every step during the manufacturing requires special attention, as the mechanical performance is strictly related with manufacturing.

The preform used in RTM should be designed in an architecture that meets the mechanical requirements of the component; this architecture, as well as its advantage of near-net-shape should be realized with appropriate techniques. Then, an understanding of the internal structure is necessary for a successful resin impregnation through the dry preform. The fibrous preform can be regarded as a porous medium with heterogeneous characteristics: the micro-pores within fibre tows, and the flow channels between fibre tows. Thus, resin impregnation through the preform should also be considered in two scales: intra-tow flow within fibre tows and inter-tow flow between fibre tows. This intrinsic dual-scale internal structure within the preform, not only affects the effective permeability of preform [21-23], but also is closely related with void formation within the composite part [24, 25].

The goal of composites manufacturing is to obtain a high-quality component by reducing the potential for defect formation. Process modelling provides an efficient way to achieve successful resin impregnation by simulating the mould filling process. However, the accuracy of the flow model is dependent on a comprehensive understanding of resin filling characteristics and a range of accurate inputs, such as the preform permeability, resin pressure or velocity, mould temperature, etc. The literature hereinafter will cover recent progress related with the basics of RTM and process modelling, the determination and influencing factors of preform permeability (experimental and numerical), and the mechanisms and influencing factors of defect formation during the mould filling stage. Process optimization methods developed are also reviewed.

2.2 Basics of RTM technique and process modelling

2.2.1 Preform technology

For RTM, the preform placed in the closed mould can be prepared in different forms with various fibre types. As the fibre reinforcements within composite materials is the main load bearing part, the selection of fibre types and the design of preform are dependent on the mechanical requirements of the component. For instance, advanced composites applied in the aerospace industry are mainly fabricated with carbon fibre on account of its outstanding mechanical performance such as high stiffness and strength.

The fibre preform is fabricated with fibre yarns arranged in a particular style by various manufacturing techniques. Note that fibre tows are composed of a number of fibre filaments twisted or untwisted together before being combined into fibre preform. This results in the specific hierarchical nature of textile preforms, which can be classified into three dimensional scales, namely fibre filaments at the micro-scale, yarns or tows at the meso-scale, and fabrics or preforms at the macro-scale. This intrinsic hierarchical characteristic of preforms must be taken into consideration in the design of composites as well as their manufacturing process, as the mechanical performance of the final component and the resin impregnation through the reinforcement are directly influenced. Figure 2.1 presents the relationship between different scales of fibre reinforcement.

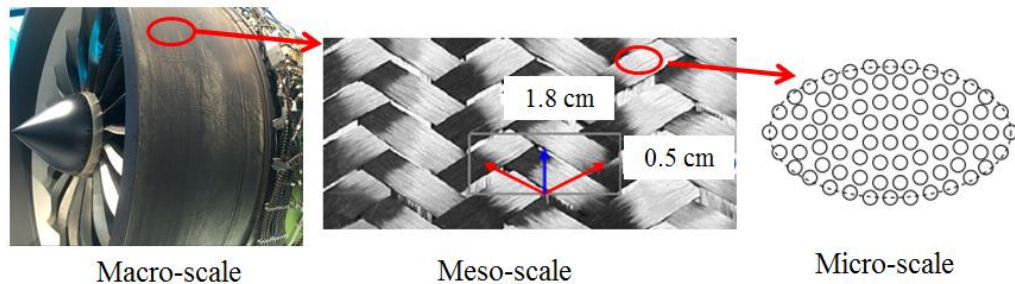


Figure 2.1 The relationship between the different dimensional scales of preform (the blue and red arrow in the meso-scale figure indicates fibre direction [26])

With various production technologies such as weaving, stitching and braiding, preforms with various internal structures can be manufactured. Furthermore, near-net-shape preforms can be produced by the technologies such as contour weaving or braiding. Accordingly, components with complex shape or geometry can be produced with improved structural performance. Also the production cost can be lowered. The design or choice of preform technology depends mainly on the required mechanical behaviour of the manufactured parts, the processability and the feasibility of the geometry. In

consideration of the material studied in the present work, weaving technology will be reviewed hereinafter.

Weaving is the process of producing a fabric by interlacing two sets of yarns, namely warp and weft. Specifically, the yarns running along the length of the fabric (0° direction) are called warp yarns, and those running along the width of the fabric (90° direction) are named weft yarns or filling yarns. Warp yarns are fed into the weaving loom from a source of yarns, which are usually wound on a warp beam. Then the warp yarns go through a harness, on which a set of heddles are equipped. A shed is created by lifting the warp yarns up and down with the movement of the harness. Thus the weft yarn or filling yarn can be inserted into the shed with an insertion device such as a shuttle or rapier. The inserted weft yarn is positioned by the forward movement of a reed, and then is locked into the fabric by the opposing movement of the harness. In this way, the fabric is fabricated. The conventional weaving mechanism is illustrated in Figure 2.2.

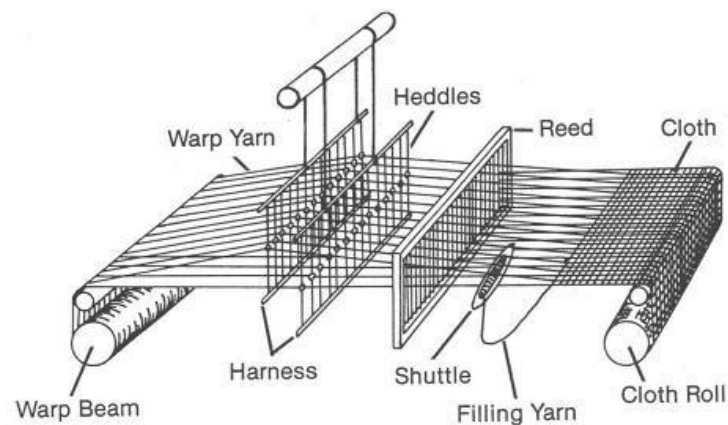


Figure 2.2 Conventional weaving machinery [27]

Note that the motion of individual warp yarn through the harness can be controlled during the weaving process. This lifting or shedding mechanism which is also named Jacquard, is crucial as it determines the interlinking of warp and weft yarns. Accordingly, a variety of fabrics with different weaving patterns can be produced, including fundamental weaves such as plain weaves, twill weaves and satin weaves, as well as other 2-D or 3-D woven fabrics [17]. Figure 2.3 presents several fundamental weaving patterns.

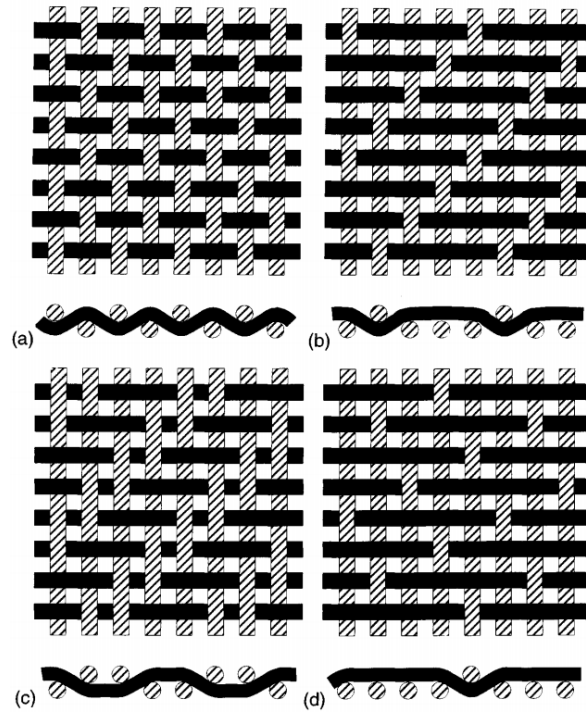


Figure 2.3 Common weave patterns: a) Plain weave; b) 3×1 twill weave; c) 2×2 twill weave; d) 5 harness satin weave.[28]

Fabric properties such as mechanical performance, drapability and fibre volume fraction are influenced by the weaving pattern. For example, a twill weave possesses good drape capability resulting from its tendency to accommodate in-plane shear; whilst a satin weave pattern features a smooth fabric surface which avoids the twill lines or diagonal configurations of crossovers.[17]. Thus it is important to understand the weaving process for designing fabrics with an appropriate architecture.

Traditional 2-D woven fabrics can be designed to possess high in-plane mechanical properties; however, the inherent drawbacks of laminated composites such as delamination and inferior impact damage resistance restrict their applications in some critical structures in the aerospace and automotive industries. To extend their usage to more advanced industries, three-dimensional multi-layer fabrics, which features through-thickness reinforcement, were introduced by textile designers, and they are gaining wide attention nowadays.

Compared with conventional 2-D woven fabrics, multilayer woven fabrics or 3-D woven fabrics are composed of distinct layers which are bound together by interlacing warp yarns (binders) with internal adjacent layers or with the face and back layers. Note that there are various nomenclatures for a certain 3-D woven fabric with a particular weaving pattern used by different researchers [4, 29, 30]. Basically, they can be

categorized based on weaving characteristic of the binder warp yarns. According to the orientation of these binder yarns (or whether the binder yarn interlace across two columns of weft yarns or more than two columns of weft yarns), 3-D woven fabrics can be grouped into two main categories, namely 3-D angle-interlock fabrics and 3-D orthogonal fabrics. Besides, considering the penetration depths of binders, these fabrics can also be classified into through-the-thickness (when the binder warp yarns go through the full thickness of the fabric) and layer-to-layer fabrics (when binder warp yarns connect separate layers of the fabric). Examples of these weaving patterns are illustrated in Figure 2.4.

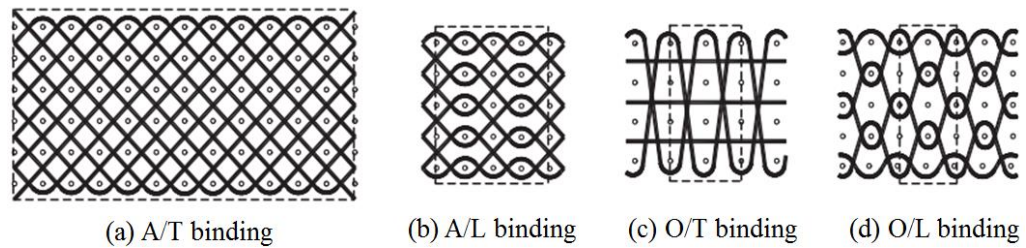


Figure 2.4 Various patterns of 3-D woven fabric [31]

The 3D woven fabric applied in this research is illustrated in Figure 2.5. It is also called layer-to-layer angle inter-lock 3D woven material. The binder warp yarn goes through between two adjacent weft yarn layers. In this research, fabric thickness is controlled by the numbers of weaving layers.

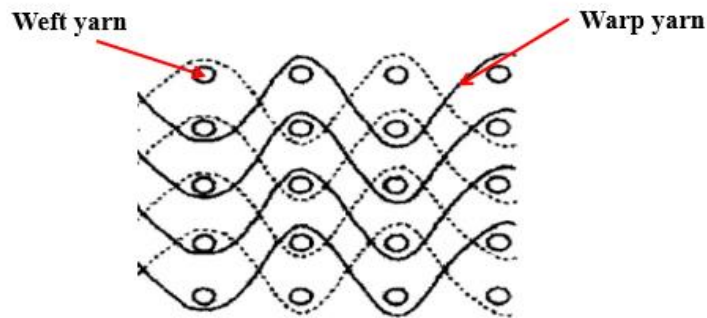


Figure 2.5 Structure of angle inter-lock fabric

Note that all the aforementioned 3-D multilayer woven fabrics are obtained by rearranging a portion of the warp yarns to serve as out-of-plane reinforcement. Basically, this production process can be realized by modifying the traditional weaving mechanisms. A key part of the 3-D weaving process lies in the dual-directional shedding mechanism, with which multiple layer warp yarns can be displaced to form alternatively

multiple column-wise and row-wise sheds. Figure 2.6 presents the schematic loom describing the 3-D weaving process developed by Mohamed [29].

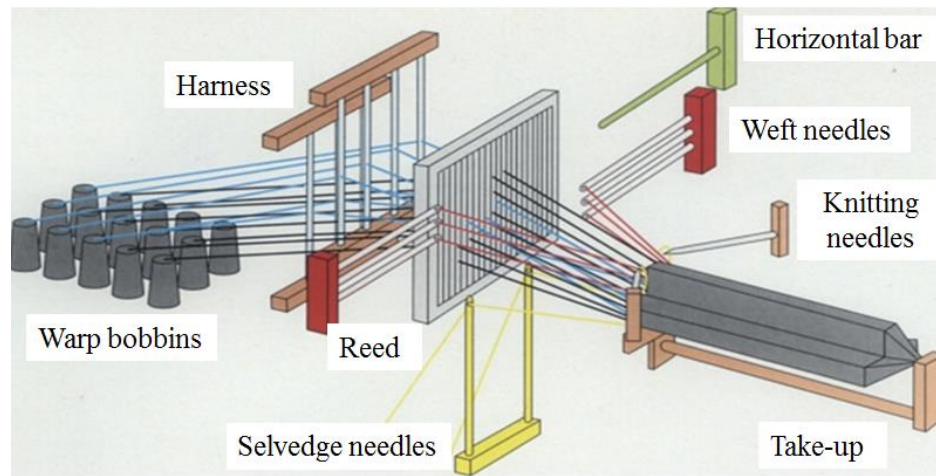


Figure 2.6 3-D multilayer weaving system consisting of warp robbins to supply multi-layer and binder warp yarns; harnesses to change the rows of binder warp yarns; a reed to position and lock yarns in the fabric; weft needles to insert weft yarns; selvedge needles; a horizontal bar to hold the selvage yarn; a pair of knitting needles; and apparatus to maintain tensions on the finished part[29]

A variety of 3-D fabrics with various internal architectures can be produced by arranging the amount and orientation of binder warp yarns, therefore, fabrics can be designed to meet various mechanical requirements in high-end industries. Furthermore, 3-D weaving techniques exhibit high potential in fabricating components with complex shapes which are expensive and complicated to produce from laminates. Examples of 3-D woven preforms with complex structures are listed by Mouritz et.al [32], including cylinder with flange, turbine rotors etc. However, the production of certain shaped multilayer reinforcements, for example, preforms with variable thicknesses or taper [33], which require the warp and weft density to vary accordingly, can be very complicated with the conventional looms. Thus, in order to achieve these near-net-shape preforms, special weaving mechanism and machinery need to be developed. Need to mention that the most recent application of large-scale structural composite components, the composite fan blades and containment case for LEAP turbine engines, are fabricated with near-net-shape weaving technologies such as contour weaving and steered weaving developed by AEC company (Albany Engineered Composites) [34, 35], as shown in Figure 2.8.

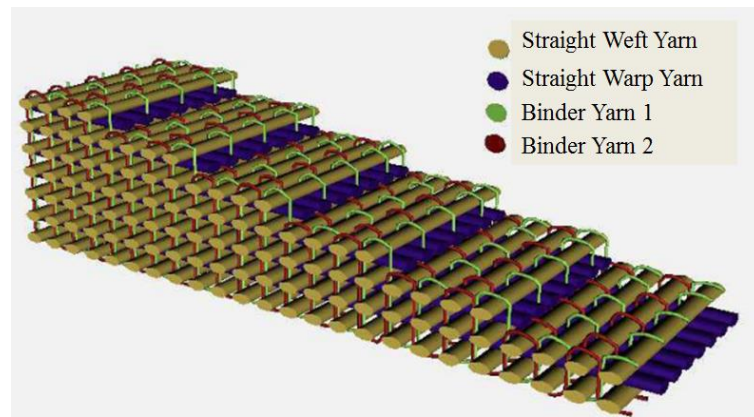


Figure 2.7 Multilayer preform with tapering thickness [33]



Figure 2.8 Composite fan blade (left) [35] and composite fan containment case (right) [34] developed with 3-D woven technologies. Note that fibre damage can occur during the weaving process. Usually this damage is caused by the repeated actions of abrasion and bending when yarns go through the loom, or yarn-to-yarn friction and loss of sizing agent, especially when using fibres which are fragile and with high friction coefficient such as glass fibres. Some researchers [36, 37] found that the accumulation of damage during weaving can lead to the loss of mechanical properties such as tensile strength of composites. Thus, various solutions are proposed to minimize fibre degradation, including use of additional sizing agent on fibres to lower yarn friction. Fibre sizing also possesses other essential functions such as protecting the fibres from environmental erosion, strengthening the bond between fibres and resin matrix, and improving the wettability of fibres during flow [38]. Fibre size should be specific to each type of resin system, as it must dissolve from the resin during forming process.

2.2.2 Resin system

The resin matrix possesses several essential functions, including forming the final structure shape with high surface quality, protecting fibre reinforcements from environmental damage, and transferring loads to the fibre reinforcement.[1] Accordingly, the selection of appropriate matrix material depends mainly on two considerations: processing characteristics and mechanical performance. In particular for RTM, a good knowledge of the physical properties of the matrix material is important for manufacturing engineers to determine the optimum process. Thermosetting resins are the main choice for RTM-based composites due to their low viscosity at room temperature and process feasibility compared with thermoplastic materials, since a low viscosity leads to a better wet-out of fibres by the resin matrix (this will be elaborated in later sections). Table 2.1 presents comparisons of viscosity among different materials.

Table 2.1 Comparison of different material viscosities [38]

Material	Viscosity (Pa.s)	Consistency
Air	10^{-5}	Gaseous
Water	10^{-3}	Thin-bodied
Glycerin	1	Liquid
Thermosets	0.05-0.5	Liquid
Molten thermoplastics at processing temperature	10^2 - 10^6	Thick-flowing

In the aerospace industry, epoxy resin is used as the principal resin for high-performance composites due to its relatively good thermal stability, excellent adhesion properties and good mechanical properties. Epoxy resin is used together with a hardener or curing agent, which can initiate the chemical cross-linking reaction of molecules within the resin (curing process). The curing process and final mechanical performance can be largely influenced by the type and amount of applied hardener. For example, three types of hardeners are provided for the epoxy resin system PRIME™ 20LV developed by Gurit Company, so a range of working time and curing speed can be available for any particular size of moulded part. [39]

In the RTM process, a knowledge of resin rheological behaviour is crucial for designing the optimum processing parameters to achieve high-quality composites parts. For instance, the initial resin viscosity, as well as the curing speed, is closely related with resin temperature; specifically, the initial viscosity of the resin system will decrease

with the elevated temperature, whilst the curing speed will increase. To obtain an optimum resin filling velocity [40], the injection pressure should be varied according to Darcy's law; also, the pot life (time before the resin cures) should be long enough for the resin to reach the vent (last port to fill). Figure 2.9 presents the relationship between the initial HexFlow® RTM6 viscosity and the temperature. It can be seen that the resin viscosity increases with time as the resin cures.

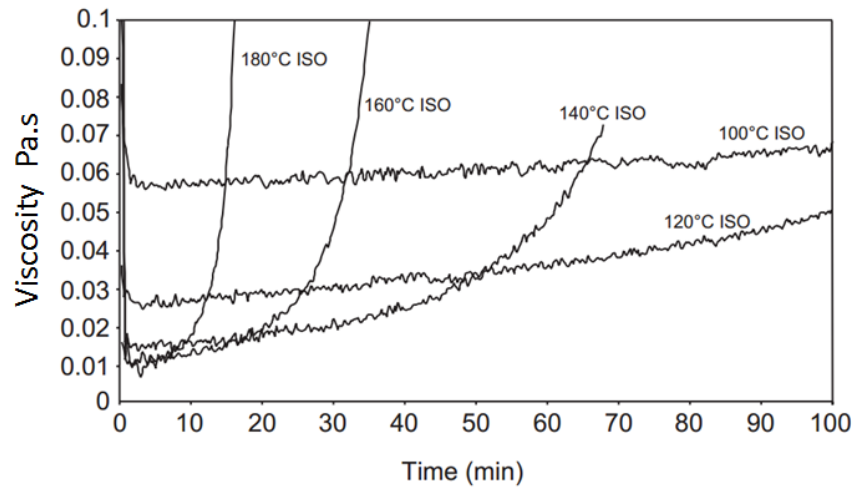


Figure 2.9 HexFlow® RTM6 Isothermal viscosity [41]

2.2.3 Mould design and Process modelling

The quality of RTM-based composite parts depends principally on the mould filling stage, which is greatly affected by the mould design to reduce the risk of air-entrapment and void formation. Factors that should be taken into consideration when designing the mould include production volume of composites parts, RTM operating temperature and pressures, dimensional tolerance and machining cost [42]. Materials commonly used for rigid moulds are steels and aluminium. Due to its high wear resistance, steel is mostly selected for high volume applications, although the initial tooling cost is high. [28]

One essential issue regarding the mould design is the location of injection gates and vents during the mould filling stage [28]. Note that the mould filling process can be regarded as the replacement of air by the liquid resin within mould; the distribution of gates and vents should guarantee complete resin wetting across the whole preform without entrapping air pockets inside the moulded part. As the resin flow path within the mould cannot be seen directly, it can be difficult for mould designers to place the vents exactly where resin arrives, particularly when the component possesses a complex shape. Often designers rely on their experience along with trial and error methods to

optimize the mould design. Nowadays, process modelling provides a more efficient and cost-effective way to help design the mould by predicting resin flow front progression during mould filling. An appropriate distribution of resin inlets and outlets can be determined based on the simulation results. Furthermore, process variables and parameters such as injection pressure or velocity can be optimized to achieve composites parts with good quality[16].

RTM process modelling is based on an understanding of the physical phenomena and constitutive laws that control the filling process, together with a series of reasonable assumptions and boundary conditions. From a macroscopic perspective, mould filling process can be considered as an incompressible fluid (resin) flowing through a porous medium (fibre reinforcement or preform) placed within a closed mould under a certain pressure. Note that thermoset resin can present shear-thinning behaviour, which means a reduction in viscosity at high rates of flow; however, as the resin velocity and the corresponding shear rate are low for most manufacturing of processes for structural composites, the resin can be treated as a Newtonian fluid with a very low Reynolds number (Re). [43] Hence, resin flow of this type can be assumed as laminar flow or creeping flow (when $Re \ll 1$)[44]. Based on the above assumptions, the impregnation of a preform can be modelled by Darcy's Law, which was derived from the experimental study of water flowing through sand layers by Henri Darcy in 1856 [45],

$$\vec{u} = -\frac{\vec{K}}{\mu} \nabla P \quad (2.1)$$

Here $\vec{u}$ represents Darcy's velocity or volume averaged fluid velocity, $\vec{K}$ is the permeability tensor of the porous medium, μ is the viscosity of the fluid, ∇P is the driving pressure gradient along the flow direction. Note that $\vec{K}$ is a material property which characterizes the ease of fluid flow through the porous medium (this will be elaborated in next section). As the preform used in RTM is usually anisotropic, Darcy's law can be extended to three-dimensions as,

$$\begin{pmatrix} u_x \\ u_y \\ u_z \end{pmatrix} = -\frac{1}{\mu} \begin{pmatrix} K_{xx} & K_{xy} & K_{xz} \\ K_{yx} & K_{yy} & K_{yz} \\ K_{zx} & K_{zy} & K_{zz} \end{pmatrix} \begin{pmatrix} \frac{\partial P}{\partial x} \\ \frac{\partial P}{\partial y} \\ \frac{\partial P}{\partial z} \end{pmatrix} \quad (2.2)$$

Here u_i are the resin velocity components and K_{ij} are the permeability tensor components. If the composite parts have a thin-shell nature, transverse flow in the through-thickness direction can be ignored[38], and the resin filling process can be reduced to 2-D flow. Thus, Darcy's law can be written in two-dimensional form as,

$$\begin{pmatrix} u_x \\ u_y \end{pmatrix} = -\frac{1}{\mu} \begin{pmatrix} K_{xx} & K_{xy} \\ K_{yx} & K_{yy} \end{pmatrix} \begin{pmatrix} \frac{\partial P}{\partial x} \\ \frac{\partial P}{\partial y} \end{pmatrix} \quad (2.3)$$

The resin is assumed as an incompressible fluid, thus the equation of mass conservation is,

$$\nabla \cdot \vec{u} = 0 \quad (2.4)$$

Or
$$\frac{\partial}{\partial x}(u_x) + \frac{\partial}{\partial y}(u_y) = 0 \quad (2.5)$$

For isothermal flow modelling, combining Darcy's equation and the equation of mass conservation by substitution of the velocity terms in equation (2.5) in terms of pressure gradient in equation (2.3), leads to,

$$\nabla \cdot \left(\frac{\vec{K}}{\mu} \nabla P \right) = 0 \quad (2.6)$$

Or, in extended second order partial differential equation form as,

$$\frac{\partial}{\partial x} \left(\frac{K_{xx}}{\mu} \frac{\partial P}{\partial x} \right) + \frac{\partial}{\partial x} \left(\frac{K_{xy}}{\mu} \frac{\partial P}{\partial y} \right) + \frac{\partial}{\partial y} \left(\frac{K_{yx}}{\mu} \frac{\partial P}{\partial x} \right) + \frac{\partial}{\partial y} \left(\frac{K_{yy}}{\mu} \frac{\partial P}{\partial y} \right) = 0 \quad (2.7)$$

According to the RTM process, usually the resin will be injected under constant pressure (P_{inj}) or constant flow rate (Q_{inj}). Thus, for the resin domain, boundary conditions can be set as,

Resin inlet:
$$\begin{cases} P = P_{inj} \text{ (Constant pressure)} \\ Q = Q_{inj} \text{ (Constant flow rate)} \end{cases}$$

Resin flow front:
$$P_{front} = P_{vent}$$

Mould walls:
$$\frac{\partial P}{\partial n} = 0 \quad (\text{n is normal direction towards mould walls})$$

Note that resin flow is assumed to be quasi-steady state. The pressure field within the mould can be solved based on equation (2.7) at each time interval. Accordingly, resin velocity field can also be obtained by Darcy's law. Depending on this process, the pressure field and velocity field during mould filling can be solved until the injection is finished[46]. Furthermore, airflow and fibre motion are neglected in the above governing equations. Also, it can be seen that the permeability of the preform plays an essential part in flow modelling. This will be addressed in the next section.

2.3 Preform permeability

2.3.1 Definition of permeability

Permeability is the description of resistance of a porous medium to the fluid flow thorough it. It is based on Darcy's law, which was discovered by Henry Darcy in 1856 from his famous experiment [47]. In that experiment, Darcy investigated the flow of water through *vertical* homogeneous sand layers, and he concluded that the volume flow rate (Q) is directionally proportionally to the cross-section area of the flow conduit (A) and the piezometric head loss ($h_1 - h_2$), but inversely proportional to the length of the conduit (L), as presented in equation (2.8),

$$Q = -K_c A \frac{(h_1 - h_2)}{L} = -K_c A \frac{dh}{dx} \quad (2.8)$$

Note that here the coefficient of proportionality K_c is named hydraulic conductivity, which depends on both the porous medium and fluid properties. To make Darcy's formula (2.8) more generalized, flow through an *inclined* tube with homogeneous porous medium is considered, as described in Figure 2.10.

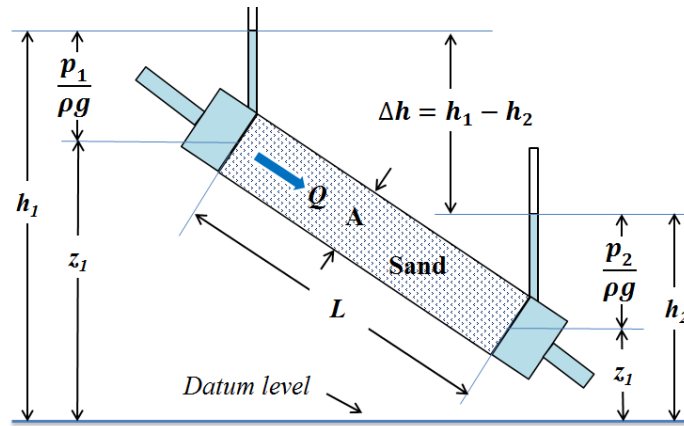


Figure 2.10 Schematic drawing of Darcy's experiment

It can be seen that the piezometric head h contains two parts, namely the external pressure (p) applied on the fluid and the potential energies of the fluid per unit weight (z) measured from a datum level, as expressed in equation (2.9).

$$h = z + \frac{p}{\rho g} \quad (2.9)$$

Actually, the total mechanical energy loss during this process also includes the kinetic energy loss which is associated with the fluid's motion. However, the kinetic energy

head along the flow path is usually neglected as it is much lower compared with the piezometric head loss.[45] From the obtained empirical formula, it can be seen that the hydraulic conductivity K_c is a coefficient which is related with both the fluid and porous medium. From the analytical derivations for Darcy's law, Muskat [48] proposed K_c can be expressed as,

$$K_c = \frac{K\gamma}{\mu} = \frac{Kg}{\vartheta} \quad (2.10)$$

Here K is named Permeability (or intrinsic permeability) of the porous medium, which depends only on the characteristics of the porous medium, such as pore size and distribution. Thus, by substituting K for K_c in Darcy's formula (2.8), we can get,

$$Q = -\frac{K\rho g \cdot A}{\mu} \cdot \frac{d(\frac{p}{\rho g} + z)}{dx} \quad (2.11)$$

For incompressible fluid ($\rho = \text{const}$) and horizontal flow ($\Delta z = 0$), Darcy's law can be transformed as,

$$Q = -\frac{KA}{\mu} \cdot \frac{dp}{dx} \quad \text{or} \quad u = -\frac{K}{\mu} \cdot \frac{dp}{dx} \quad (2.12)$$

Darcy's law in the form of equation (2.12) is widely applied to investigate the fluid transport phenomenon through a specific homogeneous porous medium. However, it is found that the linear relationship between the volume flow rate and the pressure gradient revealed by Darcy's law is only limited to laminar flow at low Reynolds numbers (1~10). Deviations will appear as Re increases beyond this range. [49] A detailed discussion of the application condition of Darcy's law can be found in [45].

Although Darcy's equation (2.12) is based on one-dimensional flow in a homogeneous porous medium, it can be extended to its tensor form for porous media with anisotropic characteristics, as presented in equation (2.1). The nine components of permeability (K_{ij}) in a 3D space or the four components in a 2D space can be written as,

$$\vec{K} = \begin{bmatrix} K_{xx} & K_{xy} & K_{xz} \\ K_{yx} & K_{yy} & K_{yz} \\ K_{zx} & K_{zy} & K_{zz} \end{bmatrix} \quad \text{or} \quad \vec{K} = \begin{bmatrix} K_{xx} & K_{xy} \\ K_{yx} & K_{yy} \end{bmatrix} \quad (2.13)$$

In composite manufacturing related with resin flow through a fibrous preform, the preform can usually be macro-scopically regarded as a porous medium with orthotropic

characteristics, thus the permeability tensor is symmetric ($K_{ij} = K_{ji}$, $i \neq j$). When the global coordinate system coincides with the principal directions of flow for the preform, the permeability in principal directions for 3D or 2D preform can be solved, as shown in equation (2.14) and (2.15) respectively,

$$\begin{pmatrix} u_x \\ u_y \\ u_z \end{pmatrix} = -\frac{1}{\mu} \begin{pmatrix} K_{xx} & 0 & 0 \\ 0 & K_{yy} & 0 \\ 0 & 0 & K_{zz} \end{pmatrix} \begin{pmatrix} \frac{\partial P}{\partial x} \\ \frac{\partial P}{\partial y} \\ \frac{\partial P}{\partial z} \end{pmatrix} \quad (2.14)$$

$$\begin{pmatrix} u_x \\ u_y \end{pmatrix} = -\frac{1}{\mu} \begin{pmatrix} K_{xx} & 0 \\ 0 & K_{yy} \end{pmatrix} \begin{pmatrix} \frac{\partial P}{\partial x} \\ \frac{\partial P}{\partial y} \end{pmatrix} \quad (2.15)$$

Then by coordinate transformation, the non-diagonal permeability values can be calculated. Hence, the permeability tensor for a preform can be determined experimentally based on Darcy's law. A number of studies have been made on this topic; this will be discussed in the following section.

2.3.2 Experimental determination of preform permeability

The experimental measurement of preform permeability is typically based on homogenisation of the internal dual-scale pore network [50] as a homogeneous porous medium. Measurement of permeability in the case of an isotropic porous medium is usually conducted based on steady or unsteady one dimensional flow through cylindrical-shaped samples.[51] As most of fibre reinforcement shows an anisotropic characteristic, a variety of measurement methods has been developed over the years. According to different classifications, these methods can be categorized as: unidirectional or radial flow (based on flow pattern), saturated or unsaturated (based on saturation state of fabric), and constant pressure or flow rate (based on injection condition).[52]

The typical tooling for unidirectional measurement of preform permeability is presented in Figure 2.11. The tooling is basically composed of top and bottom mould, and a frame between them which is used to control the compression state (or height) of the fabric. The reinforcement specimen with proper dimensions is placed in the closed mould, and test fluids such as engine oil or vegetable oil are injected from the inlet port under constant pressure or flow rate. Usually the top mould is made with transparent materials such as acrylic panels, such that the linear flow front at different time intervals can be

tracked with a video camera. For unsaturated linear injection, permeability value can be obtained from time integration of Darcy's law along the flow direction, of which the details can be found in [53-57]. For saturated linear injection, Darcy's law can be directly used to obtain permeability[58]

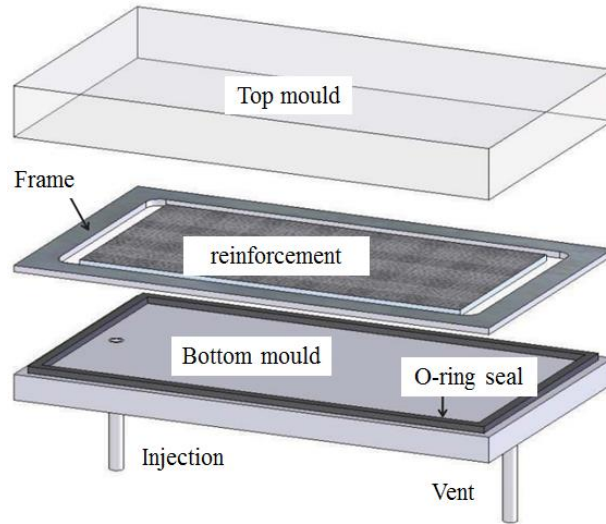


Figure 2.11 Schematic of unidirectional permeability measurement tooling[59]

For radial flow, the test fluid is injected from the centre of the mould and the flow front will show an elliptical shape when the preform is anisotropic [60]. A circular hole should be cut at the centre of the specimen to make sure the flow is in-plane. Injection under constant pressure will lead to unsaturated flow, which is governed by the Laplace-equation derived from combination of Darcy's law and the equation of continuity[61, 62]. Based on the analysis of section 2.3.1, the permeability tensor of anisotropic materials will be symmetric; when the global coordinates coincide with the principal axes of the preform, which are the major and minor axes of the elliptical flow front, the permeability tensor matrix becomes diagonal; thus the principal permeabilities can be measured directly. Some researchers strengthen the mould (bending stiffness) by using a steel frame [55] to overcome the mould deflection problems. Other researchers like Hoes[63] and Liu [64] applied electric sensors to monitor the position of the flow front, with the signals from sensors and transducers processed by a PC systems, allowing transparent toolings to be used. A typical flow pattern is presented in Figure 2.12. The detailed process to calculate the permeabilities can be referenced to the work of Weitzenböck et al [65, 66]. For saturated flow under constant flow rate injection, permeability can be derived by measuring the constant pressure gradient in different directions, thus Darcy's law can be applied.[67-69].

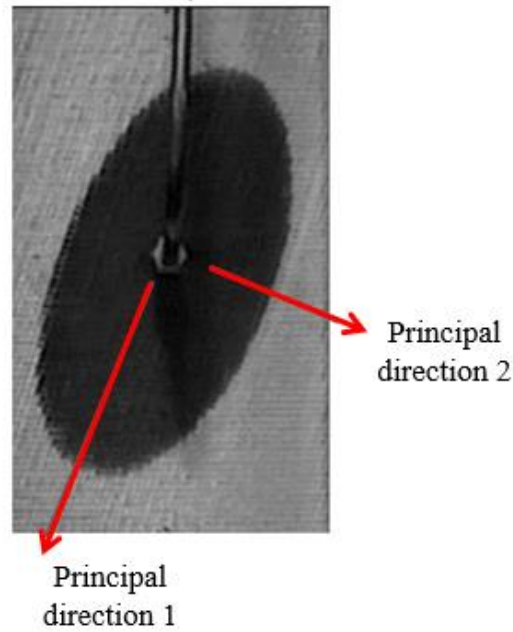


Figure 2.12 Typical flow pattern for radial injection method [38]

Until now, both of these permeability measurement techniques (radial and unidirectional) were being employed to obtain the in-plane permeability of fabrics, whilst there still exist some differences between them. The main advantages of the radial flow method are that both the principal in-plane permeability components and their orientations can be obtained in one measurement; also, the race-tracking effect [70] which can appear in the unidirectional flow test can be avoided. Some researchers [55-57] found that the unidirectional technique tends to show higher reproducibility. Note that differences may occur between saturated and unsaturated flow tests, as the unsaturated flow through the dry preform is affected by the capillary pressure within fibre tows; thus flow front velocity is a combined effect of external driving pressure and internal capillary pressure. As a result, the transient permeability is found to be dependent on the injection pressure [71].

RTM for which components can involve through-thickness flow, it is essential to obtain the transverse permeability in Resin Film Infusion and Vacuum-assisted Resin Transfer Moulding. Scholz[72] proposed a transverse permeability measurement apparatus (Figure 2.13) with alterable thickness mould cavity, avoiding the integration of sensors in the preforms and enabling the continuous measurements of permeability as a function of fibre volume fraction.

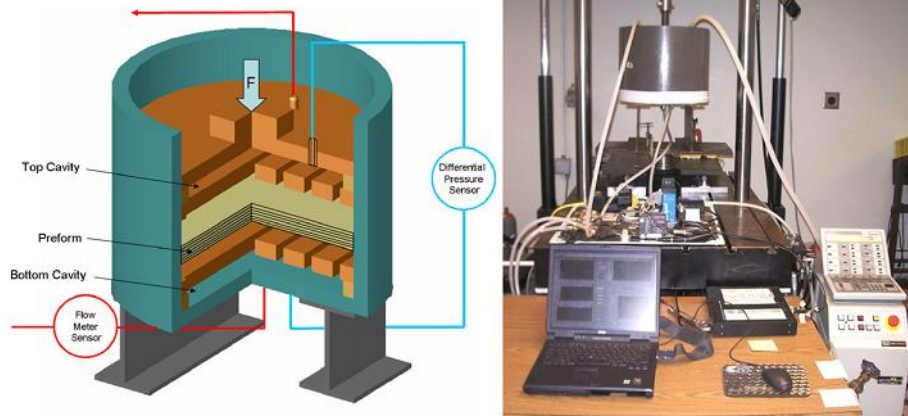


Figure 2.13 Design of the through-thickness permeability cell[72]

Although experimental methods for determining the preform permeability are the most reliable, there is no denying that it is time consuming and generates a lot of scatter. To obtain a credible permeability value, a series of tests is required. Besides, the experimental set-up needs to be carefully prepared and when the architecture of the preform used in LCM changes, it has to be reconstructed. Also the result is influenced by various factors such as human handling, edge effects and random errors etc. Meanwhile, the preforms used in RTM manufacturing process are variable and inhomogeneous. With this large variety, it is necessary to develop an easier way to determine the preform permeability. The need for permeability prediction of the preforms therefore arises.

2.3.3 Analytical prediction of permeability

As Darcy's law is an empirical relationship derived from a designed experiment of a Newtonian fluid flowing through a vertical column of porous medium in steady state, many researchers have attempted to derive Darcy's law from the fundamental theory of hydrodynamics.

One of the most widely accepted theories was proposed by Kozeny in 1927. The porous granular bed is assumed to be equivalent to a group of similar parallel channels with the same length. In his assumption, the total internal surface and volume of these channels are equal to the particle surface and pore-volume respectively. [73] Actually, this model is more like a capillary tube model as the velocity components normal to the channels are not considered. Kozeny's equation for permeability was obtained by solving the Navier-Stokes equations simultaneously for all of the channels, as shown in equation (2.16):

$$K = \frac{c_0 \phi^3}{M^2} \quad (2.16)$$

Here c_0 is called *Kozeny's constant*, which depends on the geometrical cross-section shape of the individual channels; ϕ is the porosity of porous medium; M denotes the specific surface of a porous medium, which is defined as the total interstitial surface area of the pores per unit volume of the porous medium [45]. When the specific surface is expressed in regard of unit volume of solid (M_s) instead of unit volume of porous media (M), the well-known Kozeny-Carman equation can be obtained as shown in equation (2.17):

$$K = \frac{c_0 n^3}{(1-\phi)^2 M_s^2} \quad (2.17)$$

From the conception of a hydraulic radius model, Carman suggested the coefficient c_0 should be 1/5, which agrees well with experiments but is different from Kozeny's assumption.[45] When applied to the porous media composed of fibres, the above equation can be transformed as equation (2.18) [74],

$$K = \frac{R^2 (1-V_f)^3}{4c_0 V_f^2} \quad (2.18)$$

Here R is fibre radius, V_f is the fibre volume fraction. Obviously the permeability derived from Kozeny-Carman equation will be isotropic, which is not suitable for a unidirectional reinforcement. Thus, modifications to this equation were proposed by some researchers, for example, Gutowski et al. [75, 76] proposed a heuristic model considering the anisotropic property of unidirectional reinforcement. However, the parameters for these modified models have to be determined by experiments, and their dependence on geometric features is not clear. Gebart [74] developed an analytical model for an idealized unidirectional reinforcement consisting of regularly ordered, parallel fibres, using Navier-Stokes equations both for flow along and perpendicular to the fibres. The equations (2.19) and (2.20) are obtained for quadratic and hexagonal fibre arrangements:

$$K_{\parallel} = \frac{8Rf^2 (1-V_f)^3}{c V_f^2} \quad (2.19)$$

$$K_{\perp} = C_1 \left(\sqrt{\frac{V_{fmax}}{V_f}} - 1 \right)^{5/2} R^2 \quad (2.20)$$

Here $K_{\parallel}$ and $K_{\perp}$ represent the permeability along and transverse with the fibre arrays respectively, V_{fmax} is the maximum fibre volume fraction related with fibre packing

arrangements, C_1 and c are curve-fitting values for different fibre packing types. However, it can be seen that these analytical models are only suitable for basic cases of uniformly distributed filaments and fibre yarns. For fabrics with dual scale porous porosity [77], these analytical predicting models are not well adapted. For this reason, more complex models were developed [78].

2.3.4 Numerical prediction of permeability

As there are various textiles used in RTM processes, it is unrealistic to obtain analytical models for permeability prediction for all arrays. Thus, numerical prediction of textile permeability has advantages if the geometry of various textiles can be modelled accurately. Textile deformation during composites manufacturing and the influence of nesting (for multi-layered fabrics) can also be taken into consideration when generating the models.

As mentioned in previous sections (Section 2.2.1, Figure 2.1), textile composites are hierarchical materials consisting of different structural levels. Accordingly, resin flow through the fabric also involves different flow characteristics regarding the various dimensional scales. However, due to the heavy computational load, it is not possible to consider all details of textile structures from fibre volume fraction distribution across the whole fabric to the filament arrangements with the fibre tows. Textile fabrics are usually composed of regularly arranged fibre yarns in a particular pattern. Thus, this repetitive pattern is commonly applied to analyse the resin flow characteristic instead of the whole fabric. This representative volume element (RVE) can also be called a **unit cell** [17], which represents the meso-scale dimension of fabrics. The routine of numerically predicting textile permeability for a unit cell is based on solving flow equations across the flow domain and back-calculating the permeability value with Darcy's law. Note that usually there is still dual-scale flow to be considered; including micro-flow (or capillary flow) within the fibre tow, and the channel flow between fibre tows.

As the flow characteristics of these two flow domains are different, usually different flow theories are applied. *Stokes flow* is assumed across the whole flow domain (including intra-tow flow within fibre yarns and inter-tow flow between fibre yarns) by some researchers, however, due to its heavy computational demand, this methodology is limited to textiles with simple internal structures.[79]

A plain weave textile was studied by Šimáček and Advani [80]. The two flow domains are processed respectively, with a boundary condition to match the two flows. Resin

flow through the porous fibre tow is assumed as Newtonian and governed by Darcy's law. A coupling of velocity and pressure was set at the interface between the tow and the fluid domain. It is assumed that the flow through the preform is a one-dimensional problem and this model is valid for saturated permeability only. However, this model has many simplifications which prohibited its usage, for example, Stokes flow was described using scalar expressions and Darcy flow in the preform was simplified by assuming the diagonal components are of the same order.

Phelan[81] investigated transverse flow in unidirectional fibrous media by using a finite element analysis (FEA) method. Periodic, rectangular arrays of cylinders with elliptical cross-section models were constructed. The Brinkman equation is used to model flow inside the tow and Stokes equation is used to model flow in the open media. As the Brinkman equation has the form of superposition of Darcy's law and the Stokes' equation, it is able to illustrate Darcy flow in the porous yarn region where velocity gradient is low, and as a result of the second order terms, it can also describe the boundary conditions (continuity of velocity and stress) at the fluid-porous interface. The author derived a semi-analytical lubrication solution for calculation of the overall permeability. The influence of intra-tow flow increases with the degree of resistance of flow geometry outside the tow.

Chen and Lin[82] constructed a unit cell plain weave model, using the Stokes equation to simulate the flow in the inter-tow region, and calculate the permeability by back substituting the generated velocity and pressure field into Darcy's law. The intra-tow permeability was defined by Gebart's equation and transformed to align with the global coordinate system. The global permeability of the unit cell was calculated by solving Darcy's law across the two-phase porous medium; the continuity equations at the interface between the two flow regions are satisfied. The influence of geometrical structure on the plain weave model was studied.

Ngo[83] introduced a 3D woven unit cell considering the flow in the intra-tow areas. The Brinkman equation was used to describe the intra-tow flow. The permeability of intra-tow flow was obtained from Gebart's equation, and was assumed to be transversely isotropic. A prescribed pressure gradient was imposed on the two boundaries in the flow direction to drive the flow in the unit cell. Then the effective permeability was computed through back substitution of Darcy's law. The modelling results were very close to the experimental results. The author attributes the discrepancy to the inaccuracy of the microstructure dimensions (overall unit cell dimensions and effective porosity values) and the assumption of hexagonal packing of filaments in the-

fibre bundles and the use of Gebart's equation. By using various values of pressure gradient and viscosity, the author also found that these different pressure/viscosity combinations have little influence on the predicted permeability (as low as 3%). This finding is in agreement with the theoretical belief that permeability is only a function of the unit cell structure and is independent of the pressure gradient and viscosity values.

Wong et al.[84] investigated the effect of textile structure on the predicted permeability. The textile model was generated by TexGen[85], which construct a model based on vectorial description of the structure and an assumed tow cross section. The author applied two numerical approaches including 'stream Surface' and 'Grid Average' methods to calculate the permeability. The results were compared with CFD calculations and showed a good agreement. It is worth noting that with TexGen, one can generate the required 2D or 3D model with complex structure efficiently. This will continue to be applied in the author's later work.

2.3.5 Influence of fibre tow interface on the numerical prediction of permeability

The permeability of the fabric unit cell is influenced by: 1) resin flow between the tows 2) flow in the tows and 3) the interaction between the micro and meso scale flow[86]. Typically, the flow in the meso-scale fibrous medium is modelled by Darcy's law. The permeability tensor K obtained from the law lumps the complex interaction between the fluid flow inside and outside the yarns. Generally, the intra-yarn area is treated as a homogeneous porous field, although practically the filaments within the yarn are usually arranged in a random distribution[87]. Gebart's equation[74] is commonly applied to obtain the intra-yarn permeability, which is then used as an input for the calculation of the meso-scale unit cell permeability.

Wang et al.[88] constructed a plain weave model and solved the flow field inside the whole porous domain in one step applying a continuous flow field (Fig. 2.12). The distinction of inter-yarn and intra-yarn domains is avoided, so this can provide an accurate permeability prediction. The commercial CFD code Fluent was used. A steady state laminar incompressible air flow was imposed, and the code used a finite volume method to cope with the continuity and conservation of momentum in the flow domain. It is indicated from the result that there is a relatively good agreement between the prediction of Gebart's equation and the full 3-D simulations (Figure 2.14).

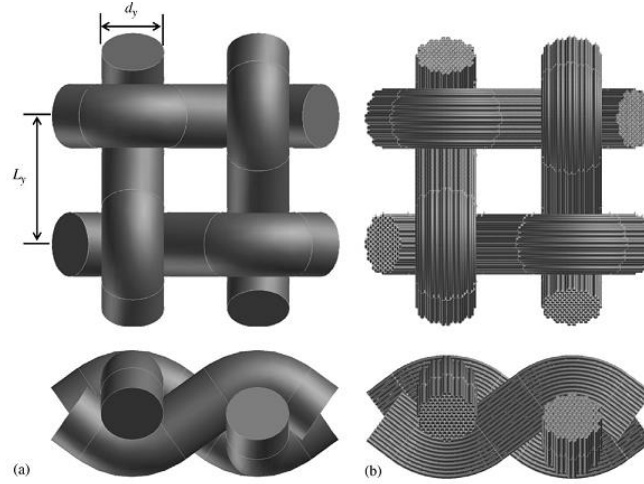


Figure 2.14 (a) Unit cell of a monofilament woven fabric. (b) unit cell of a multifilament woven fabric with 139 filaments packed in a hexagonal arrangement within yarns having the same diameter as the monofilament fabric[88]

Despite Wang's work for simulating simultaneously both intra- and inter-yarn areas by applying Stokes' equation and obtaining the overall permeability by back substituting the ratio of pressure gradient and flow flux into Darcy's law, most researchers treat the two domains(inter and intra tow) separately, by applying Stokes' equation on the inter tow area and Darcy's law on the intra tow area([80, 81, 89-92].

Papathanasiou [23, 90] investigated the influence of inter- and intra-bundle porosities on the effective transverse permeability of arrays of permeable fibre tows. By using the Boundary Element Method, Stokes' flow was solved across the unit cell. The flow at the fluid-porous interface was avoided. It is found that only a small proportion of resin flows through the bundle even when the tow porosity is as high as 50%, and a power law relationship between the effective transverse permeability of square or hexagonal arrays of permeable tows and impermeable tows was found. However, the tow model used was only designated certain amount of fibres with square or hexagonal packing configuration, so the flow field around the tow-fluid interface was not studied.

Nedanov and Advani[91] employed a homogenization method to formulate the governing equations and boundary conditions to predict the permeability of anisotropic fibrous porous media. A no-slip boundary condition was used at the tow surface. It was confirmed that the effect of tow permeability on the effective preform permeability was significant at high fibre volume fraction. This effect can be neglected when the tow permeability is two orders of magnitude less than the effective macro permeability. Obviously, for unit cell numerical prediction of permeability, when the intra-yarn flow and inter-yarn flow are treated separately, the fluid-porous interface coupling problem

is unavoidable at the surface of the yarn. Generally, there are two methods to deal with this problem. In one approach, Stokes flow and Darcy's law are applied in the inter-tow region and intra-tow regions respectively. The boundary condition on the fluid-porous interface is set by coupling the velocity[80] or setting continuity of pressure and zero tangential velocity[91]. The slip boundary condition proposed by Beavers and Joseph[93] was applied by several researchers[84, 94].

This coupling problem is avoided by applying the Brinkman equation in the intra-yarn domain, as the Brinkman equation is the same order as the Stokes equation, so there is automatic continuity of velocity and pressure on the interface. When applying the Brinkman equation, the stress across the interface is assumed to be continuous or there is a stress jump. On these two conditions, Tan and Pillai[95] used the finite element method to model the flow through the fluid and porous medium, and compared the continuity and jump condition. A 3D flow simulation in a unit cell was conducted. A volume averaged method was used to generate the average velocity profile from the point-wise solution of Stokes flow in the 2D region. It was found that, at high porosity, the Brinkman equation with stress jump condition results in accurate flow characteristics; while at low or medium porosity, there is little difference between the two results. The numerical permeability predicted from the stress jump condition was found to be in accordance with experimental results by simulating 3D flow through a fibrous medium, and for the low porosity of fibre tows (0.4742), the permeability obtained from the stress-jump and stress continuity condition are close to each other.

Despite all of the different methods studied, a key problem lies in the influence of the fluid-porous interface on the flow behaviour of the whole unit cell domain, as it has been proved that the intra-yarn flow rate often contributes little to the global flow rate of the unit cell even when the yarn porosity reaches 50%[23, 90].

2.3.6 Variation of textile permeability

As described above, permeability of preforms is affected by a large number of factors such as the architecture of the fabric, the porosity, and even the handling of the preform. The permeability of actual fabrics shows high variations, which is caused by a number of factors such as local changes in fibre orientations and superficial fabric density[96], nesting of multi-layers of fabrics[97] etc. The study of variability is very important to flow modelling for real preforms, as it has relevance with the void formation and defect distribution in the final composite, which can have a highly negative impact on mechanical properties. The sources of variation of permeability are discussed here.

Berdichevski[98] predicted the longitudinal and transverse permeability of an aligned fibre bundle by using a self-consistent method and finite element simulations. It was found from the numerical simulation results that, not only fibre volume fraction but also the fibre packing array have a significant influence on the permeability prediction. Small gaps in the transverse flow and open spaces in the longitudinal flow affect the resin flow resistance. Phelan[81] investigated the transverse flow in aligned fibre tows with rectangular shape. A semi-analytical lubrication method was used to analyse the influence of bundle shape and the intra yarn permeability on the global permeability. Results showed that the influence of the intra-tow permeability increase with the inter-tow packing and the increasing tow ellipticity.

Pan et al.[96] used finite element simulations to investigate the permeability variations of aligned fibre beds. Parallel and transverse flow was investigated respectively. In the numerical simulations, hexagonal and square stacking patterns were applied, with a certain section of fibres removed in some sort of pattern. So these designated packing arrays are considered to have barely distributed void in the yarn. The results show that the influence of openings on the permeability varies in different flow directions. In parallel flow, the openings offer a flow passage to the fluid; in transverse flow, the openings decrease the gap between fibres, resulting in high flow resistance. Random stacking for the fibres results in some locations which are more open and other regions which have a higher concentration of fibres.

As to the transverse permeability of regular ranges of porous cylinders, Ranganathan [22] developed a generalized model for this, and the author compared the model with rigorous finite element calculations using FIDAP (flow modelling software) for the case of cylinders with elliptical cross sections, and gained good agreement. He found that the shape of individual tows, the porosity of the tow, and the packing configuration of tows contribute greatly to the overall permeability. For solid tows, a no-slip wall boundary condition was set on the surface of ellipses; periodic BCs and symmetry BCs were set on the inlet/outlet and top/bottom of the unit cell respectively. It is found that the actual permeability changes greatly when altering the tow shape, although the qualitative relation of the permeability with the fibre volume fraction is unchanged. The overall permeability of the tow is largely affected by the shape of the tow cross section. The results show that with the increasing axis ratio of the ellipse for the hexagonal stacking configuration, the permeability is decreased significantly. The overall influence of tow permeability on the fluid flow is determined by the nominal fibre volume fraction. The influence of intra-tow flow increases with increasing nominal

fibre volume fraction. This is critical for the case when fibre bundles contact with each other, which is the condition in actual fibrous preform.

At the fibre bundle scale, Bechtold and Ye [99] characterized the random filament distribution. Micrographic analysis on the fibre bundle cross section was performed, and the observed degree of order in arrangement was described by the Morisita index. As to the effect of fibre distribution on the transverse permeability, it was indicated that with the increasing disorder of fibre arrangement, the permeability decreased as the minimum gaps between the filaments are reduced. The effective permeability of a randomly distributed fibre bundle depends on the regions with low fibre thickness. The axial permeability rises as the microstructure changes from a regular distribution to random distribution.

Regarding the non-uniformity at the fibre bundle scale, Endruweit[100] analysed the influence of local fibre volume fraction distribution on the global fibre bundle permeability. To obtain different compaction levels, the fibre bundle was formed at different mould cavity height. Bundle cross section geometry and local fibre distribution were characterised experimentally. The local permeability is illustrated as a function of local fibre volume fraction only. It is found that the local axial permeability decreases continuously with the increasing fibre volume fraction, but the transverse permeability decreases discontinuously. It is indicated that theoretical predictions for idealised arranged fibre filaments' axial permeability is underestimated, compared with realistic randomly distributed fibre bundles. The axial yarn permeability is not influenced by the shape of the cross section, where the transverse tow permeability changes with the tow aspect ratio.

At the unit cell scale, Endruweit and Long[101] investigated the variability in spacing between fibre bundles. The method is based on local variations of the normally distributed fibre angles. The permeability of the textiles is obtained from the determined fibre angles, and local porosity. The inaccuracies resulting from obtaining local permeability values from overall permeability distributions are avoided by calculating local permeability values from local textile properties. The authors used a Monte Carlo method to generate the local variations in textile permeability. The stochastically distributed fibre angles are attributed to the local discretised domain model for numerical injection simulation. According to the simulation result, the average values and standard deviation of times for fully filling of the mould improved with the increasing fibre angle variation. However the actual permeability variation is underestimated by the simulation.

Endruweit and Long[102] also investigated the variability of fibre spacing in bi-directional non-crimp fabrics (Figure 2.13), based on a spectral expansion implementing trigonometric functions with the random parameters of frequency and phase. From the functions describing the fibre tow distances, the distribution of local porosity was obtained considering fabric geometric characteristics and the author estimated the local permeability with a Kozeny-Carman approximation. Resin injection was simulated using PAM-RTM finite element code. It can be concluded that the geometric scale of fabric inhomogeneity increases with rising mean fibre tow distance. The mean permeability value and relative permeability variation are affected by ratio R_p/a_0 (R_p : semi-major axis of fibre tow cross section, a_0 : average of a) of in-plane fibre tow's dimensions and average distance (see Figure 2.15). The variations of permeability generally rise with decreasing R_p/a_0 . However, it is not suitable to compare different fabrics based on R_p/a_0 alone as the effect of fabric architecture on the permeability is also important.

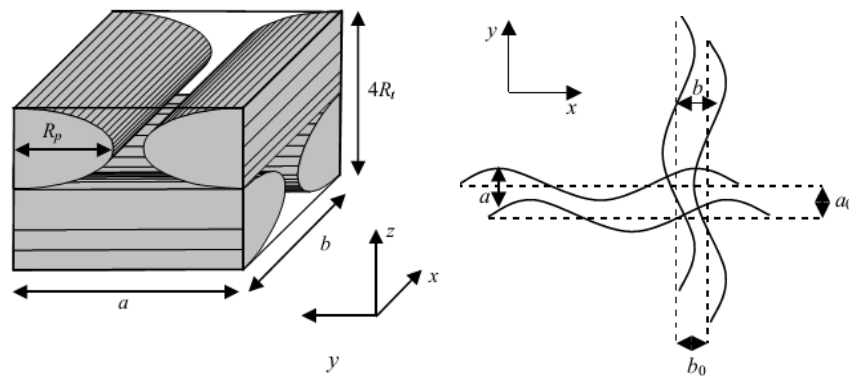


Figure 2.15 Unit cell of bi-directional non-crimp fabric (left) and distances between the axes of wavy fibre tows (right) [102]

To study the stochastic characteristics of textile permeability, Pan et al.[96] studied four major factors in permeability testing, including preform edge protection, fabric weight control, operator's skill level and complexity of mould shape. The author applied a unidirectional flow saturated permeability measurement technique on two types of E-glass fabrics. From the analysis results, it was found that the complexity of mould shapes and edge protections were the most influential factors for knitted fabric. For woven fabric, weight control, cavity complexity and edge protection were major factors. Operator skill was not a significant influential factor with the two types of fabrics. The permeability followed a normal distribution. The author suggested that the averaged permeability values can be used as a suitable measure to represent the inherent characteristics of the preforms.

Hoes[97] studied the nesting induced scatter of permeability values in layered fabrics. At least 20 measurements need to be conducted to get a within 10% of the expected population mean. By reducing the effect of handling conditions, random experimental error, and eliminating the influence of micro-scale flow and heterogeneity, it is found that the uncontrolled shifting and nesting of layers is the major reason for the resulting scatter in permeability measurements.

From the above literature, it can be concluded that there exists many sources of variability in the prediction and measurement of the permeability. Obviously, it is beneficial to the numerical or analytical determination of the textile permeability to consider all of the possible variability sources. In accordance with the hierarchical features of the reinforcement, permeability variability is studied at different length scales; micro scale variation related with the fibre arrangement within the fibre bundles and meso-scale variation related with the tow shape, spacing or angles between the fibre bundles in a typical unit cell. Furthermore, discrepancies resulting from the handling and deformation of textiles such as nesting and shearing during moulding should also be considered when determining the permeability of fabrics.

2.4 Review of defects generation

Undoubtedly, RTM benefits the composite manufacturing industry greatly considering near net shape, relatively fast cycle times with good surface conditions, and the potential for reduced cost for complex structures compared to prepreg processing. However, it is only effective when the composite part is completely wetted with minimal resin-free regions at macro- and micro scales, that is to say, the least percentage of void should be achieved.

The presence of void is considered highly detrimental to mechanical characteristics[103]. Void formed during RTM can be classified based on their dimensions as macro, meso, and micro void [104]. During RTM, mechanical entrapment is the major reason for void formation. According to their size and location, void defects can be classified into three groups: dry spots, void between tows and intra tows[104]. Dry spot void are produced when the mould is not fully filled due to various reasons such as the race tracking effect. The other two types of void result from the dual-scale structure of tow-based preforms, which have an impact on the flow behaviour at the meso-scale.

In the study carried out by Patel et al. [105], a unidirectional stitched fibre glass mat was investigated for the formation and elimination of void. The flow front varied

according to the liquid injection velocity. A ‘wick flow front’ can be found due to the presence of the ‘wicking effect’. The shape of the flow front is also related with liquid properties such as viscosity and surface tension. Basically, voids content can be reduced by injecting the mould at relatively high flow rates. However, micro-void within fibre tows can be found for this condition due to incomplete wetting of fibre tows. Thus, it was assumed that a critical flow rate for any specific injection fluid exists such that the total the void content can be minimized.

Generally, fibre preforms can be described as dual scale porous media, consisting of micro pores within the fibre bundles and macro pores between the bundles. As a consequence, the resin impregnation of the dry fabric includes two mechanisms, namely the filling of the macro pores and the infusion of micro-pores[40]. Accordingly, there are two forces that dominate the motion of the fluid: viscous and capillary forces [106]. In the macro pores (gaps) between the tows, the resin flow is viscous, and in the micro pores between the filaments capillary forces govern the flow motion. Macro void are observed when the injection flow rate is low for the reason that the viscous flow between the tows is delayed by the capillary wetting of the tows; micro void emerge at high flow rates when the gap between the tows dominate the filling processes, and the resin flow faster around the fibre bundles producing a partial impregnation of the bundles, or when transverse flow penetrates a tow (Figure 2.16).

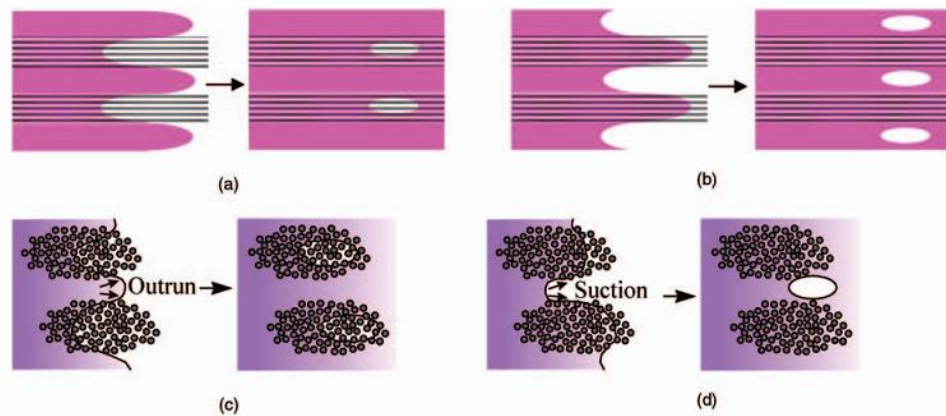


Figure 2.16 Mechanism of micro void formation: (a) void within tows (longitudinal flow) (b) void between tows (longitudinal flow) (c) void within tows (transverse flow) (d) void between tows (transverse flow) [104]

The Capillary number was proposed to measure the ratio of the viscous and capillary forces:

$$Ca = \frac{\mu v}{\gamma_{LV}} \quad (2.21)$$

μ is the liquid viscosity;

v is the superficial velocity of the liquid;

γ_{LV} is the surface tension of the liquid;

Wetting of fibre tows would continue after the flow front passed; or there is a lateral dispersion from wet areas to relatively dry areas. During this wetting process, the solid-air interface is replaced by the solid-liquid interface, and adhesion tension (A) is the critical factor of this process. Adhesion tension [25] is defined as:

$$A = \gamma_S - \gamma_{SL} = \gamma_{LV} \cdot \cos \theta \quad (2.22)$$

Where γ_S and γ_{SL} are solid surface tension and solid-liquid interfacial tension respectively. Thus, the wettability of solids by liquids can also be characterized by one essential parameter, namely the contact angle (θ). Accordingly, with contact angle included, the modified capillary number [25] was proposed as:

$$Ca^* = \frac{\mu v}{\gamma_{LV} \cos(\theta)} \quad (2.23)$$

Thus, void formation at the flow front (micro and meso) also depends on the flow competition between the two flow mechanisms [106]. Based on this assumption, a process window considering the modified capillary number [25] was developed to determine the voids contents and the potential optimal flow process [24], as shown in Figure 2.17.

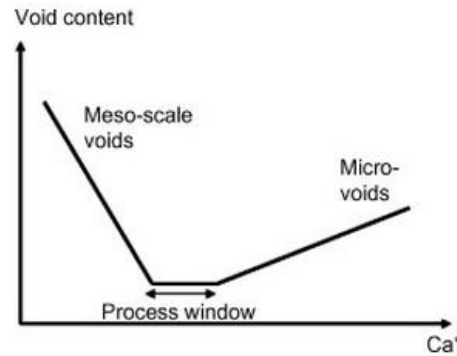


Figure 2.17 Void contents as function of Ca^* [106]

According to this dual-scale flow theory and the above defect formation mechanisms, Ruiz et al. [40] proposed an optimization methodology to minimize the void content during the manufacturing of composites parts by RTM. Based on the experimental measurement of void fraction against a number of flow velocities, both macro-void content and micro-void content were plotted as a function of capillary number. Thus, this modified capillary number is used to generate an empirical law for both the macro-void and micro-void as:

$$V_M = -A - B \log C_a^* \quad (2.24)$$

$$V_m = A' + B' \log C_a^* \quad (2.25)$$

V_M and V_m are macro and micro void fractions respectively; A and B are constants depending on the material. Thus, for the optimum capillary number at which the void contents can be minimized, the relevant optimum resin velocity can be determined. Based on the relationship between the volume averaged velocity and the injection pressure illustrated in Darcy's law, the injection conditions can be accordingly optimized. It should be noted that this optimization method assumes that the optimized capillary number is constant across the flow front for the whole composite part; however, due to internal geometric variabilities, the optimum capillary number would vary depending on location across the component.

2.5 Discussion

This chapter reviews the background and state of the art in analysis of the RTM process. As an advanced composite manufacturing method, RTM involves a number of influencing factors, including raw materials such as resin and preform, as well as manufacturing process parameters. With the introduction of numerical simulation methodology, the manufacture of composites with RTM can be designed to achieve the best quality with lowest defect content. Besides, material characterisation of the dry preform and a knowledge of resin flow characteristics during impregnation should be studied carefully beforehand, as it provides the fundamental basis for process modelling.

Of all the elements during RTM, permeability of the preform plays an essential role, as it affects the resin impregnation process, which is subsequently related with void formation. Experimental measurement of preform permeability is still the most reliable method; yet numerical prediction based on an assumed "unit cell" is investigated widely. In spite of the accurate description of geometric features by unit cell based on material characterisation, geometric variability across the whole preform induced by preform production and handling processes should also be taken into consideration. Another issue to be determined is the micro- and meso-scale flow characteristics within and between fibre bundles, and their interaction.

As well as the defects caused by macro-scale air entrapment, other defect generation mechanisms also arises. Due to the dual-scale porosity of the fibrous preform, resin flow within and between fibre tows are driven by viscous and capillary forces respectively. Defects could be formed when these two flows become uneven. A

modified capillary number is introduced to illustrate the relation between defect content and injection conditions.

3. Material characterisation and analysis

3.1 Introduction

Textiles are composed of arranged fibre tows interpolated with each other to form the internal structure of the dry fabric. Various internal structures would influence the flow channels within the fabric. With regard to flow process modelling, it is essential to obtain the accurate internal geometry of the dry fabric. Besides, two essential factors should be carefully considered: the ‘reasonable’ representation of real fabric by reconstructed unit cell models, and the application of a reliable modelling approach.

It was demonstrated by many researchers that the influence of internal geometry can be significant on the resulting simulation [84, 98, 107-109]. There are several ways to characterize the internal structure of woven materials, including optical microscopy and X-ray micro-CT [110]. Both can obtain the dimensional information related with the fabric. Optical microscopy consists of preparing the samples with a series of steps including grinding and polishing the specified cross sections. During this preparation process, sand paper of different grades will be used. The polished cross sections can be observed with optical microscopy. As the cross sections are dependent on the sample location, thus biased cross sectional images will be generated.

It should be noted that biased dimensions will be generated as only the geometrical dimensions of the observed location can be obtained. With this aspect being considered, X-ray micro-CT has become widely applied by various researchers as a non-destructive method[111, 112]. The tedious preparation work can be largely eliminated. The obtained data can be used to generate a 3D internal geometry of the specified material.

The permeability tensor needs to be characterized experimentally to validate the predictive model for this property. The measurement of a textile’s permeability, including in-plane and through-thickness permeability, has been addressed in chapter 2. In this present research, these permeability measurements are completed with techniques described in section 3.5.

Panels or components are moulded with the RTM process. The moulded part quality can be assessed by characterizing the contents and distribution of void or defects within the moulded panels. The defects characterization methodology is presented in section 3.6.

3.2 Preform information from SINOMA

The textiles studied in this research are 3D woven angle interlock glass fibre fabric or carbon fibre fabric. There are two batches of 3D woven fabrics, GF and CF, which represent glass fibre fabric and carbon fabric respectively. It should be noted that the superficial densities are different due to the different fibre density between carbon fibre and glass fibre. The basic material specifications are presented in Table 3.1.

Table 3.1 Material specification from supplier

Fabric name	GF	CF
Fibre type	E-glass	IM7-12K
Fibre size	80s/2×3 (75Tex)	-
Fabric configuration	2.5D angle interlock	2.5D angle interlock
Number of filaments in Warp yarn	-	12K
Number of filaments in Weft yarn	-	24K
Warp density (number of fibre/cm)	8.0	8.0
Weft density (number of fibre/cm)	2.6	2.5
Fabric thickness ¹ (mm)	4.2	4.1
Superficial density (g/cm ²)	0.571±0.004	0.407±0.005

1- Fabric thickness is measured manually with calliper.

3.3 Sample preparation

3.3.1 Moulded sample preparation

The resin used in this sample preparation is Prime20LV, one epoxy resin produced by Gurit company specially applied in a variety of resin infusion process such as RTM, SCRIMP. The Prime 20LV resin system can be applied in a series of curing processes with various curing speeds. This can be controlled by the selection of hardener. The ratio between resin and slow hardener is 100:26 by weight. The curing schedule includes pre-cured process in the mould at temperatures slightly above room temperature, and post-curing process at 7 hours at 65 degrees or 16 hours at 50 degrees.

In this study, the sample for micro-CT was prepared with Resin Transfer Moulding (RTM) (Figure 3.1). The resin (Prime 20LV mixed with hardener) was injected into a closed mould within which the dry fabric was placed. By controlling the mould cavity thickness, various fibre volume fractions can be achieved according to:

$$V_f = \frac{\rho_s}{\rho_g * H} \quad (3.1)$$

where

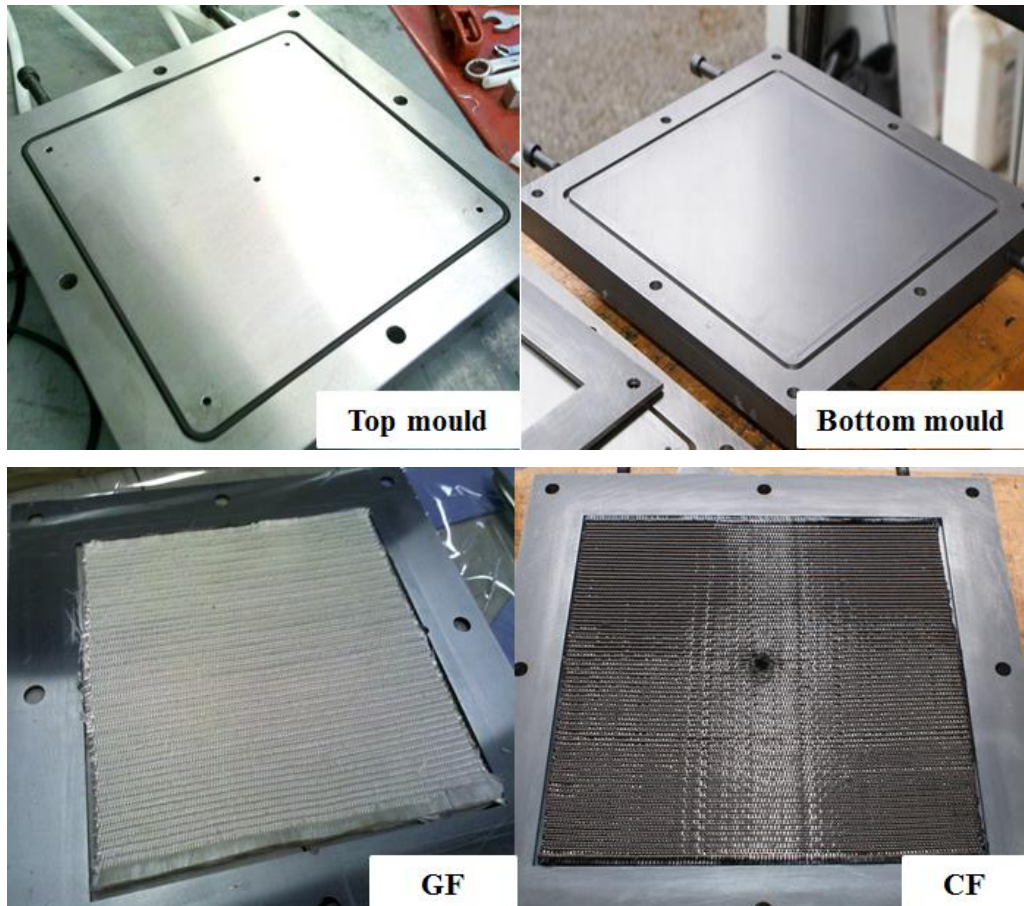
V_f is the fibre volume fraction of the moulded panel;

ρ_s is the areal density of the dry fabric;

ρ_g is the glass fibre density;

H is the mould cavity thickness.

The average areal density measured of dry glass fibre fabric provided by SINOMA was 0.571 ± 0.004 g/cm²; with the mould cavity thickness and glass fibre density being 3.7mm and 2.54g/cm³, respectively, the moulded panel V_f can reach around 61% (Table 3.2). It should be noted that V_f here means the averaged value across the whole moulded panel (300mm by 300mm); local V_f may vary as the fabric is inhomogeneous.



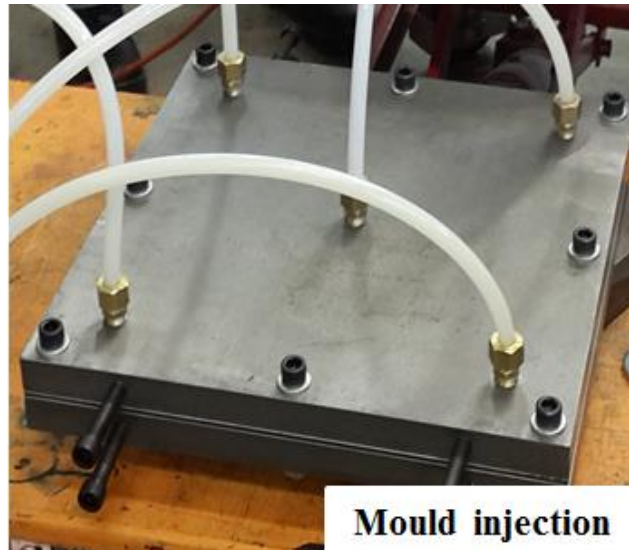


Figure 3.1 Tooling of RTM

The 3D woven dry glass fibre fabric or carbon fibre fabric is placed in the mould. Mould cavity thickness is determined by the height of picture frame between the top mould and bottom mould. Rubber seal is used to make sure airtightness. Epoxy resin mixed with slow hardener is degassed first and then injected into the vacuumed mould. The panel is pre-cured and post-cured to obtain the best mechanical strength. Note that all these above experiments are conducted within the lab in the author's research group. The technicians in the lab gave valuable instructions and support.

The specimen for micro-CT was prepared with a dimension of 22.7 x 12.8 x 3.7mm in warp, weft and through-thickness direction respectively. Thus, several unit cells can be included in the scanned result.

3.3.2 Micro-CT image acquisition

The internal structure of the moulded panel was characterized by X-Ray micro-Computed Tomography (μ -CT). The reliability of this characterization methodology has been proved in a number of studies [110, 113-115]. The 3D images as well as the internal yarn weave geometry can be reconstructed by processing and analysing a series of thin image slices through the entire sample. The image acquisition process by micro-CT is presented in Figure 3.2. A series of 2D image slices can be obtained by rotating the sample progressively through 360° with certain increments per step. The projected slices containing information of position and density of the scanned sample can then be used for volumetric reconstruction of the internal structure.

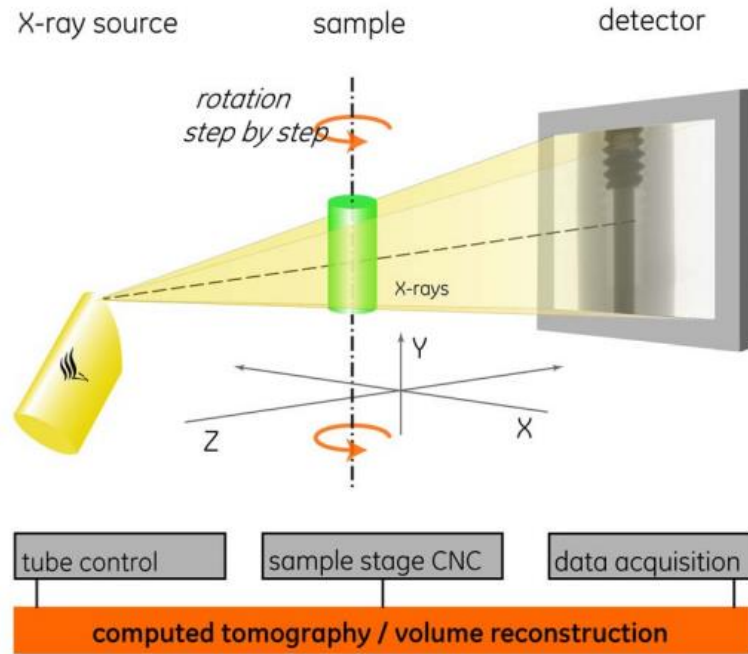


Figure 3.2 Function principle of cone beam computed tomography [116]

X-ray micro-CT for this study was conducted on the Phoenix V|TOME|X M 240 (GE Sensing & Inspection Technologies GmbH). The images were captured using X-rays of energy 100kV and with a current of 100 μ A. The entire sample data consisted of 1576 by 1412 by 540 slices in warp, weft and through-thickness directions, respectively. With this scanning method, a pixel resolution of 12 μ m can be obtained. Note that this work is supported by the office colleague Xuesen who helps send the prepared specimen to the micro-CT lab located in another campus. The scanning of these specimen are all operated by professional technicians and image data with very high quality is obtained.

3.3.3 Analysis of the internal geometry

The acquired data set was analysed with ImageJ[117], with which the 3D internal structure can be reconstructed. The internal geometry was characterized by measuring dimensions of the warp and weft yarns, as well as the spacing between the yarns on each image slice. Various image slices were selected from the data set. Fibre yarn cross sections can be characterized by fitting elliptical shape on the yarn cross sections. Note that there exists a certain level of inherent variability on the internal dimensions.

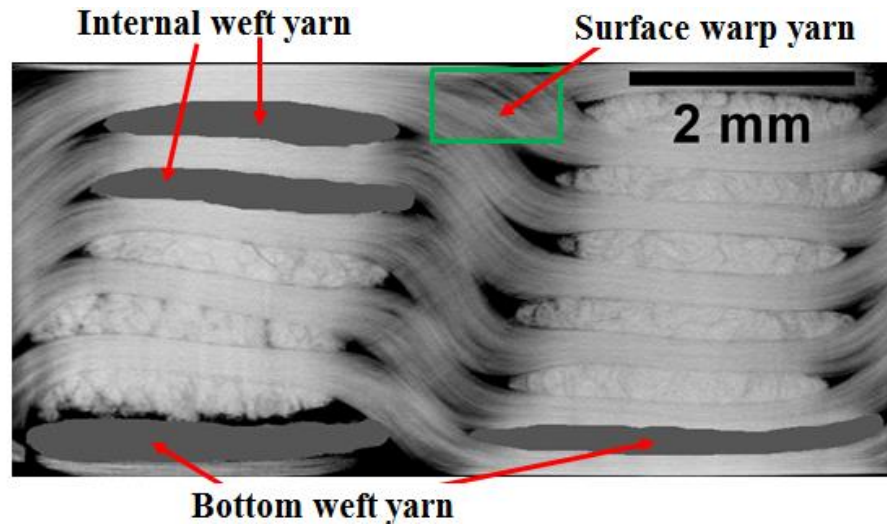


Figure 3.3 Micro-CT Image of cross section with GF

As shown in Figure 3.3, cross-sectional images of the 3D woven glass fibre fabric are presented. It can be observed that there are 6 layers of warp yarn and 6 layers of weft yarn in through thickness direction, with overlapping warp yarns on top surface. Note that the permeability will be influenced by these geometric deviations. Besides, due to the inherent weaving strategy, it can be observed that the weft yarns are highly stacked in 'column'. The 'column' of weft yarns exhibits a 'flattening' effect which makes its cross section deviate from an ideal elliptical shape. Accordingly, warp yarns are also influenced by this 'flattening' effect at cross-overs. Therefore, the shape of warp yarn cross section is changing along the warp direction. Besides, the bottom weft yarns also experience an 'elongation' effect caused by missing bottom bounding warp yarns around them as well as from contact with the mould inner surface.

Thus, the geometric characteristics illustrated above should be included in the determination of the internal geometry. In this work, ImageJ is used to process the dimensional information by fitting elliptical shapes over yarn cross sections. Note that the final results are obtained from averaging a number of measurements.

3.4 Analysis of geometric variability

The accurate characterization of internal geometry consists mainly of: fibre yarn cross section shape, which is affected by the compaction state of the preform; yarn path, which illustrates the weave pattern and relative positions of different fibre yarns; yarn spacing and surface yarn deviations. The analysis of internal geometry in the last section reveals the complexity in determining the internal geometry. To make it clear, this geometric variability will be discussed in detail in this section.

3.4.1 Micro-CT data processing

Theoretically, the exact internal weave structure can be regenerated from processing all of the slices along the yarn path (the interval between neighbouring slices equals the pixel resolution $12\mu\text{m}$ in this study). However, model generation shall not ‘copy’ the real fabric structure, but should contain the critical information. Specifically, the critical information related to the internal structure in this study is the weft yarn cross section centroid at the crossover locations, as not only weft yarn path and spacing can be described by these centroid loci, but also warp yarn information such as yarn height can be acquired indirectly. For this micro-CT sample, the weft yarn in the middle of the specimen is selected as the reference weft yarn; image slices will be stacked along this yarn. The stacked images are located at the crossover location between warp yarn and weft yarn. The stacking schematic is presented in Figure 3.4.

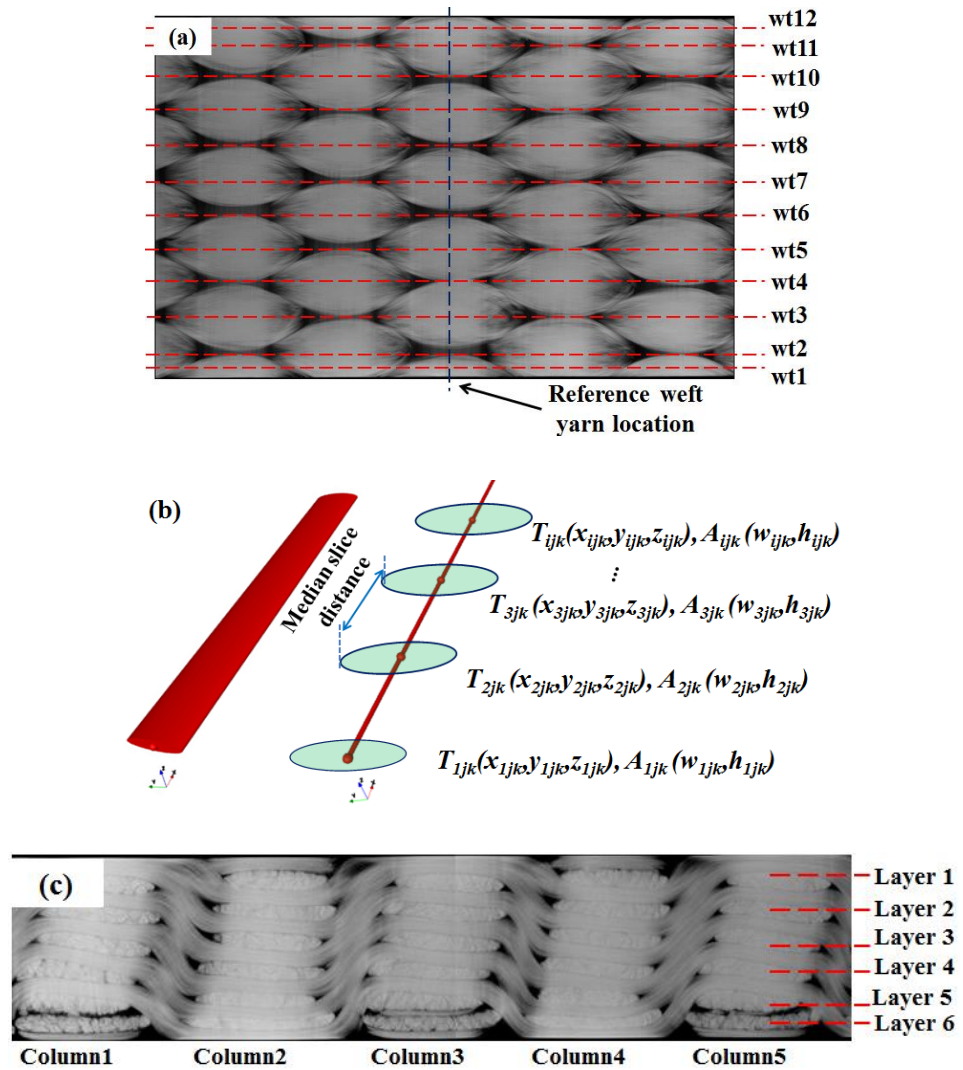


Figure 3.4 Slice stacking schematic

- (a) View from through-thickness direction; (b) View from warp and weft direction;
(c) Weft cross section recognition in one stacked image

In this way, 12 stacked images can be obtained (wt1~wt12) by grouping all the slices manually. For each stacked image, information including weft yarn cross section shape and area and centroid (which represents yarn loci) can be retrieved from fitting yarn cross sections. All these data are stored in the form of $T_{ijk}(x_{ijk}, y_{ijk}, z_{ijk})$, $A_{ijk}(w_{ijk}, h_{ijk})$, of which:

T_{ijk} refers to the specific weft yarn cross section;

i represents the specific stacked image number, ranging from 1 to 12;

j represents layer number, ranging from 1 to 6;

k represents ‘column’ number, or crossover number along the warp direction, ranging from 1 to 5;

x, y, z represents yarn cross section centroid coordinates in warp, weft and through-thickness direction respectively, note that actually, y is the median slice location in the weft direction, which is determined by the applied slices-stacking arrangement;

A represents the specific weft yarn cross sectional area;

w, h represents the major and minor lengths of the fitted elliptical sections;

Detailed stacking information is presented in Table 3.3. The different quantity of stacking slices (or distance between neighbouring median slices) indicates that warp width (or warp spacing) also varies at crossovers along the reference weft yarn. Without considering the median slice at two ends, the average median slice distance is 1.242 ± 0.022 mm, with around 1.8% deviation, which is less than the intervals of 3 slices. This will be investigated in later study. Nevertheless, the weft path loci along the weft direction are not influenced as it is determined by the credible median slice location. Note that the first and last stacked image wt1 and wt12 are omitted in the following variability analysis, as their ‘median slice’ location is not at crossovers.

Table 3.3 Slices stacking arrangement in weft direction

Stack Info	Start-ing slice	Endin g slice	Quantity of stacked slices	Median slice	Median slice* location (mm)	Distance between neighboring median slices (mm)
wt1	10	40	30	25	0.2	
wt2	40	186	146	113	0.90	-
wt3	186	350	164	268	2.14	1.24
wt4	350	490	140	420	3.36	1.22
wt5	490	665	175	577.5(578)	4.62	1.26
wt6	665	810	145	737.5(738)	5.9	1.28
wt7	810	980	170	895	7.16	1.26
wt8	980	1120	140	1050	8.4	1.24
wt9	1120	1290	170	1205	9.64	1.24
wt10	1290	1430	140	1360	10.88	1.24
wt11	1430	1590	160	1510	12.08	1.2
wt12	1590	1642	52	1616	12.93	-

*Median slice location in weft direction is calculated as the product of median slice number and slice intervals (8 μ m)

From the above image processing and measurement, a series of data can be acquired to characterize the internal woven structure of this angle-interlock 3D woven glass fibre fabric and analyse its geometric variability. This will be presented in the following section.

Note that the above work is supported by the office colleague Dr Xuesen Zeng who helps send the prepared specimen to the micro-CT lab located in the Hounsfield Facility at Sutton Bonnington campus, University of Nottingham. The scanning of these specimen are all operated by professional technicians and image data with very high quality is obtained.

3.4.2 Yarn cross section

Due to the variability of internal weaving structure, yarn cross sections are not constant. The cross sections can be characterized by fitting various curves such as lenticular, elliptical or power ellipse shapes. For this 3D woven glass fibre fabric, elliptical fitting are employed as the weft yarn cross sections can be best fitted. More than 100 weft yarn cross sections are selected at evenly distributed locations along the sample in weft direction. The final result (yarn width **w** ad yarn height **h**) is calculated by averaging all

these measurements with deviation values. Figure 3.5 presents one specific weft yarn cross section obtained from the image processing of micro-CT data.

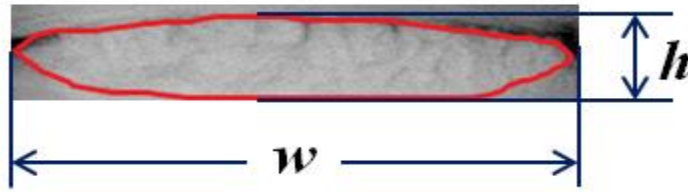


Figure 3.5 One example of weft yarn cross section

In spite of weft yarn cross sections, warp yarn cross sections present a different feature as shown in Figure 3.6: for the internal 4 warp yarns, it can be seen that warp height is changing regularly along warp yarn direction. Basically, the minimum warp height can be found at crossover locations, while the thickest part is at the ‘bridge’ locations between the adjacent two weft yarns. This characteristic is also explained in section 3.2.3. Note that in flow modelling based on unit cell, the internal flow channels will be narrowed down or widened accordingly with the changing of yarn cross sections. Therefore, the modelled permeability will also be influenced greatly.

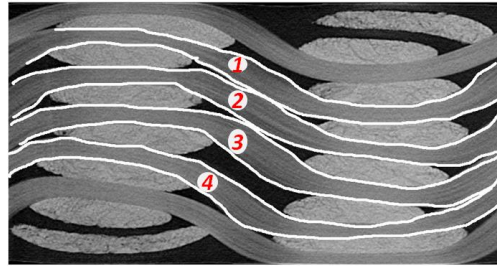
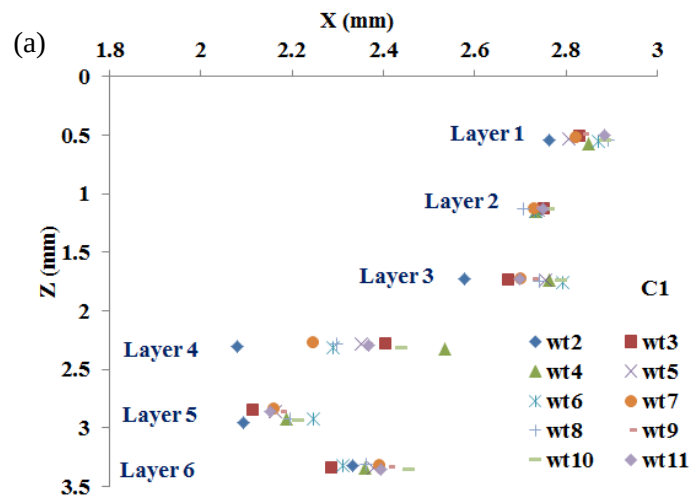


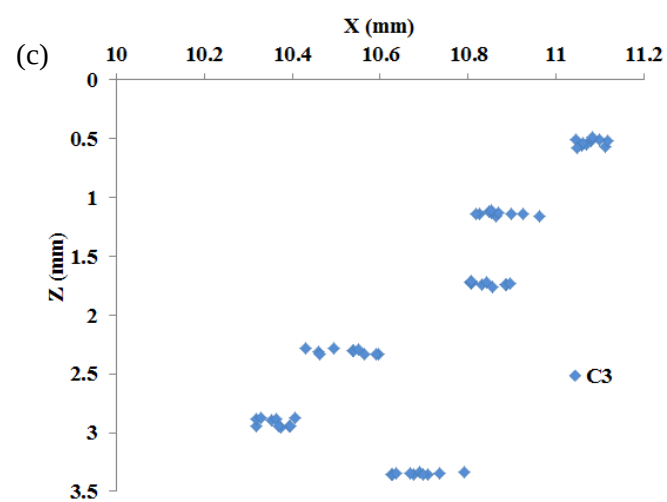
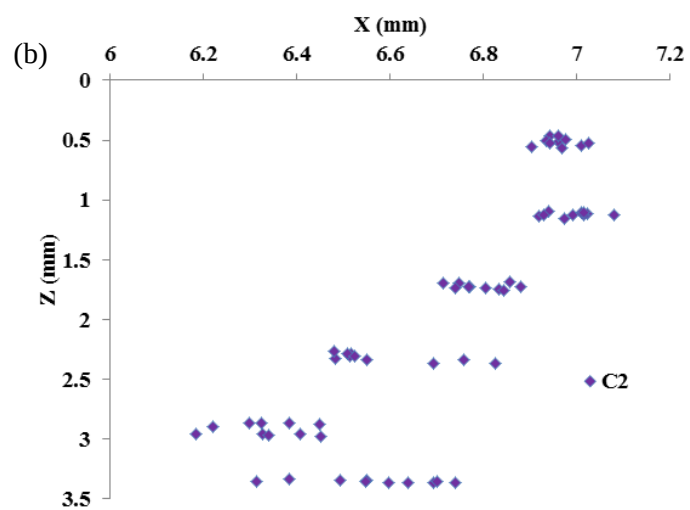
Figure 3.6 Warp yarn cross sections variabilities

3.4.3 Weft yarn shear deformation

The cross section centroids are re-positioned as shown in Figure 3.7 and their location distributions are plotted according to the centroids coordinates. Following the notation rules described in section 3.3.1, the axes x , z in Figure 3.7 represent the distance from the top left corner on each stacked image (wt2~wt11) in the warp direction and through thickness direction respectively (assuming a plane coordinate system is set on each image with the top left corner as the origin). Figure 3.7 (a) to (e) shows the piled weft centroids from a weft projection view displayed by ‘Column’ (C1~C5), with detailed information in (a). An obvious regular ‘shear’ deformation in the through-thickness direction is revealed from these inclined columns. Besides, a ‘shift’ phenomenon can be observed with each weft yarn represented by the 10 weft centroids in the weft direction, but with various shifting range on each layer.

From the intuitive characteristic, it is rational to hypothesize a linear fitting to illustrate this shear deformation. Due to the multi piled x variables within each column, multi linear regression analysis is applied for each column data. Figure 3.7 (f) presents the linear fitting results from Layer 1 to Layer 5 for each column. Layer 6 will be analysed separately as it shows a large deviation from the perceived linear fitting derived from the other 5 layers, yet still with regular location distribution between columns. Note that the slope coefficient is minus as z axis is in reverse order. Therefore, the shear deformation can be determined by the fitted linear slope.





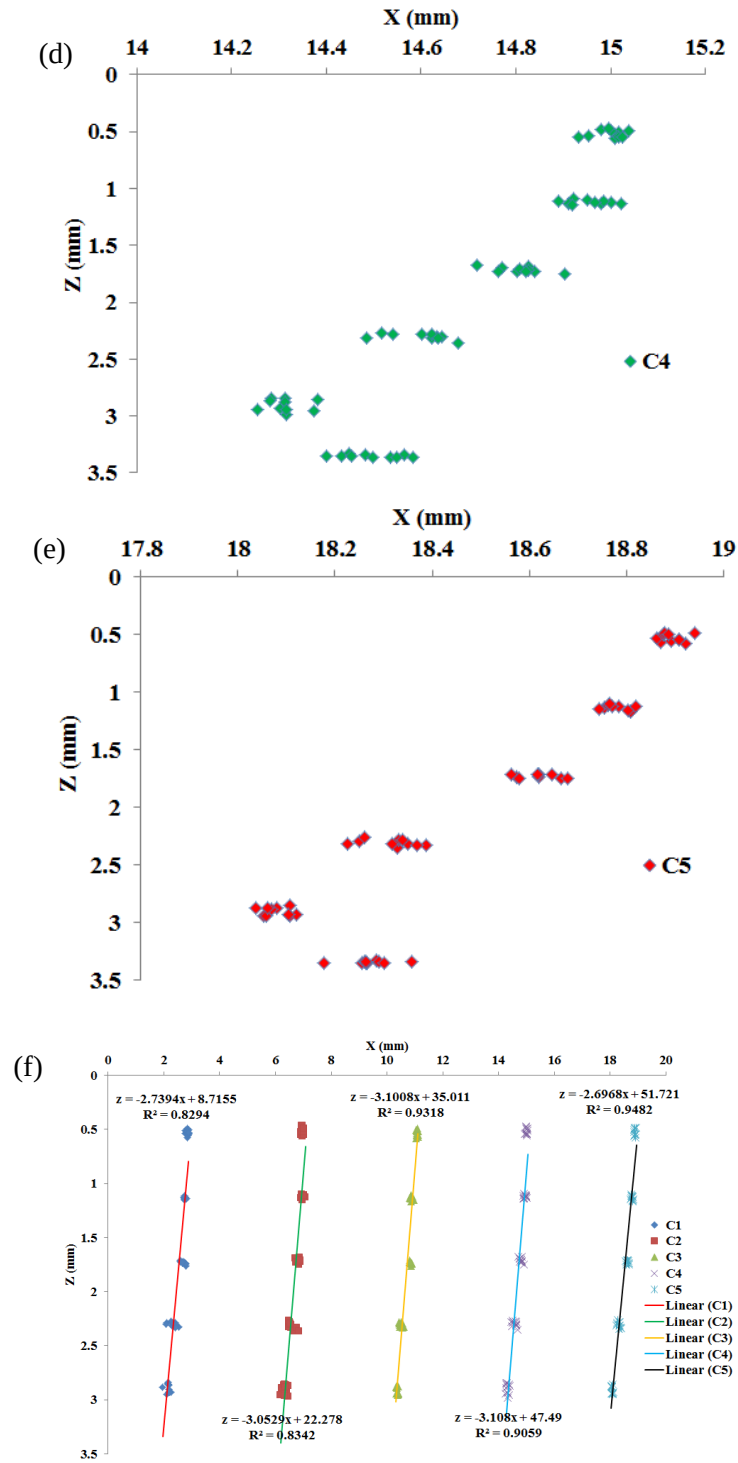
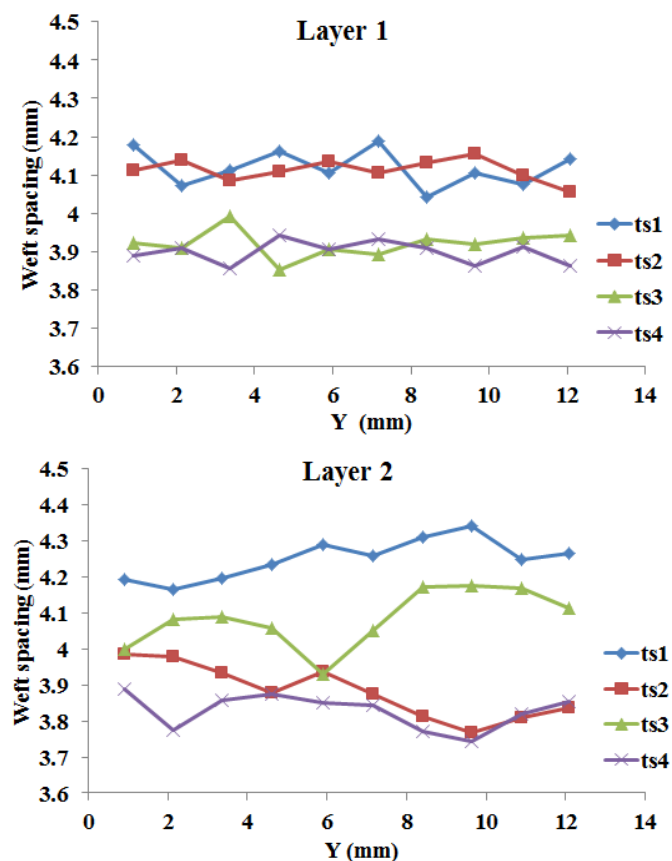


Figure 3.7 Shear deformations of weft yarn columns ((a), (b), (c), (d) and (e) present the piled weft centroids from the weft projection view in each column respectively (C1-C5); (f) presents the linear fitting for each column)

This ‘shear’ deformation in through-thickness direction may come from the manufacturing process or the later handling of this fabric. This feature should be reflected in our later permeability validation work as the architecture of unit cell model will be influenced.

3.4.4 Weft yarn spacing

Another geometric variability is related with weft yarn spacing. The ‘shifting’ effect of weft yarn cross section centroids in the warp (x) direction will inevitably impose a deviation on weft spacing. Figure 3.8 presents an overview along the weft spacing in different layers along weft direction (axis Y). The notation ‘*tsi*’ is used to refer to the four weft spacing values obtained in each stacked image. The specific weft spacing deviations along weft direction exhibit a stochastic characteristic, yet a general deviation from the nominal weft spacing (3.85mm displayed as the red dashed line) from the supplier can be found. Actually the mean spacing is around 4mm. Besides, a decreasing trend can be found among the four acquired values, generally with the maximum value for *ts1* and the minimum value for *ts4*. This may be caused by the instability of weaving process; moreover, an obvious ‘complementary’ effect can be revealed between the adjacent two weft spacing, which can be assumed as a certain ‘periodicity’ from the perspective of a unit cell.



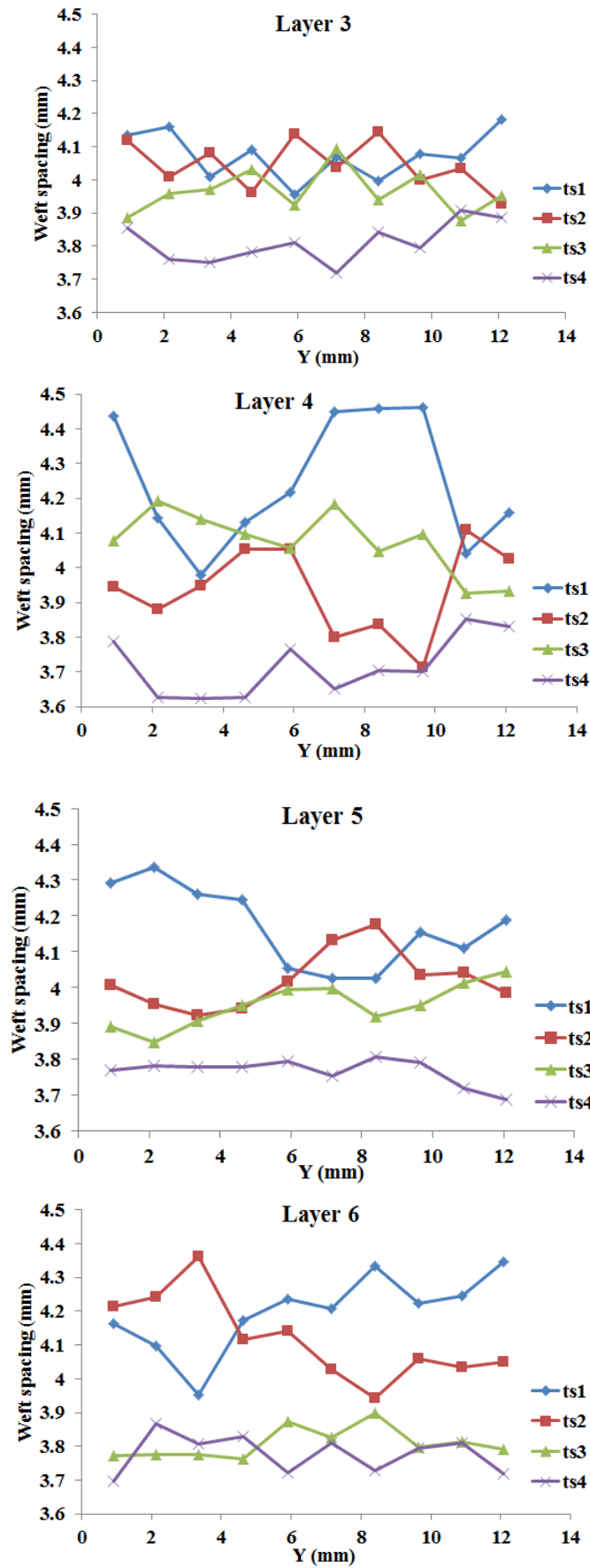


Figure 3.8 Weft spacing variability

3.4.5 Surface yarn deviation

Surface structure deviation should be analysed when modelling the fabric with full thickness. A unit cell is usually represented by the internal repeated pattern, which means the pattern is repeatable in warp, weft and through-thickness directions. However, for the real preform, there are limited layers in through-thickness direction. As is shown in Figure 3.9, different surface yarn arrangement can be found at the top and bottom surface respectively: overlapped surface warp yarn on the top surface but ‘suspended’ weft yarn at the bottom surface. This feature is introduced by the intrinsic weaving style as well as the same number of layers with warp and weft yarn. Besides, both external weft yarns and external warp yarns will present a “widening” effect due to the neighbouring yarn confinement. Thus, yarn height will be reduced due to its contact with the inner mould surface. Flow channels will be affected accordingly.

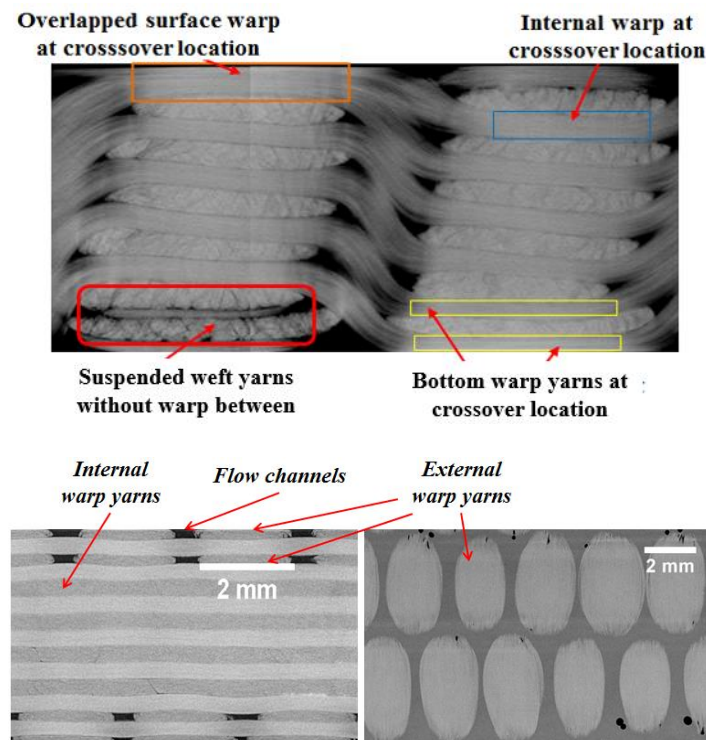


Figure 3.9 Structural deviation of surface yarn

3.4.6 Geometry characterization of carbon fabric

In addition to the glass fibre fabric illustrated in this research, 3D woven carbon fabric is also employed for later permeability modelling work in Chapter 5. Basically the same internal geometry characterization methodology is applied. Moulded specimen was prepared for micro-CT scanning. The internal dimensions were obtained by processing the acquired image slices. Section 5.3 in Chapter 5 depicts this process.

3.5 Experimental determination of permeability

3.5.1 In-plane permeability

For anisotropic materials, a radial flowing front for central injection has an elliptical shape, for which two in-plane principal permeability components and their orientation can be obtained in a single test. This methodology has been investigated widely in a number of studies [55, 65, 66, 118, 119]. For 3D woven glass fibre fabric used in the current research, radial injection with constant pressure was applied to determine the in-plane permeability tensors. Photographs of the experimental equipment for measuring in-plane permeability are shown in Figure 3.10.

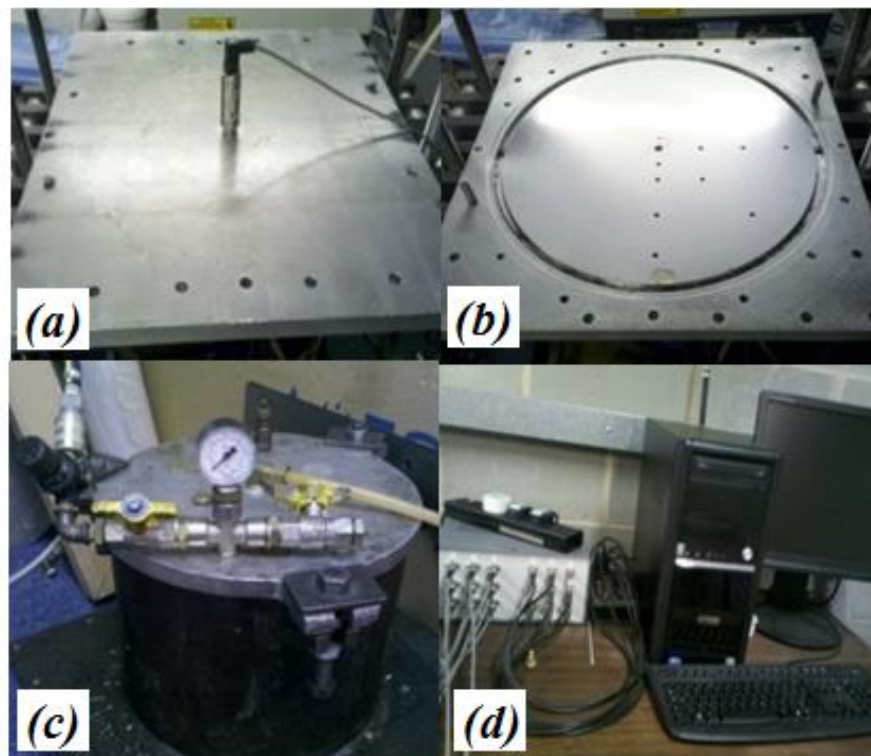


Figure 3.10 Experimental equipment for determining in-plane permeability via the radial flow method: (a) top mould (b) bottom mould (c) pressure pot (d) data acquisition and processing system

In the experiments, fabric is placed inside the mould tool, which is shown in Figure 3.10 (a) (upper part) and (b) (bottom part). A central injection method is applied; the upper mould is equipped with an injection gate positioned at the centre of the mould. On the bottom mould, equally-spaced pressure transducers are placed along 0° , 45° and 90° directions as can be seen in Figure 3.10 (b). The diameter of the circular mould cavity is 400 mm. Mineral oil is supplied into the mould by a pressure pot shown in Figure 3.10 (c). Data acquisition and processing equipment, with which the two principal

permeability components and their orientations are determined, is shown in Figure 3.10 (d). In this research, permeability is measured for three V_f will be measured. This can be realized by using spacers to achieve different cavity thicknesses.

The injection fluid is engine oil (5W-20). The viscosity of the oil was measured prior to injection at test temperature using a Brookfield viscometer. Flow front propagation along three co-planar axes was determined by monitoring the readings from the array of pressure transducers (shown in Figure 3.11):

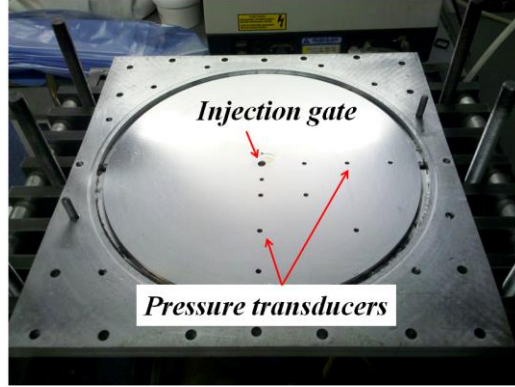


Figure 3.11 Pressure transducers

The data capture and processing is performed via National Instruments LabVIEW™ software. No post processing of the measured raw data is required, as the orientations of the principal permeability axes and the principal permeability values are calculated automatically by the software. The in-plane permeability values of the fabric, K1 and K2, were determined in unsaturated radial flow experiments at constant injection pressure, based on measurement of the flow front ellipse as a function of time.

For this type of experiment, the permeability of an anisotropic material in an equivalent isotropic system of elliptical co-ordinates is:

$$k_e = \frac{\Phi \eta R_{01}^2}{4 \Delta p t} \left(\left(\frac{R_1}{R_0} \right)^2 \left(2 \ln \left(\frac{R_1}{R_0} \right) - 1 \right) + 1 \right) \quad (3.2)$$

Here,

R_1 is the semi-major axis of the flow front ellipse,

R_0 is the radius of the circular injection gate,

Δp is the gauge pressure at the injection gate,

t the time for the flow front to reach R_1 ,

Φ the porosity of the fabric lay-up,

η the viscosity of the injected fluid.

The equivalent injection gate dimension R_{01} in direction of R_1 in elliptical co-ordinates is

$$R_{01} = \sqrt{\frac{R_2}{R_1}} R_0 \quad (3.3)$$

where R_2 denotes the semi-minor axis of the flow front ellipse. With $R_1(t)$ and $R_2(t)$ determined experimentally, the principal permeability values K_1 and K_2 are calculated from

$$K_1 = k_e \frac{R_1}{R_2} \quad \text{and} \quad K_2 = k_e \frac{R_2}{R_1} \quad (3.4)$$

The method described by these equations can be modified to determine the principal permeability values and the orientation of the principal permeability axes regardless of the relative orientation of the principal axes with respect to the measurement direction.

3.5.2 Through-thickness permeability measurement

The tool for determining the through-thickness permeability consists of a stiff cylindrical flow channel with a liquid inlet at the bottom, and a liquid outlet on top, as shown in Figure 3.12. The inner diameter of the flow channel is 80 mm. The specimens are held in position by perforated plates, which allow a parallel flow perpendicular to the fabric plane.

The distance between the perforated plates is given by the height h of spacer rings. Fibre volume fraction of the fabric is varied by using spacers of different heights. As for the in-plane experiments, each specimen was weighed before the test to determine the superficial density and hence fibre volume fraction. The flow rate, Q , was set on a gear pump and monitored using an ultrasonic flow meter. Pressure transducers are mounted on both sides of the fabric specimen for measurement of the pressure drop, Δp . The same test fluid as for characterisation of in-plane permeability was used.

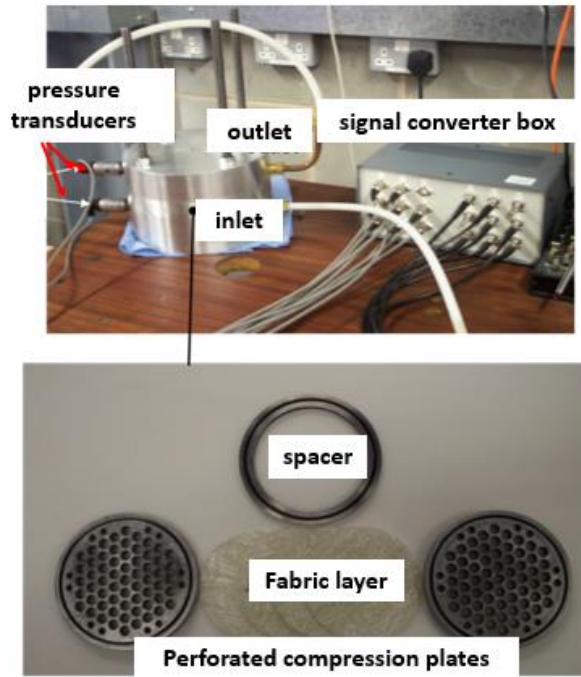


Figure 3.12 Configuration of the K_3 measurement tooling

The through-thickness permeability of the fabric was determined in saturated uni-directional flow experiments at constant volume flow rate, Q . Measurement of the pressure drop, Δp , across the specimen allows to calculate through- thickness permeability, K_3 , according to

$$K_3 = - \frac{Q \eta h}{\Delta p A} \quad (3.5)$$

where h is the thickness of the specimen, A the cross-sectional area of the cylindrical flow channel, and η the viscosity of the test fluid.

The data capture and processing is controlled via a National Instruments LabVIEW™ program. The permeability is calculated from the acquired pressure data when the measurement is stopped. Before the measurement can be started, it is ensured that the textile is completely wetted and no air is entrapped in the cavity. To achieve this, a pre-experiment is run until the appropriate pressure values become stable.

Note that the above permeability testing experiments are all undertaken in the Composites Research Group at the University of Nottingham. Thanks to the advanced testing systems and experienced technicians for these tedious labour-intensive testing work.

3.5.3 Permeability measurement results

3.5.3.1 Glass fibre fabric

With the radial injection tooling as described in Section 3.5.1, permeability measurements for fabrics in this research were carried out. The glass fibre fabric with three different V_f (53%, 59%, 64%) were tested with four repeats for each value. The measured permeability values in warp in weft weave directions are shown in Figure 3.13.

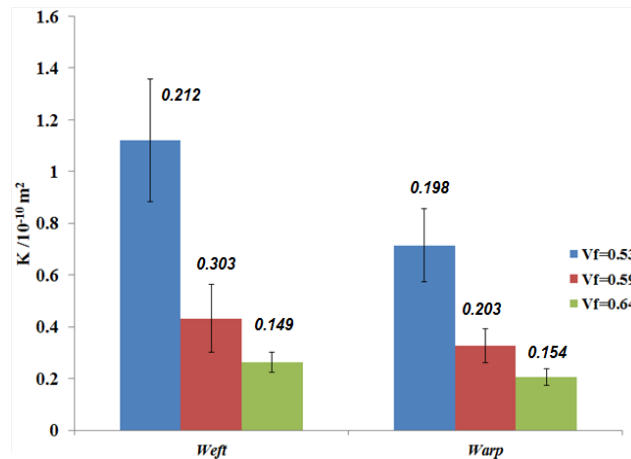


Figure 3.13 Comparison of K measurements under three V_f

It can be observed that there exists scatter in the measured results, with the coefficient of variation being around 20%. This may be caused by the heterogeneous characteristic of the fabric itself, such as the V_f not being constant across the fabric, and deformation introduced when handling the fabric, which may influence its internal structure. Generally, measured K decreases with increasing V_f , and the ratio between the two principal permeabilities becomes lower, as shown in Figure 3.14. This indicates that the fabric becomes more like an isotropic porous medium under high compression.

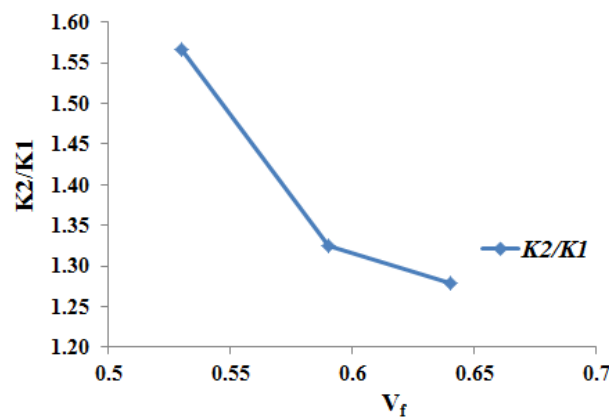


Figure 3.14 Ratio between the two principal permeability components

(K1 and K2 represent measured permeability in warp and weft direction respectively)

3.5.3.2 Carbon fibre fabric

Permeability of this 3D woven carbon fibre fabric under three fibre volume fractions (59%, 53% and 50%) was tested. For each value, four repeats were undertaken to obtain an averaged result.

The testing results are presented in Figure 3.15; the percentage value near each error bar represents the coefficient of variation for each measurement. From the measurement results, the tested permeability again has a coefficient of variation of up to 23%, higher for measurements at low fibre volume fractions. For measurements at high fibre volume fraction (59%), the measured permeability presents a low level of scatter.

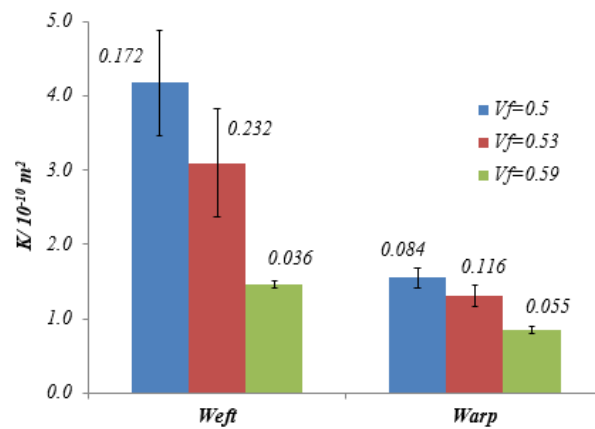


Figure 3.15 In-plane permeability measurements for 3D carbon fibre fabric under three compression states

Again the permeability ratio between weft and warp directions decreases with the increasing fibre volume fraction (Figure 3.16).

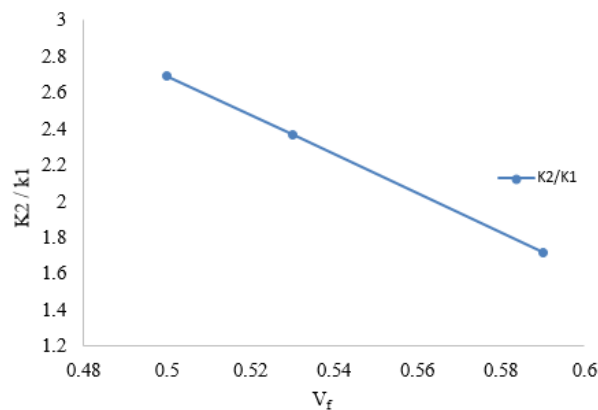


Figure 3.16 Ratio of principal permeabilities in warp (K1) and weft (K2) direction

3.6 Summary

This chapter illustrates the basic information of the preform used in this study, including material characterisation methodology for this preform. X-ray micro-CT technology and image processing methodology was applied to characterize the internal geometry of the preform. Thus, the influence of geometric variability on the prediction of preform's permeability based on unit cell can be studied later. Besides, experimental determination of preform's permeability was carried out. Also, defects generation mechanism with RTM was discussed.

In this chapter, geometric variability with yarn cross section, weft yarn shear, yarn spacing, as well as surface yarn deviation are investigated. An image processing methodology is applied to obtain the various dimensions caused by these variability. This processed results can be used in Chapter 5. Furthermore, permeability measurement method applied in this research, including in-plane and through-thickness permeability tests, are introduced.

Note that in this Chapter material characterisation method and process are illustrated with 3D woven glass fibre fabric. As the 3D woven carbon fibre fabric has the same internal structure, its geometrical characterisation process is not included in this section. Besides, the geometrical dimensions data can be found in Chapter 5.

4. Modelling of tow interface boundary conditions

4.1 Introduction

As is reviewed in section 2.2.1, the fibrous preform is a hierarchical material, consisting of three different scales: micro scale, which is related with numbers of fibre filaments arranged randomly within a fibre yarn; meso-scale, which is related with the interlacing between fibre yarns in designed orientations; and the macro scale, from which the preform can be regarded as a porous medium.

In manufacturing processes for composite components such as RTM, the resin impregnation process through this fibrous preform can be regarded as a fluid flowing through a porous medium under a certain injection pressure or flow rate. According to Darcy's law, permeability is one of the essential material properties that affects this flowing progress. As discussed in section 2.3, numerical prediction of textiles' permeability based on the meso-scale unit cell is intensively investigated at present. Due to the intrinsic internal structure of a woven fabric, the modelling of resin flow through a unit cell also consists of two length-scales: flow in the channels formed between interlaced fibre yarns, and flow through the fibre yarns.

4.2 Interface problem

The 3D woven fabric can be regarded as a dual scale structure, namely the intra-tow region and inter-tow region. Accordingly, there exist two types of pores inside the woven fabric: micro-pores inside a fibre tow and macro-pores between fibre tows. The resin flow process within the two different regions will accordingly show different characteristics. It was found that the channel flow between the fibre yarns has a strong effect on the overall permeability of the unit cell. Based on this multiscale feature of fabric, resin flow through the fabric also can be divided into two flow regimes: inter-yarn flow through the channels between fibre yarns, and intra-yarn flow through the porous fibre yarn (formed by numbers of filaments).

The computation of the permeability on meso-scale should consist of both the flow flux across the channel and the porous fibre yarn. However, as there is at least one order of magnitude difference between fibre and yarn dimensions, it is not possible to capture all the geometric features across the two scales due to the required computational resources. To simplify the problem and reduce the potentially heavy computation load, the intra-yarn flow and inter-yarn flow are always solved with various equations. Generally the flow between fibre yarns are described by Stokes equation (equation 4.1),

as the resin is in a creeping flow regime ($Re \ll 1$); the flow through the fibre yarn is solved with Darcy's equation (equation 4.2), where the fibre yarn is assumed as a homogeneous porous medium.

$$-\nabla P + \mu \nabla^2 v = 0 \quad (4.1)$$

$$\nabla \left(\frac{K}{\mu} \nabla P \right) = 0 \quad (4.2)$$

The difficulty lies in how to couple these conservation equations in both the channel and porous medium regions on the fluid-porous interface, as the Stokes equation has a shear term while Darcy's equation does not.

One method to solve this coupling problem is applying Brinkman's equation (equation 4.3) within the intra-yarn flow region, as this equation is a combination of Stokes equation and Darcy's law, thus, the continuity of velocity and stress at the fluid-porous interface can be satisfied.

$$\nabla \langle P \rangle = \mu \nabla^2 \langle u \rangle - \mu K^{-1} \cdot \langle u \rangle \quad (4.3)$$

Note that the velocity and pressure are volume averaged properties within the Brinkman equation. However, this boundary condition cannot be realized conveniently within the current flow modelling software Ansys CFX.

Another method to illustrate the transition of fluid on the interface is the boundary condition proposed by Beavers and Joseph in 1967 [93]. The tangential component of the flow velocity at the fluid-porous interface was investigated by assuming a parallel channel flow adjacent with a permeable porous wall, as shown in Figure 4.1.

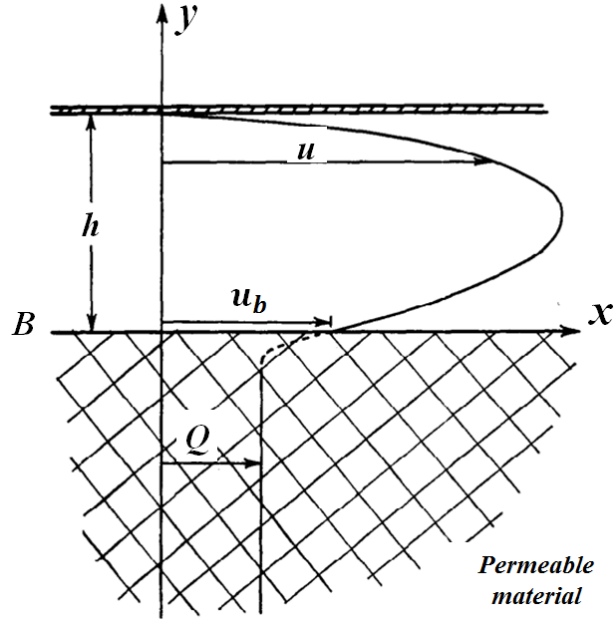


Figure 4.1 Velocity profile near the fluid-porous interface [93]

The flow through the channel and the permeable material was supposed to be driven by a uniform pressure gradient in the longitudinal direction. Fluid flow within the porous medium was assumed to be governed by Darcy's law. The authors postulate a slip velocity u_b at the permeable boundary that is greater than the Darcy's filter velocity within the porous medium. Furthermore, the slip velocity at the boundary was assumed to be proportional to the shear rate of the fluid at the permeable boundary. Thus, the Beavers and Joseph boundary conditions was obtained, as presented in equation 4.4.

$$\frac{du}{dy} = \frac{\alpha}{\sqrt{k}}(u_b - Q) \quad (4.4)$$

Note that α is a dimensionless coefficient which depends on the material properties such as the structure of the porous material. Experiments were designed to obtain this slip coefficient for various porous materials, of which the values can be ranged from 0.1 to 4 for different porous medium.

4.3 Slip boundary condition on fibre yarn with regularly arranged filaments

According to the above investigations, it can be seen that at meso-scale, the permeability is affected by three categories: flow within fibre yarn, flow between fibre yarns, and the influence of intra-tow flow on the inter-tow flow.

It has been observed that the flow within the fibre yarn contributes little to the overall flow rate across the unit cell, even when the porosity within fibre yarn reach is as high

as 50%. [90] Thus, the porous fibre yarn can be modelled as an impermeable solid entity during the meso-scale permeability modelling process. Therefore, it can be assumed that the influence of intra-yarn porosity on the overall flow flux is only dependent on the influence of fibre yarn boundary conditions.

Although the slip boundary condition at the fluid-porous interface put forward by Beavers and Joseph [93] is based on experimental observations and theoretical analysis, due to the development of flow modelling methods, this slip condition at the yarn surface can be investigated numerically. To obtain the slip velocity (coefficient) at the boundary of a fibre yarn, Stokes flow equations are solved in a micro-scale unit cell, as presented in Figure 4.2.

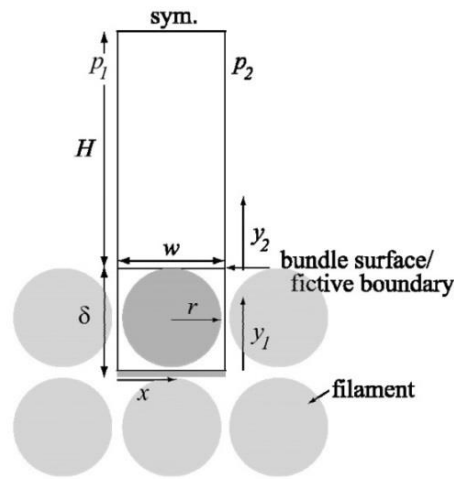


Figure 4.2 Micro-scale unit cell by Grouve and Akkerman[86]

Grouve and Akkerman[86] solved the two-dimensional Stokes equation in a micro-scale domain to obtain a slip boundary condition for flow transverse to a fibre yarn. Then the boundary condition can be implemented on the inter-bundle flow model, so that there is no need to solve intra-bundle flow with the Brinkman equation. It gives a good representation of the actual velocity field by applying the slip velocity at the interface. The discrepancy of volume flux between the numerical solution and the result based on the slip coefficient is less than 0.2%. It is also found that the no-slip boundary condition can be used when the fabric is loose (ie. yarn spacing is large).

Admittedly, this investigation by Grouve provides a practical way to determine the slip co-efficient at the meso-scale when there is flow through the porous fibre bundles. However, the prescribed micro-model is based on an idealised distributed fibre array in the bundles. In reality the random fibre arrangement in the bundle observed for real materials may produce different results. It is reasonable to suppose that a non-uniform

distribution of filaments at the bundle surface would also affect the fluid-porous interface.

There are some studies which concentrated on the axial flow within fibre tow by some researchers. For example, two-dimensional Stokes equations were used to model the axial flow through unidirectional fibre array by Chen and Papathanasiou [27]. The relations between the fibre tow permeability and fibre distribution was studied. Shou and Ye [120] investigated longitudinal permeability of squared packed filaments theoretically. Jump velocity is considered at the interface between fibre tow and channel flows. It was found that the filaments clusters in tows shows higher permeability than uniformly distributed fibres. However, there are no previous study on the effect of axial flow within fibre tow on the channel flow between fibre tows when fibre filaments have a random distribution.

4.4 Tow interface analysis with random filament arrangement

4.4.1 Random model generation

The model of randomly distributed fibres is generated using the nearest neighbour method (NNA) implemented in MATLAB. Note that the distribution of filaments within this model is characterised experimentally on carbon fibre bundle cross-sections [121]. The model was first generated within a larger bounding box (Figure 4.3a) to reach the estimated fibre volume fraction [122]. A small area is chosen near the bottom boundary of the fibre domain adjacent to the open fluid channel (Figure 4.3b). The dimensions of the fibre domain are specified by H_1 and L . The open fluid channel height H_2 can be modified to simulate various channel widths between real fibre bundles.

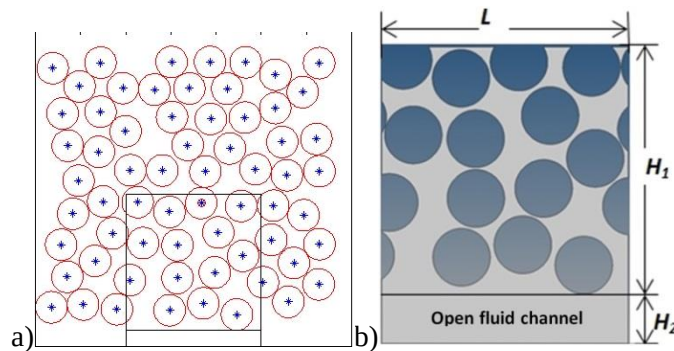


Figure 4.3 Generation of randomly distributed fibre model

a) Generation of random filament distribution b) Random model with open channel

For this study, random models are generated with three different open fluid channel heights, one model in each category. It should be noticed here that, for simplification, the selected channel heights are multiples of the fibre diameter (D). Table 4.1 shows the dimensions of the three model domains.

Table 4.1 Model dimensions with random fibre distribution

	V_f within tow /%	Fibre diameter (d)/ μm	Flow length (L)/ μm	Fibre domain height (H_1)/ μm	Open fluid channel height (H_2) / μm
M_1D	60%	7	30	30	7
M_5D	60%	7	30	30	35
M_10D	60%	7	30	30	70

4.4.2 Flow simulation

CFD software Ansys FLUENT 14.5 is employed to simulate the 2-dimensional transverse flow through these models. The minimum required meshing size can be obtained by the automated local mesh approach implemented in Matlab [121]. Steady state, saturated, laminar air flow is applied in this simulation.

Figure 4.4 displays the boundary conditions across this random model: all filament surfaces are treated as impermeable no-slip walls; the upper boundary parallel with flow directions is assumed as a no-slip wall; the bottom boundary to the open-fluid channel end is set as a symmetry; pressure inlet and pressure outlet boundary conditions are introduced to achieve the 0.1 Pa pressure gradient across the model.

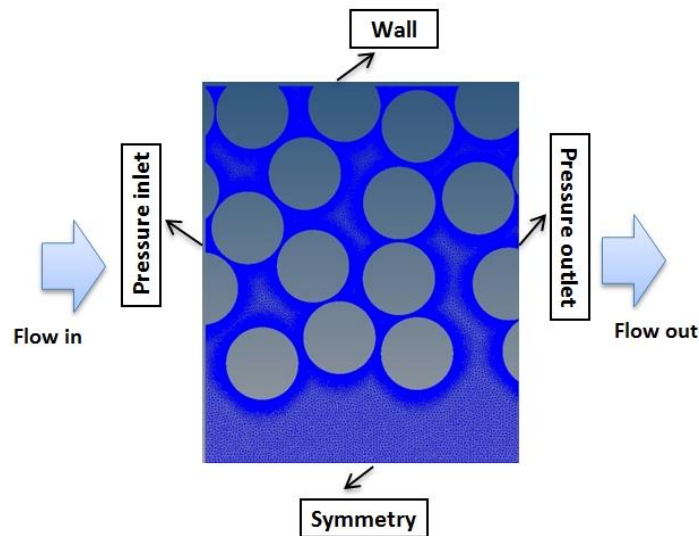
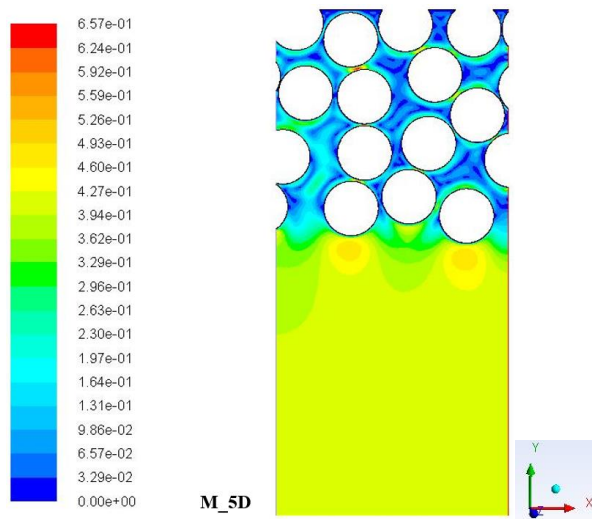
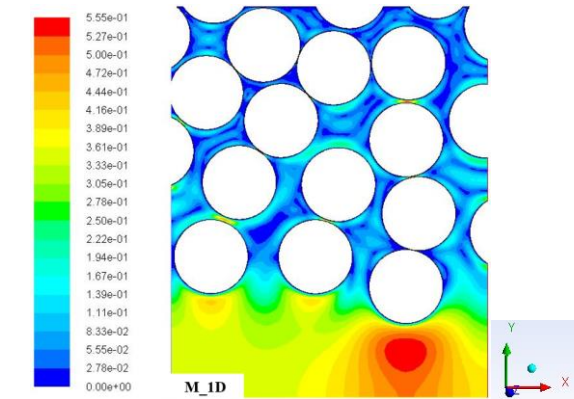


Figure 4.4 Applied boundary conditions

Resulting fluid velocity contours in the flow direction for these three models are plotted in Figure 4.5. It can be seen that, due to clustering of fibres, some flow channels in the random filament arrangement are blocked. The flow velocity in the X direction through a randomly distributed fibre domain is much lower than through the open fluid channel. In addition, the velocity within the open fluid channel tends to be uniform whereas the open channel height is in proportion much larger than the fibre diameter.



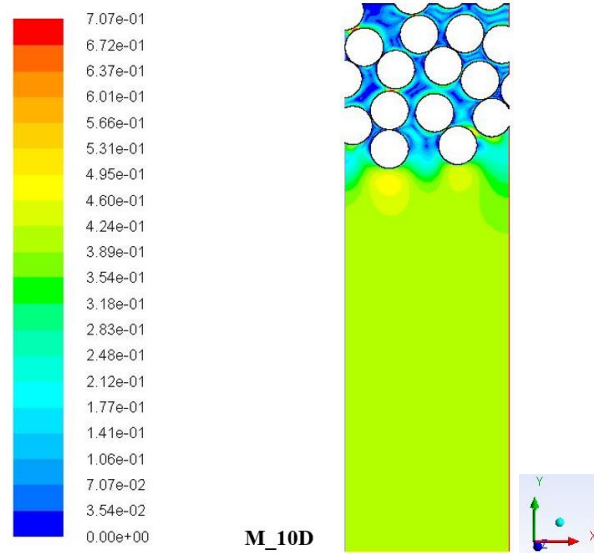


Figure 4.5 Velocity contour in X-direction

To obtain a general understanding of the velocity profile near the assumed interface on the bundle surface, 6 evenly located septal lines (assumed parallel lines in Y direction across the channel) vertical with the bottom boundary are selected, as shown in Figure 4.6 (a). Similarly, to investigate X-velocity profiles along the flow direction, septal lines parallel with the bottom boundary are selected, with a distance of one fibre diameter (1D) between neighbouring septal lines, as shown in Figure 4.6 (b). These parallel septal lines are named B-1, B-2, B-3, etc. In this study, the model with the largest channel height (M_10D) is selected.

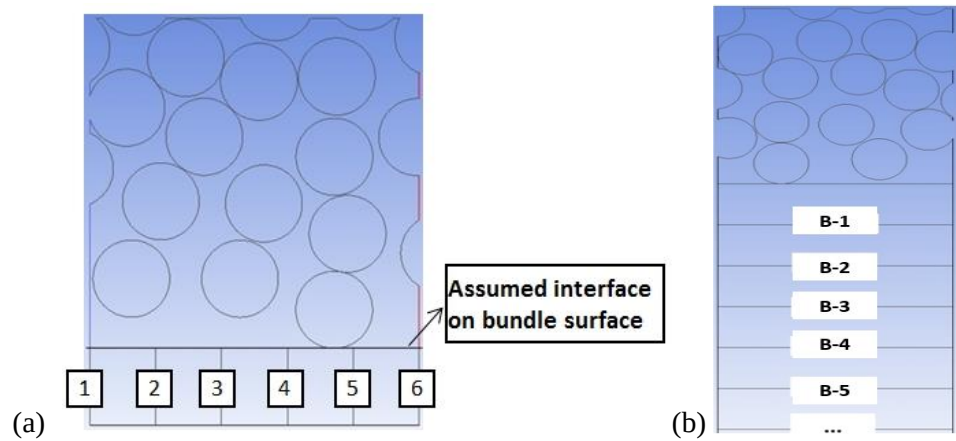


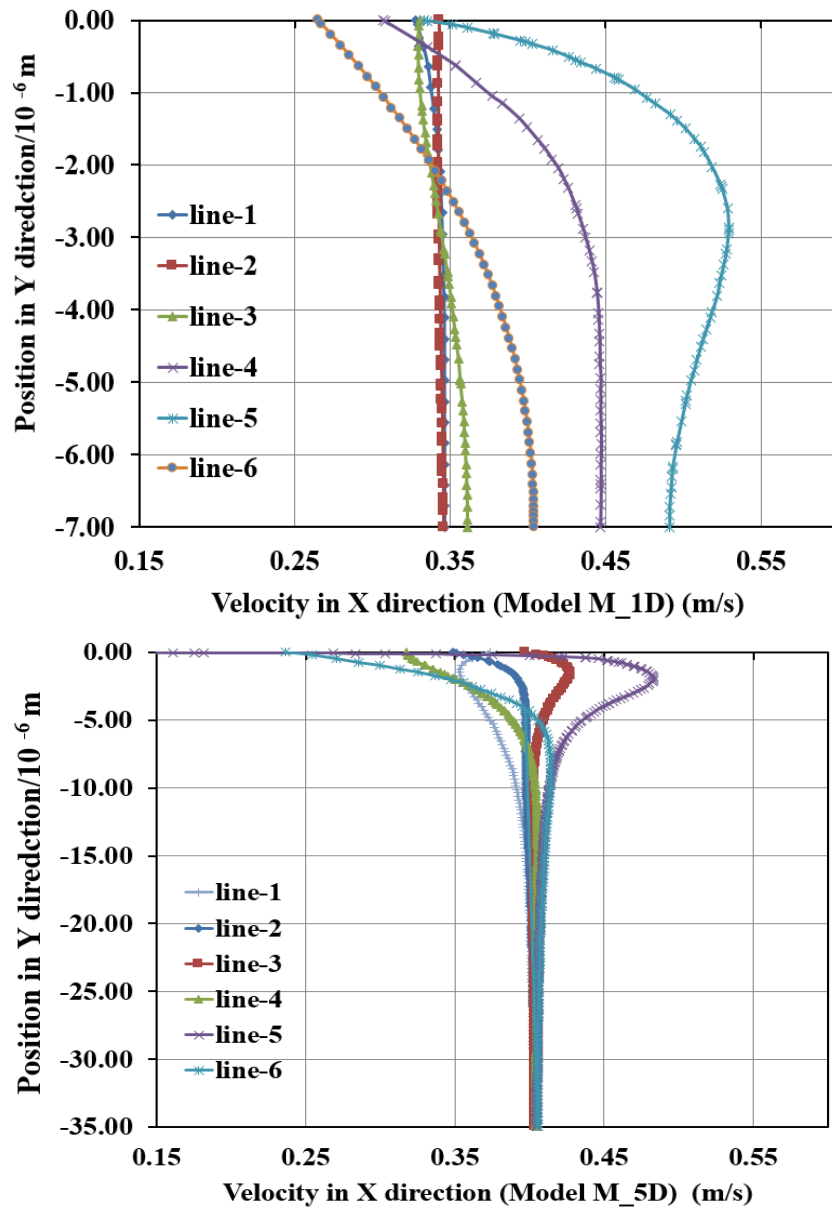
Figure 4.6 Schematic location of the selected cross-sections within three models

(a) Cross-sections added along vertical to flow direction; (b) Cross-sections added along flow direction

Figure 4.7 shows the fluid velocity profile in flow direction along the selected septal lines (Figure 4.6 (a)) within the three models. It is found that, due to the random location

of fibre filaments at the bundle surface, the velocities at the interface between fibre bundle and open fluid channel also show a random distribution. Furthermore, this random velocity distribution influences the flow rate through the open-fluid channels greatly when the channel height is equal to the fibre diameter (Figure 4.7 M_1D).

However, it is shown that this random effect is restricted to a finite distance from the pre-defined interface. The affected distance is found to be within the length of several fibre diameters. Furthermore, the flow velocity tends to reach a uniform value with the increasing channel height, as shown in Figure 4.7. It is indicated that the velocity profile reaches a ‘flat’ state with increasing distance from the fibre yarn boundary.



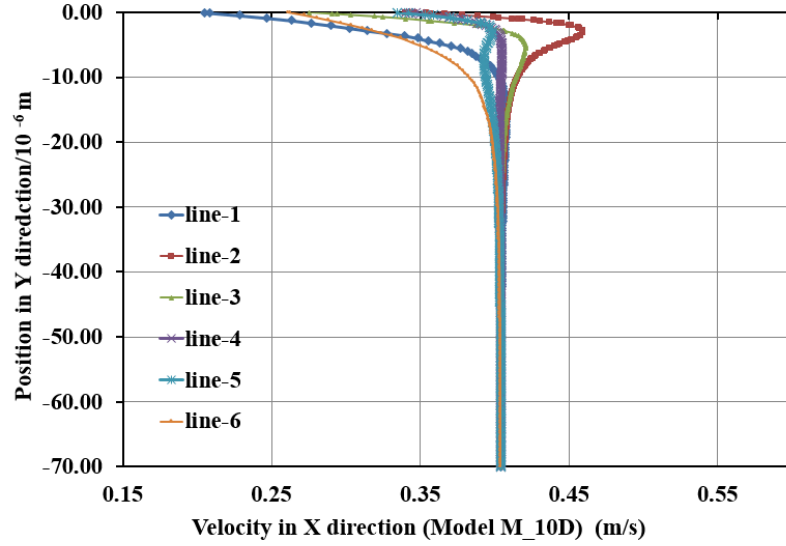


Figure 4.7 X-Velocity profile along septal lines vertical to the flow direction

In the research implemented by Beavers and Joseph [93], the assumed slip velocity at the fluid-porous interface was considered to be caused by the shear effect of the fluid near the interface. Similarly, in the research by Grouve and Akkerman [86], the flow profile was considered in comparison with Poiseuille flow between two plates.

In this research, it can be seen from Figure 4.7 that a velocity disturbance exists near the yarn interface towards the flow channel. This disturbance is caused by the random placement of filaments within the fibre yarn. With increasing distance from the yarn interface to the channel, the flow velocity profile tends to reach a constant value. This velocity disturbance area can be regarded as a transition layer before the flow velocity profile reaches a constant state between fibre yarns. Figure 4.8 presents the velocity distribution along the septal lines that are parallel with the flow direction (see Figure 4.6 (b)). It is clearly illustrated that the velocity disturbance is decreased with the increasing distance from the yarn surface.

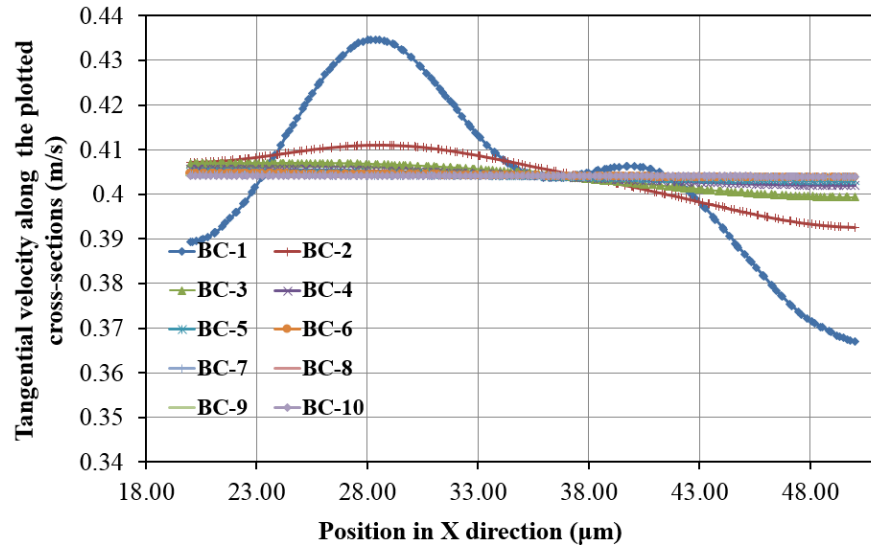


Figure 4.8 Velocity profile along septal lines parallel with the flow direction

Considering this channel flow as Poiseuille flow between two parallel moving plates, the velocity vertex should be located at the bottom boundary (the septal line together with the symmetric boundary conditions at the bottom boundary of the flow B-10 in Figure 4.6 (b)). The converged velocity vertex value can also be obtained from Figure 4.8 at the septal line BC-10. Based on this assumption, the velocity profile within the flow channel can be described with a parabolic shape [123].

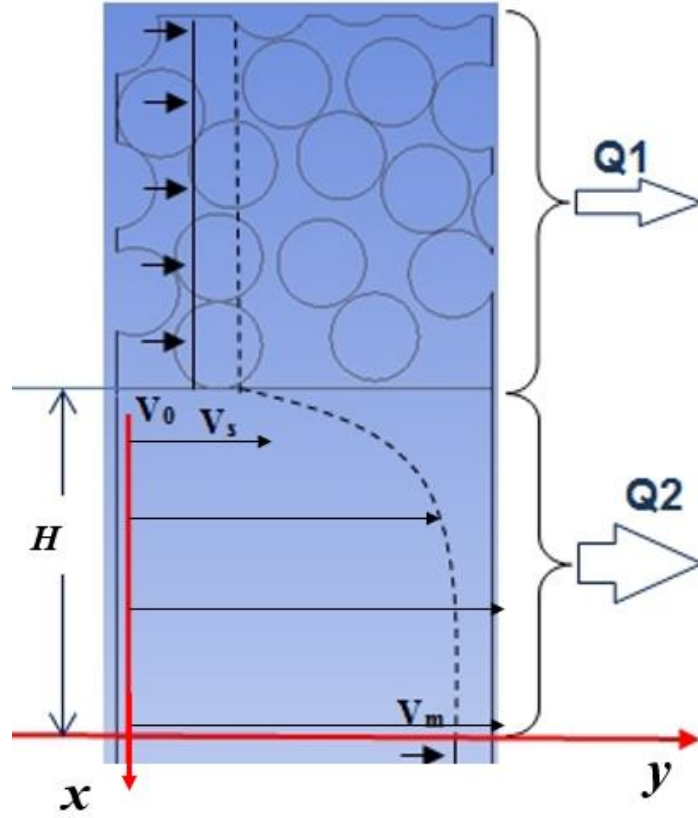


Figure 4.9 Assumed velocity profile near the fluid-porous interface

As illustrated in Figure 4.9, the volume flow rate through the random fibre yarn and the channel are Q_1 and Q_2 respectively. These two flow rates can be obtained from CFD analysis. It is calculated that the volume flow rate across the random fibres contributes only 4.8% to the total low rate. Thus, based on the permeability calculation method from Darcy's law, it can be concluded that the flow through the random fibres can be omitted in this case, and the permeability is assumed to be only dependent on the channel flow.

4.4.3 Comparison with no-slip boundary condition assumption

A model with uniform porous area is generated to compare with the random model. As the interface condition between the porous medium and the fluid channel is set as a no-slip wall condition, the velocity on this interface is assumed as zero. As shown in Figure 4.10, it can be seen that the converged velocity value is nearly the same as that from figure 4.7 (0.404 m/s). Also, the difference of volume flux across the fluid channel on these two circumstances is less than 2%. Thus, it can be verified that the no-slip condition can be applied here for later meso-scale permeability modelling. Figure 4.11 represents a zoomed image in the view of velocity profile near the tow interface.

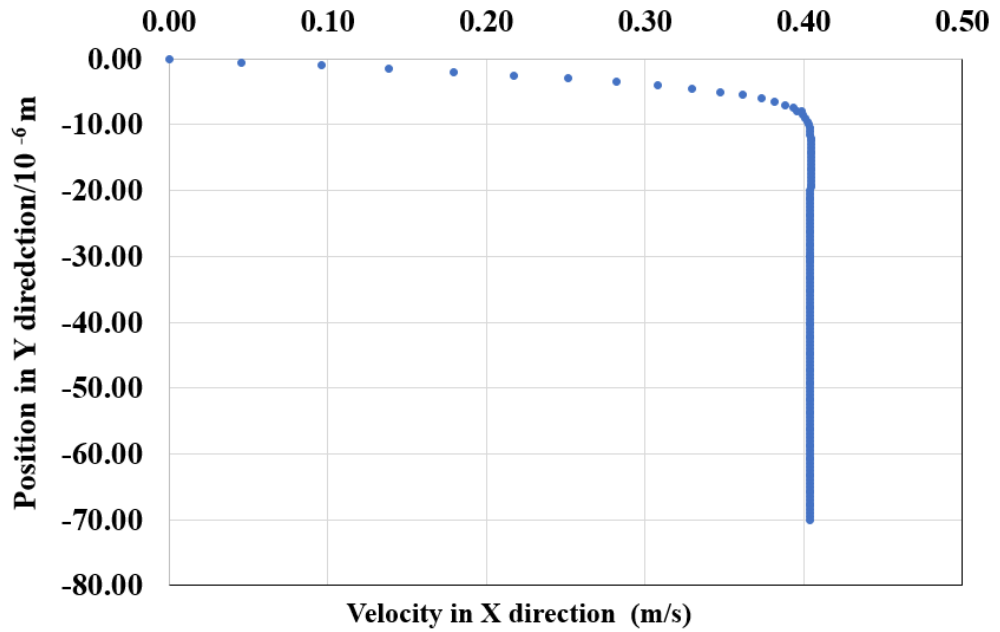


Figure 4.10 Flow velocity profile across septal lines vertical to the flow direction

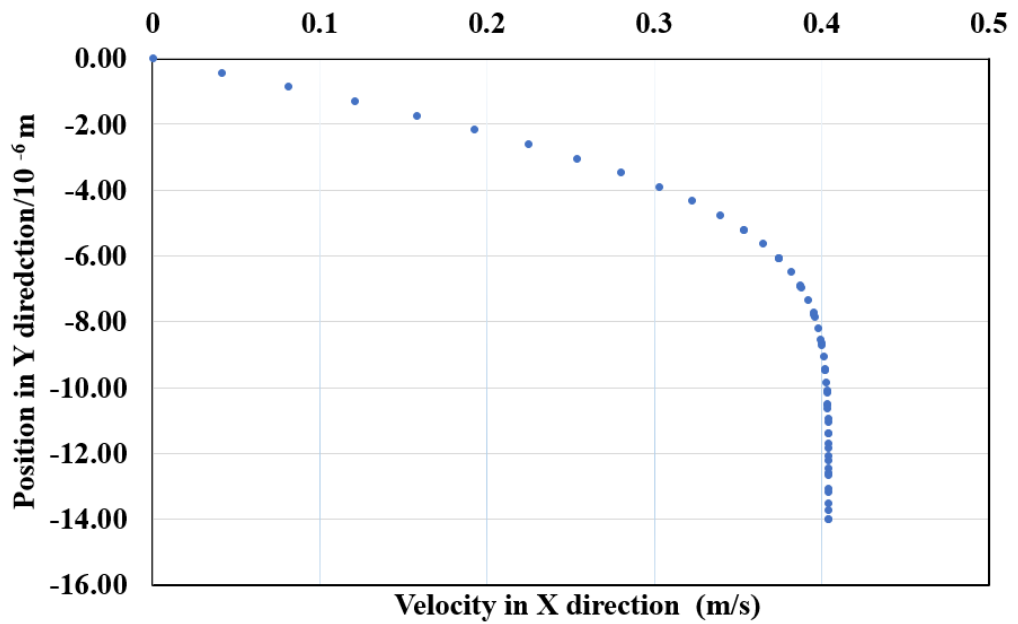


Figure 4.11 Zoomed in velocity profile across septal lines vertical to the flow direction

4.5 Discussions and future work

In this chapter, the influence of fibre tow with regularly arranged filaments and random filaments on the prediction of permeability is discussed. According to the basic research from Beavers and Joseph [93], a slip velocity was assumed at the fluid-porous interface

when there is flow both in the porous medium and the channel. Grouve and Akkerman [86] investigated the influence of the tow interface on the volume flux through the fibre yarn, and found that no-slip boundary condition can be applied when the channel height is comparatively large (the channel height is 8 times larger than the inter-fibre distance within the fibre yarn). CFD modelling based on the random fibre distribution indicates that the intra-tow flow only contributes 4.8% to the total volume flux; besides, the volume flow rate through the channel under a no-slip condition is merely 2% less than that of a random model. Thus, from the above analysis, the no-slip boundary condition can be applied on the fibre yarn during the prediction of fabric's permeability. With this simplification, the computing time of permeability modelling based on unit cell can be significantly reduced.

It should be noted that tow interface boundary conditions modelling in this chapter is only concentrating on the transverse flow within fibre tow. The influence of axial flow within the tow on the channel flow between fibre tows will be investigated in future work.

5. Permeability modelling and variability study

5.1 Introduction

As described in previous chapters, preform permeability is one of the most essential material properties that influences the resin impregnation process. As presented in chapter 3, the experimental determination of 3D woven fabrics' permeability requires a lot of work but provides the most reliable testing results. With the application of various types of fabrics in engineering industries such as aerospace, fabrics or preforms with highly-complicated internal structures are developed to meet specific requirements. Thus, numerical prediction of textiles' permeability provides an alternative method, which can help avoid repetitive and tedious testing.

5.2 Permeability modelling theory and control equations

Permeability prediction for textile fabrics is based on solving Darcy's law within meso-scale unit cell models. Basically, this process can be realized in three steps: the construction of the unit cell, which is composed of different flow domains; the solving of flow equations within the unit cell models; and the calculation of permeability from the flow simulation results. ANSYS CFX, which was chosen as the flow solving software, is based on the Finite Volume Method [124]. With this technique, the region of interest is divided into small sub-regions, called control volumes. The equations which describe the processes of momentum, heat and mass transfer (Navier-Stokes equations), are discretized and solved iteratively for each control volume. As a result, an approximation of the value of each variable at specific points throughout the domain (including the values required for solving Darcy's law) can be obtained.

In Figure 5.1, the process of permeability prediction is presented with a flow chart. It consists of three stages: model construction and meshings, flow simulation through the unit cell models and permeability calculation. The details will be elaborated in the following sections.

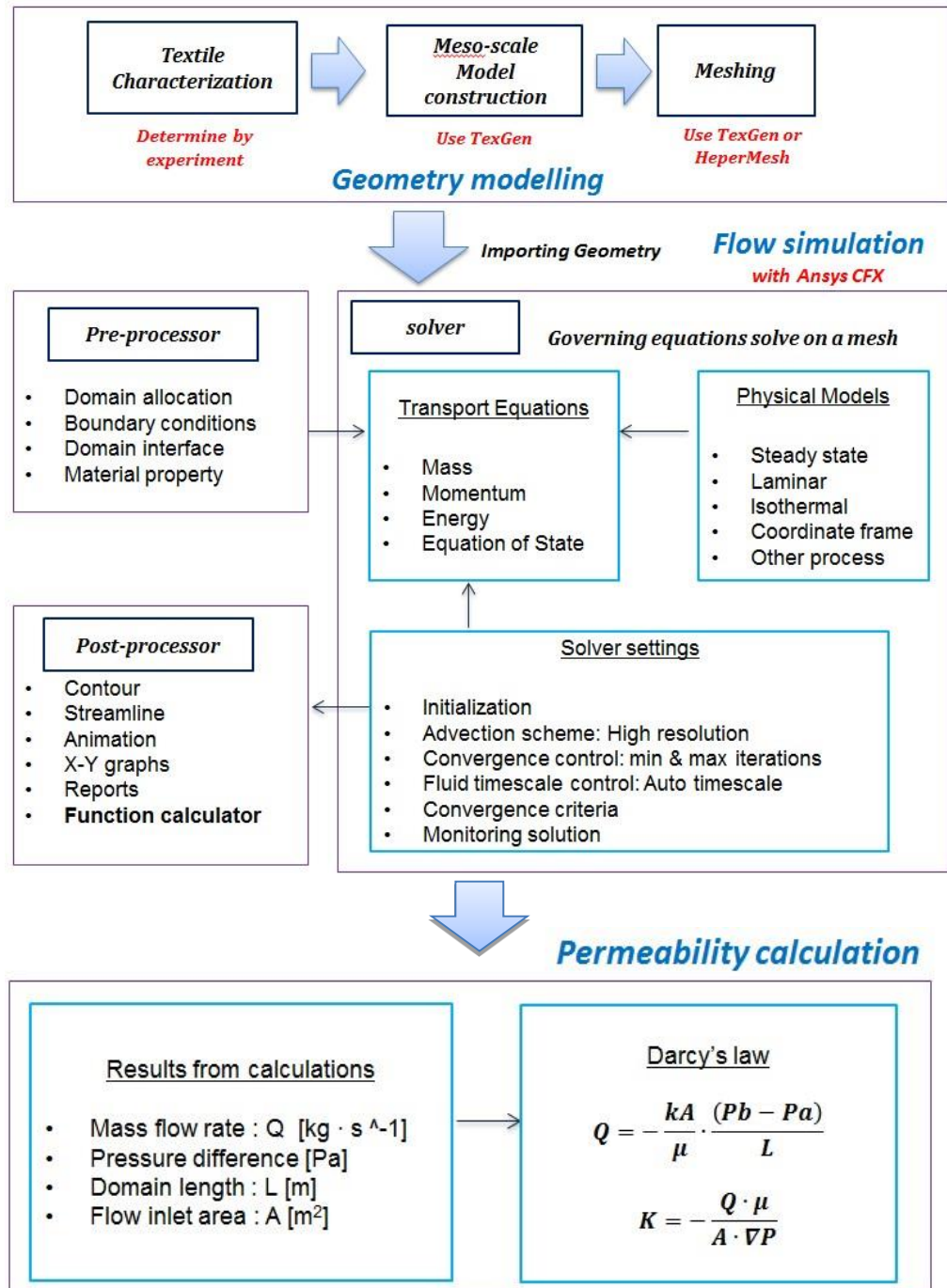


Figure 5.1 Schematic flow chart of permeability prediction process

5.2.1 Unit cell model construction

In the present research, the meso-scale unit cell model is generated with TexGen. As an open source software, TexGen was developed by the Composites Research Group at the University of Nottingham for modelling the geometry of textile structures[85]. By creating yarn paths, assigning cross-sections and interpolation, an accurate fabric model can be constructed through the graphical user interface (GUI). For example a plain weave fabric (Figure 5.2) can be presented with the model in Figure 5.3. Note that

TexGen can be used to generate models with simple internal structures such as plain weave fabrics as well as fabrics with complicated structures. Also, a Python scripting interface is available for programming. In order to obtain an accurate model for later flow modelling, reasonable and accurate dimensional inputs from the real fabric are essential. The material characterisation process from which the internal dimensions are obtained has been illustrated in detail in Chapter 3.



Figure 5.2 A plain weave fabric [125]

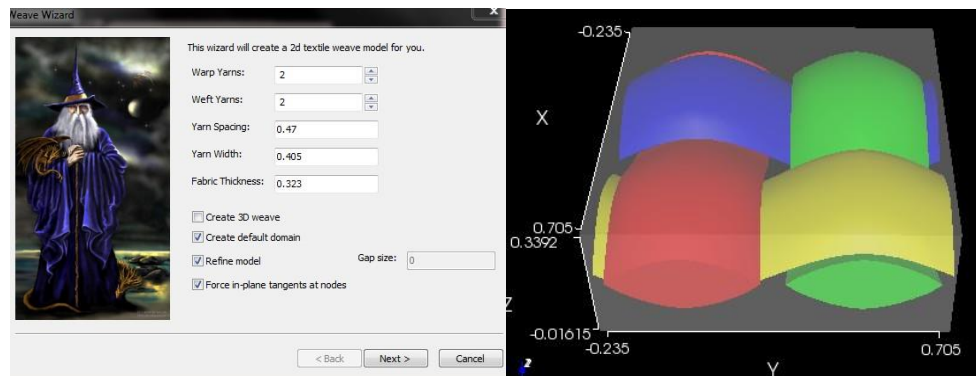


Figure 5.3 Model construction with TexGen

(x and y represents warp and weft direction respectively)

After the unit cell model is generated, meshing of the model can be accomplished with TexGen or with HeperMesh software.

5.2.2 Flow simulation

The meshed model is imported into Ansys CFX to perform the flow simulation. A typical flow simulation process by Ansys CFX uses the pre-processor, solver and post-processor.

1) Pre-processor

This step consists of definition of a flow simulation problem within the user interface. This procedure involves:

- Definition of flow domains;
- Definition of fluid properties;
- Assignment of interface and boundary condition settings.

Specifically the flow domain settings in the present preform unit cells include two domains, namely the fluid domain and the porous domain. The fibre tows within a unit cell are considered as homogeneous porous domains. Thus, the actual flow process includes two types of flow inside the unit cell, namely channel flow and flow within yarns. This is also in accordance with the dual-scale porosity structure of the fabric. As the flow inside the porous fibre tow contributes little to the overall flow rate across the unit cell, tow flow is neglected by assuming the fibre tow as solid. Also, it has been discussed in previous chapter that tow interface boundary conditions can be set as non-slip (see chapter 4).

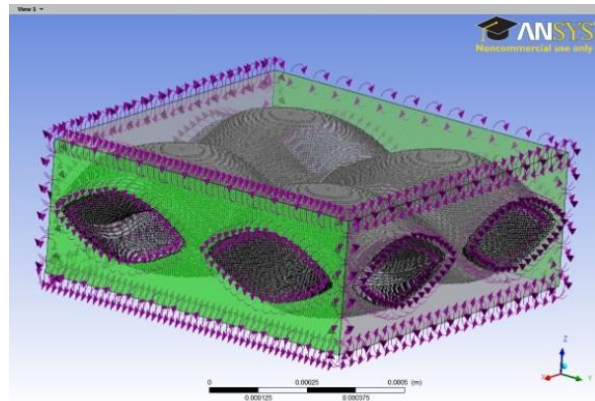


Figure 5.4 Boundary conditions setting

Note that the applied fluid is assumed as incompressible and laminar, steady and viscous flow analysis is employed. Another issue to be paid attention to is the periodic or translational boundary conditions at the pairing ends of the unit cell. In the present research case, constant pressure was applied on the fluid domain interface in the flow direction. The example of plain weave unit cell model boundary condition setting is presented in Figure 5.4.

2) Solver control

Special attention is required to the convergence criteria for the flow simulation. By plotting the residuals for each equation at the end of each time step, we can know how well the solution is converging. A reasonably converged solution requires a maximum residual level no higher than 5×10^{-4} [126]. Also typically, the RMS (Root Mean Square) residual will be an order of magnitude lower than this. The Maximum Residuals and/or

the RMS residuals can be displayed in the convergence history plots by selecting a specific monitor setting. RMS residual level 1×10^{-5} [126] indicates good convergence, so in our case, this residual level value is selected. Lower values may be required for geometrically sensitive problems. Also the default value of convergence target is set as 0.01 (1%) [126]. Then the solver is run and the convergence process is monitored. When it reaches the convergence criteria, the calculation stops and the results are output.

3) Post-processing and Calculation of Permeability

The CFX graphical user interface includes a viewer pane in which all graphical outputs are plotted, as shown in Figure 5.5. It also supports a variety of graphical and geometric objects used to create post-processing plots, to visualise the mesh, and to define locations for quantitative calculation. In this research, velocity streamlines or pressure contours can be presented in the post-processor to examine the flow process. The total mass flow rate can be obtained, as well as the pressure gradient and flow path length. Thus, with these obtained values, Darcy's law can be solved to determine the permeability of the unit cell.

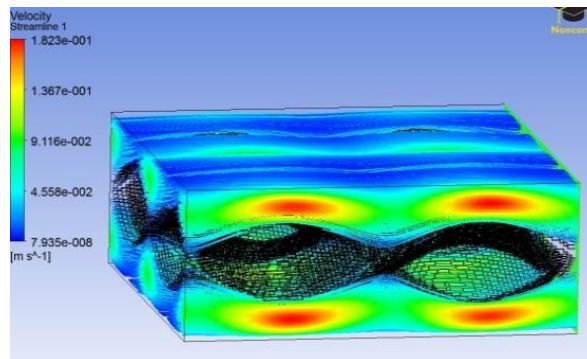


Figure 5.5 Typical plot of velocity streamlines

5.3 Warp yarn cross-section variability study

5.3.1 Geometric characterization

Two types of materials are analysed in this present research, namely 3D woven carbon fibre fabric and 3D woven glass fibre fabric. Note that the geometrical variability analysis is based on glass fibre fabric, as the two materials possess the same internal weave structure. In this section, several variables and their influences on the unit cell's permeability will be discussed. Note that not all variable parameters will be included.

The specimen for the following dimensional characterization is prepared with VARTM process. The moulded panel thickness is 3.8mm, with the fibre volume fraction reaching 59%. This 3D woven glass fibre preform is characterized with the same methodology

which as presented in section 3.3. The average dimensions for the selected specimen are presented in Table 5.1. The entire sample data consists of 1576 by 1412 by 540 slices in warp, weft and through-thickness directions, respectively. With this scanning method, a pixel resolution of 12 μ m can be obtained. The acquired data set was analysed with ImageJ [117], with which the 3D internal structure can be reconstructed.

Table 5.1 Internal geometric dimension for CF_3.8

	Warp yarn			Weft yarn		
	External yarn	Internal yarn	From supplier	Internal yarn	External yarn	From supplier
Width, mm	2.16 $\pm$ 0.1 6	1.26 $\pm$ 0.0 1	/	2.63 $\pm$ 0.1 4	2.94 $\pm$ 0.1 6	/
Height, mm	0.18 $\pm$ 0.0 1	0.243 $\pm$ 0. 02	/	0.34 $\pm$ 0.0 2	0.35 $\pm$ 0.0 2	/
Spacing, mm	/	1.26 $\pm$ 0.0 1	1.25	4.01 $\pm$ 0.2	/	4.0
Yarn cross Section area, mm ²	0.39	0.30	/	0.70 $\pm$ 0.0 3	0.80 $\pm$ 0.0 3	/
Pure carbon filament area, mm ²	0.2506	0.2506	/	0.5011 /IM7 24K	0.5011 /IM7 24K	/
Fibre volume fraction within yarn (V_{ff})	64.3%	83.5%		71.5%	62.6%	/

One of the geometric variables that should be considered is the yarn cross-sections. Figure 5.6 presents the cross section images seen from the weft yarn direction. In this way, it can be seen clearly that warp yarn cross-sections are changing continuously along the weave direction.

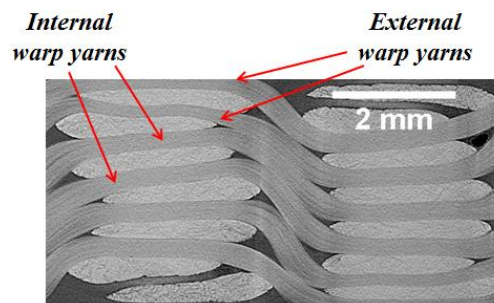


Figure 5.6 Internal structure seen from weft direction

It can be summarized that warp cross-sections become thinnest at crossovers and are thickest between the adjacent weft yarns. This structural feature is caused by the

intrinsic internal weaving pattern. Fibre yarns are highly compressed at crossover locations. A much higher local fibre volume fraction can be found in these locations due to a highly compacted state at the crossovers. However, warp yarns show kind of 'loose' state at the 'bridge' locations between weft yarns. Note that this change in warp cross-sections will lead to a subsequent changing of flow channels in the weft direction. Thus the associated permeability will be affected as the flow rate through these channels is the main contributor to the unit cell's permeability.

5.3.2 Generation of modified unit cell models

TexGen is used to generate unit cell models. Normally weft yarn cross sections hold a constant elliptical or lenticular shape; however, this is not the case for warp yarns: a systematic change in the warp yarn cross-section height can be found from the geometry analysis in the previous section. The accurate representation of internal geometry such as yarn cross-section shape and weave angles are essential for the predicted results, as flow channels within the unit cell model are dependent on them. Note that the exact warp cross-section variability cannot be described accurately. Therefore, a series of models with varying warp yarn sections are generated to investigate its effect on permeability modelling.

According to the geometric characterisation process described in chapter 3, yarn cross sections are fitted with elliptical shapes, of which the yarn width and yarn height can be characterized by processing the micro-CT images with ImageJ. Note that in TexGen, yarn cross sections can be varied including normal elliptical shape, lenticular, rectangular as well as power ellipse. In the present research, the power elliptical shape is selected when generating the unit cell models, as the yarn cross sections can be 'adjusted' according to requirements, especially for this case where the yarn cross sections are varying along the warp direction.

Note that the fibre volume fraction within the yarn will change with the shape of the power ellipse, or more specifically, with the power value, as yarn cross sectional area changes with the power value, as shown in Figure 5.7. However, according to the best possible fibre arrangement within fibre yarn, namely quadratic or hexagonal, there is an ultimate limit for this yarn fibre volume fraction, as shown in Table 5.2. Thus, this requirement should be met when varying the warp yarn cross sections in the following study.

Table 5.2 Maximum V_{ff} with in fibre yarn

Filament arrangement	V_{max}
Quadratic	$\pi/4$ (0.785)
Hexagonal	$\pi/2\sqrt{3}$ (0.907)

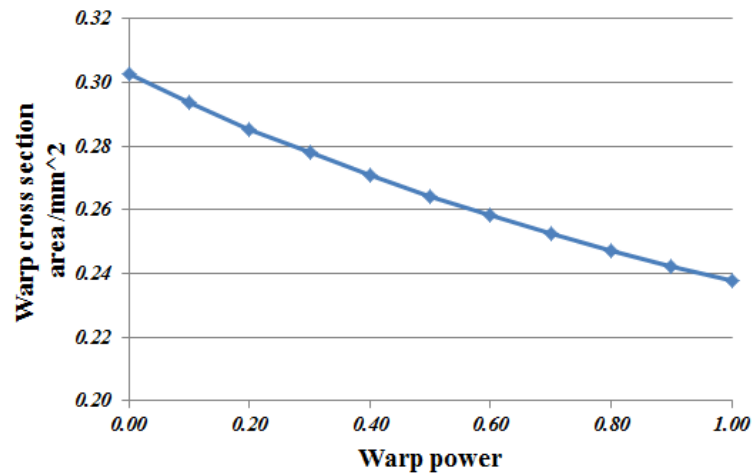


Figure 5.7 Relationship between warp cross section power value and the cross sectional area

Accordingly, yarn fibre volume fraction (V_{ff}) will also change with the power value, as shown in Figure 5.8. Warp cross sectional area decreases with increasing power value; in contrast, V_{ff} shows a reverse trend. Note that V_{ff} should meet the maximum limitations determined by the ideal quadratic or hexagonal filament arrangements displayed in Table 5.2. In this study, as the warp yarn cross sections are measured at the crossover locations, where the yarn is thinnest, the requirements of V_{ff} should be met firstly here. It is indicated from Figure 5.8 that V_{ff} reaches the possible highest value when the power value reaches 0.3. Thus, in this present study, warp power 0.3 is selected. This is theoretically reasonable for the following model optimization study.

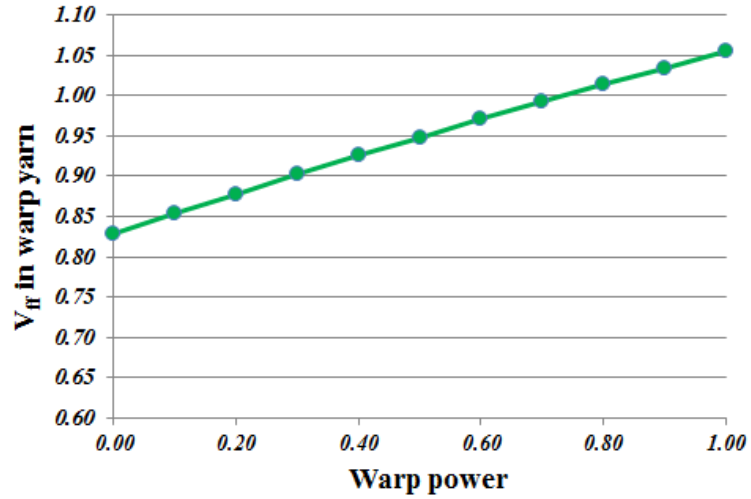


Figure 5.8 Relationship between warp cross section power value and V_{ff}

As described in Figure 5.9, the changing warp yarn height can be described in TexGen models by interpolating yarn cross sections along the warp yarn direction. However, it should be noted here that the adjacent warp yarns should not interfere with each other as this is unrealistic in practical conditions. The modified warp yarn geometry is described in Figure 5.9. Warp yarn height h at crossovers is selected as the original cross section as it also possesses the ‘thinnest’ value here. To make the following analysis simple, the interpolated cross section heights are supposed to be comparative to h , which are given by $n \cdot h$, as shown in Figure 5.9.

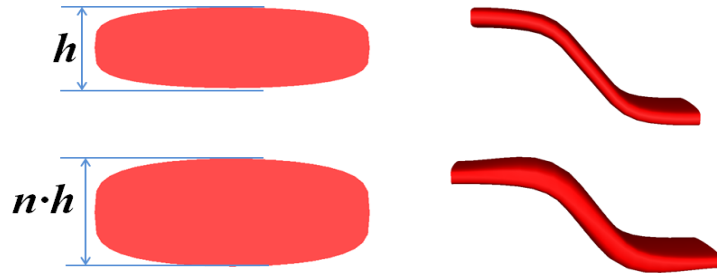


Figure 5.9 Schematic of warp cross section interpolation

It should be noted that, as the unit cell model is generated from the real specimen, the overall fibre volume fraction (V_f) needs to be consistent with the practical value, which is 59% in the present study. In order to make sure of that, the relationship illustrated in equations (5.1), (5.2), should be adapted in all the modified models. The notations V_t , V_{ff} represent yarn volume fraction within the unit cell and fibre volume fraction within the specific fibre yarn respectively, and the subscript number 1,2 denote warp and weft yarn respectively.

$$V_t = V_{t1} + V_{t2} \quad (5.1)$$

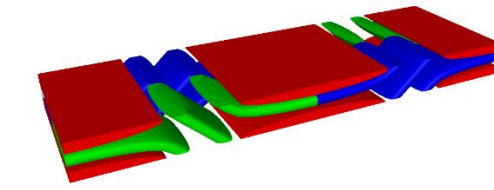
$$V_f = V_t \cdot V_{ff} = V_{t1} \cdot V_{ff1} + V_{t2} \cdot V_{ff2} \quad (5.2)$$

Note that as the fibre volume fraction within the warp yarn will vary along the warp direction, here the averaged V_{ff} is applied. Table 5.3 presents the obtained V_{ff} within the warp yarn related with the varied warp heights in a series of models. Considering the ultimate limit indicated in Table 5.2, the unrealistic modified unit cell model should be neglected.

Table 5.3 Geometric information for optimized models

Model name	Yarn height	Overall V_t	Weft yarn V_t	Warp yarn V_t	V_f	Averaged V_{ff} within warp yarn
H	h	0.651	0.28	0.371	0.59	1.05
$H12$	$1.2h$	0.676	0.28	0.396	0.59	0.98
$H14$	$1.4h$	0.701	0.28	0.421	0.59	0.93
$H16$	$1.6h$	0.726	0.28	0.446	0.59	0.87
$H18$	$1.8h$	0.752	0.28	0.472	0.59	0.83
$H20$	$2h$	0.778	0.28	0.498	0.59	0.78
$H22$	$2.2h$	0.804	0.28	0.524	0.59	0.74
$H23$	$2.3h$	0.817	0.28	0.537	0.59	0.73

Based on the above analysis, unit cells with various warp yarn sections were generated with TexGen (Figure 5.10 (a)). Flow within fibre yarns is not considered due to its small contribution to overall flow thorough the model, thus, the flow process is only dependent on the flow channels formed between fibre yarns. Thus, fibre yarns are omitted in the unit cell (Figure 5.10 (b)). A steady, laminar flow state with isothermal conditions is applied within the unit cell domain; the fluid is assumed to be incompressible. Constant pressure gradient (∇P) is applied across the unit cell in the studied direction. Navier-Stokes equations are solved in Ansys CFX to obtain the volume flow rate across the model. Figure 5.10 (b) represents the flow is in warp direction.



(a)



(b)

Figure 5.10 Representative internal unit cell and meshed model

(a)Unit cell; (b) Meshed model

Tetrahedral elements are employed in the modelling work with Hypermesh. As the influence of mesh size is significant during flow modelling, a mesh sensitivity study should be accomplished to obtain the most appropriate meshing size. Considering the computation cost as well as the accuracy of the simulation results, it is indicated from Figure 5.11 and 5.12 that an element size of 0.7 is appropriate for this study. Specifically, the simulation result reaches a comparatively constant value when the total number of elements reaches around 700000.

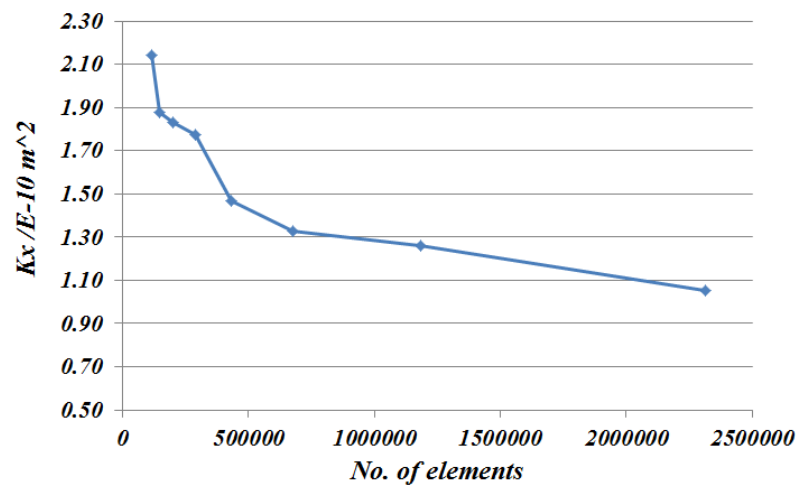


Figure 5.11 Mesh dependence study on the flow simulation in warp direction

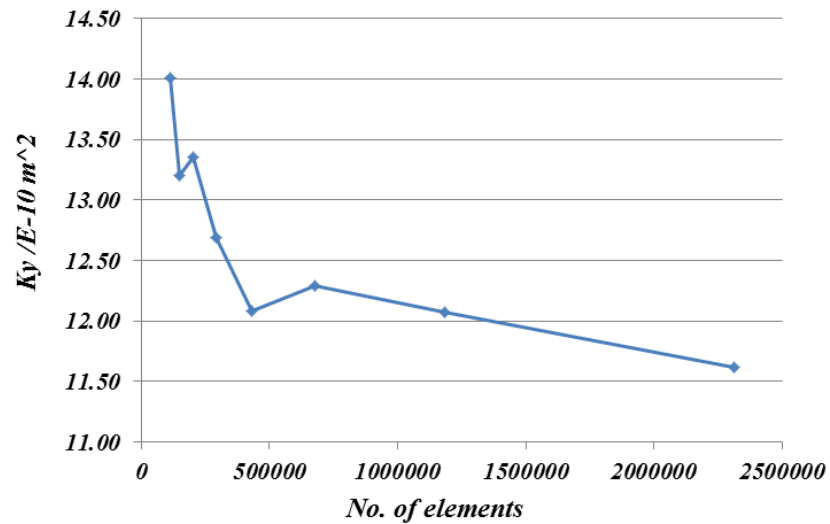


Figure 5.12 Mesh dependence study on the flow simulation in weft direction

5.3.3 The influence of warp cross section on permeability prediction

Flow simulation is conducted on this series of models based on the varied warp yarn height illustrated in Table 5.3. With the increasing of warp yarn cross section in each unit cell model, the overall yarn volume fraction is also increased. The predicted permeabilities in warp and weft directions are presented against the overall yarn volume fraction (V_t) in each model, as shown in Figure 5.13. It can be seen that the permeability in both directions is decreased with the increasing overall yarn volume fraction. However, the simulated results in weft direction are more sensitive to the warp yarn cross section variability. This can be explained by the narrowing flowing channels in the weft direction due to the increasing warp yarn height. Actually this is also the case for the real fabric. For the permeability in the warp direction, the simulated permeability is affected more by the warp yarn width but not the height. Thus, permeability in the warp direction is less influenced by this kind of yarn variability.

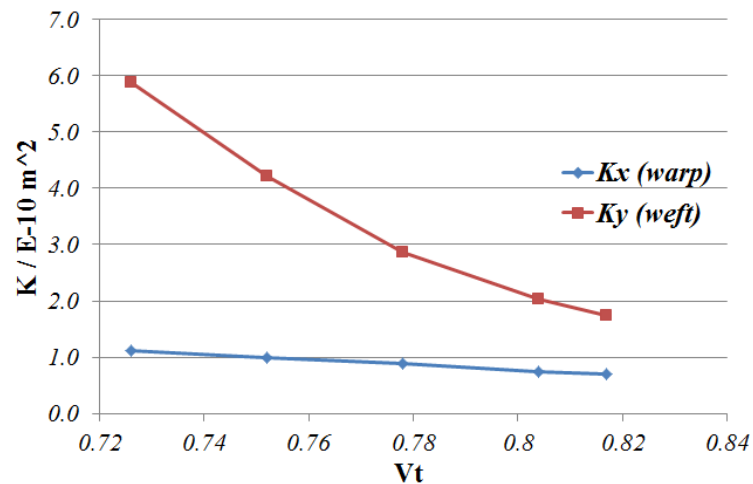


Figure 5.13 Permeability prediction trend based on optimized unit cells

The experimental characterization of the permeability of this 3D woven carbon fibre preform can be found in chapter 3. The experimental permeability value for the fabric with a thickness of 3.8 mm is selected to validate this simulation methodology. Figure 5.14 presents the comparison between experimental and predicted permeability. Clearly, with the increasing yarn volume fraction within the optimized models, the predicted permeability in warp and weft directions becomes increasingly reflective of the experimental results, especially for the model with V_t reaching 82%, the difference between prediction and experiments is less than 20%. However, it should be noted that the predicted value in the weft direction is lower than the experimental value; but in warp direction, the model seems to be ‘over-optimized’.

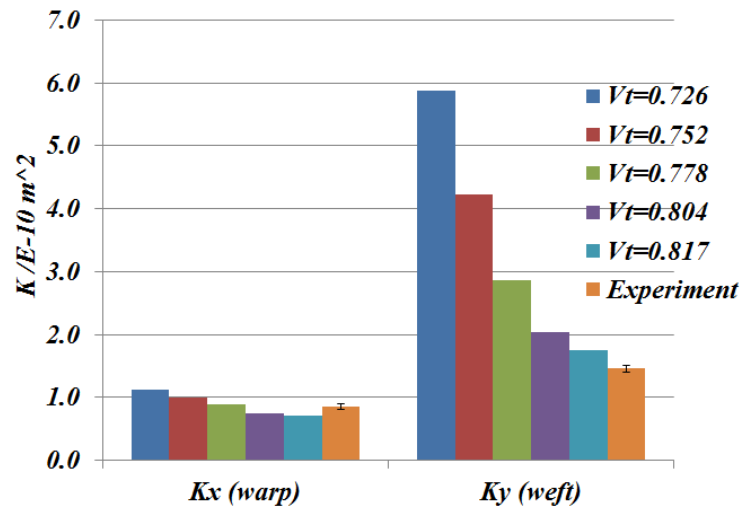


Figure 5.14 Comparison of predicted and experimental permeability for fabric with thickness of 3.8mm

5.4 The influence of weft yarn shear deformation on the predicted permeability

During the manufacturing process of the 3D woven fabric and the later handling of the preform in the RTM process, a shear deformation can be introduced to the internal structure of the preform, as shown in Figure 5.15. This kind of deformation may change the resin flow within the fabric, thus affecting the permeability. In this research, the effect of shear deformation on permeability of 3D woven glass fibre fabric is investigated.

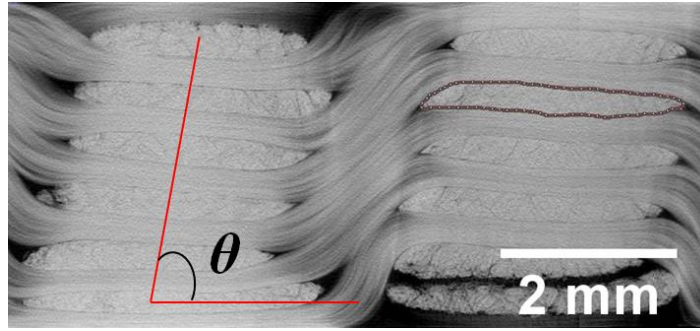


Figure 5.15 Shear deformation of the 3D woven glass fibre fabric

The characterisation procedure of internal geometric dimensions of this 3D woven glass fibre fabric is described in Chapter 3. Note that averaged results are applied in the following study, as shown in Table 5.4.

Table 5.4 Geometric information for optimized models

		Surface warp	Internal warp	Internal weft	Bottom weft
Width	mm	2.30±0.091	1.24±0.003	2.790±0.185	3.387±0.103
Height	mm	0.330±0.014	0.249±0.023	0.350±0.026	0.315±0.040
Spacing	mm	2.46±0.094	1.24±0.003	3.993±0.176	3.993±0.176

In this research, the shear deformation angle is determined from image processing of the micro-CT dataset in chapter 3. It is indicated from Figure 5.15 that weft yarn columns in the through-thickness direction display similar shear trends, where the shear angle can be represented by θ . All weft yarn centroids are located for this scanned specimen, and in all there are 5 weft columns. These characterized wet yarn centroid locations are presented in a plane-coordinate system, as shown in Figure 5.16. Note that the notations follow the rules described in section 3.2: the axis title x z represents distance from top left corner on each stacked image (wt2~wt11) in the warp direction and through thickness direction respectively.

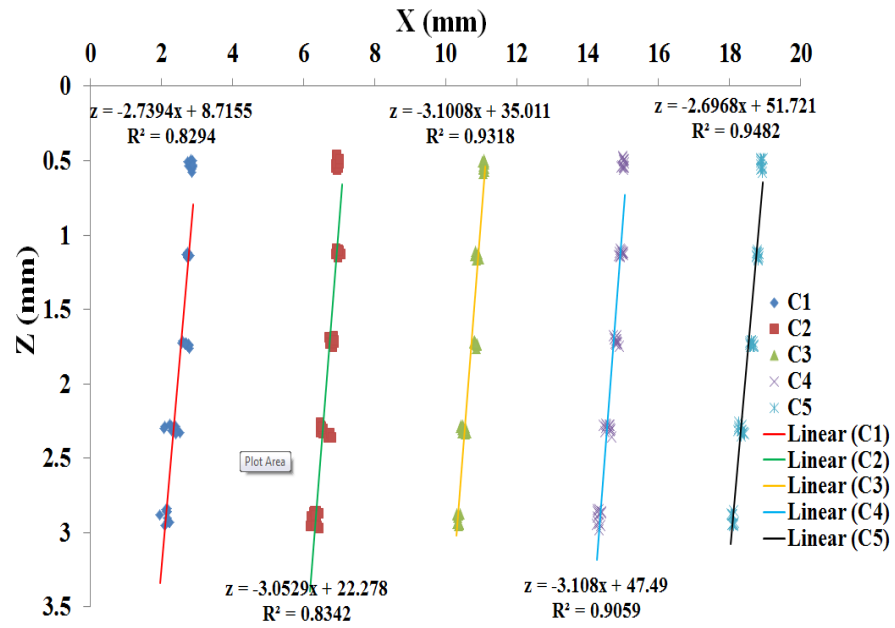


Figure 5.16 Characterisation of the shear deformation of the 3D woven glass fibre fabric from weft yarn centroid locations

An obvious regular ‘shear’ deformation in through-thickness direction is revealed from the inclined weft columns in Figure 5.16. On each layer, each weft yarn is represented by 10 centroids, within which a ‘shift’ phenomenon can be observed. This indicates that yarn path is not in an idealized ‘straight’ form, but presents a deviation in the warp direction (x direction). It is rational to hypothesize a linear fitting to illustrate this shear deformation. Multi linear regression analysis is applied on each column data as shown in Figure 5.16.

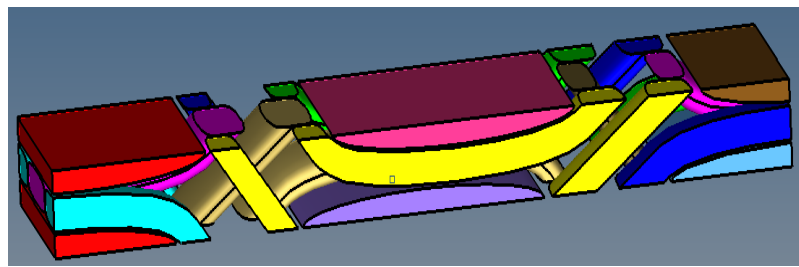


Figure 5.17 Unit cell model with shear deformation

Based on the geometric analysis on the shear deformation, the sheared unit cell can be generated as shown in Figure 5.17. Note that the shear angle of this model is the averaged value from the weft yarn columns. Also for this 3D woven glass fibre fabric, the previously mentioned warp yarn cross section variability is also taken into consideration in this comparison study. Thus, the ‘ideal’ unit cell model, sheared model as well as the model with varied warp yarn cross section were investigated in this study.

In this series of permeability models, steady state, laminar flow is applied across the flow domain; air is used as the flow media as it can be considered as an incompressible fluid at low speed. The yarns are modelled as impermeable with yarn surface simulated as no-slip walls [109]. The Navier-Stokes equations were solved within the gaps between fibre yarns. Translational periodicity is assigned in all three directions. The flow is driven by applying a constant pressure gradient across the flow domain. In this study, a conformal mesh with around 120,000 elements was generated within the flow domain. The saturated permeability in warp, weft and through thickness direction was calculated from Darcy's law with the obtained flow rate in each specific direction.

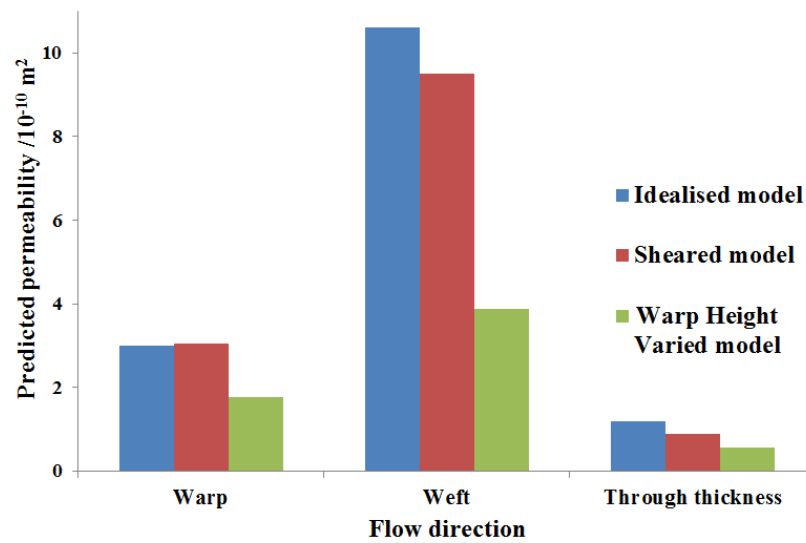


Figure 5.18 Comparison of predicted permeability among the varied models

As presented in Figure 5.18, it can be found that the influence of geometry modification on the simulation results can be significant. Generally both varied models tend to reduce the predicted permeability, with an exception that the sheared model displays a similar predicted value in the warp direction, as the shear deformation mainly affects the flow channel in the weft direction, while in the warp direction, the gaps or flow channels between warp yarns are not changed. It is also indicated that the essential influencing factor for the predicted permeability is related with the warp yarn cross section variations, as the flow paths in both warp and weft direction in this model are changed.

With the yarns simulated as impermeable solid, the flow process through these models is controlled by the flow within the gaps between yarns. Thus, permeability predicted in the weft direction in all the three models shows the maximum value as more gaps exist as flow channels in this direction. With the interpolated varied warp cross sections, the yarn volume fraction is accordingly greatly increased (can reach 79.8%), leading to

a significant reduction in the flow channels. However, although the sheared model possesses the same yarn volume fraction (67.4%) as the idealised model, the flow channels are still changed with the modified warp path from the shear deformation, as shown in Figure 5.19. In particular, it seems the flow is more affected by the ‘narrowed’ flow channels between warp yarns.

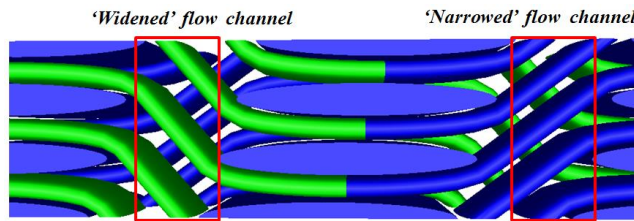


Figure 5.19 The reduced flow channel due to the shear deformation

From the above case studies, it can be concluded that the shear deformation indeed has an impact on the permeability prediction. However, this effect is relatively insignificant compared with the influence of the varied yarn cross sections. It is also indicated that the flow simulation output is highly sensitive to geometry variability such as yarn path and cross sections.

5.5 Conclusions

In this chapter the numerical prediction of preform permeability based on a unit cell is illustrated in detail. TexGen is used to generate the unit cell model based on the dimensional information described in chapter 3. Flow simulation software Ansys CFX is then employed to solve the flow process across the unit cell. Finally Darcy’s law is applied to calculate the model’s permeability.

During this procedure, the essential parts involve of the model construction and the flow simulation settings. As the representative volume element of the textile, unit cells did not consider the variability of the real material introduced during the manufacturing process of the fabric. However, in this research, it is found that the predicted permeability can be sensitive to geometrical variability of the unit cell, such as the yarn cross sections and shear deformation. It can be seen that the precision of permeability depends largely on the precision of unit cell. Besides, how to take all these geometrical variability into consideration when predicting permeability of 3D woven fabrics still needs more work to do.

Furthermore, experimental results of permeability tests are compared with the series of predicted permeability based on modified unit cells. The difference between simulation

and measurements become gradually small. Note that the precise unit cell model generation method needs to be developed, especially for fabrics with much compression and shear deformation. This is especially important for larger scale composite components, which possess all kinds of geometrical variability, even with different internal structure at different locations.

6. Multi-scale modelling and defect generation

6.1 Introduction

A key requirement of manufacturing composite parts with RTM is to obtain a component with high quality. Defects such as void and dry spots should be avoided during the resin impregnation process. In chapter 2, the mechanisms of defect generation were discussed in detail. Basically, dry spots will appear where resin fails to impregnate into; large areas of void are generated from the mismatching in viscous flow between fibre yarns and capillary flow within fibre yarns; void can be classified into two categories according to their locations: namely meso-scale void located between fibre yarns, and micro-scale void located within fibre yarns.

In order to achieve the composite components with minimum defects, the reasonable configuration of mould, such as the location of injection gates and vents, as well as processing parameters, including injection pressure, mould temperature and curing procedure, need to be studied carefully, as all of these processing parameters are closely related with the final quality of the manufacture components. With the help of RTM process modelling tool such as PAM-RTM, the influences of these processing parameters can be investigated numerically at comparatively low cost, and RTM process can be optimized accordingly. Besides, experimental characterisation of defects formation and distribution under various processing parameters is also covered in this chapter.

6.2 Parametric study on RTM process modelling

6.2.1 Process modelling procedure

As a macro-scale flow modelling software, PAM-RTM provides a way for modelling the flow process in RTM. Basically, this software considers three categories of physical phenomena: resin flow through the porous preform, thermal exchanges between the preform and the mould, and the resin curing process. Flow in a porous medium can be described by Darcy's law, together with resin mass conservation conditions; equation (6.1) is then obtained:

$$\nabla \left(\frac{\kappa}{\mu} \nabla P \right) = 0 \quad (6.1)$$

The above governing equation of single phase flow is solved based on the assumption of a quasi-steady-state process. Only the resin-filled domain is considered as a computational domain. Finite element/control volume (FE/CV) method combined with

the volume of fluid (VOF) method are employed. Non-conforming finite elements (Figure 6.1) are used to solve the flow. Note that the pressure is discontinuous along the inter-element boundaries except at the nodes, while the Darcy flow rate is continuous across the boundary of elements.

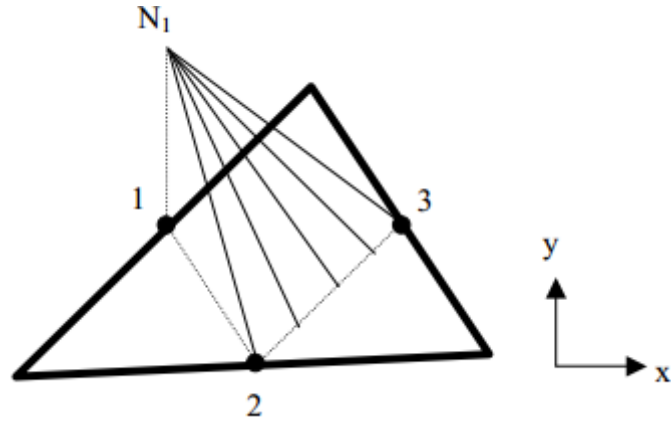


Figure 6.1 Schematic descriptions of one finite element and the assumed middle nodes

A fill factor f is associated with each element in order to track the progression of the resin flow front. The basic modelling procedure is presented in Figure 6.2.

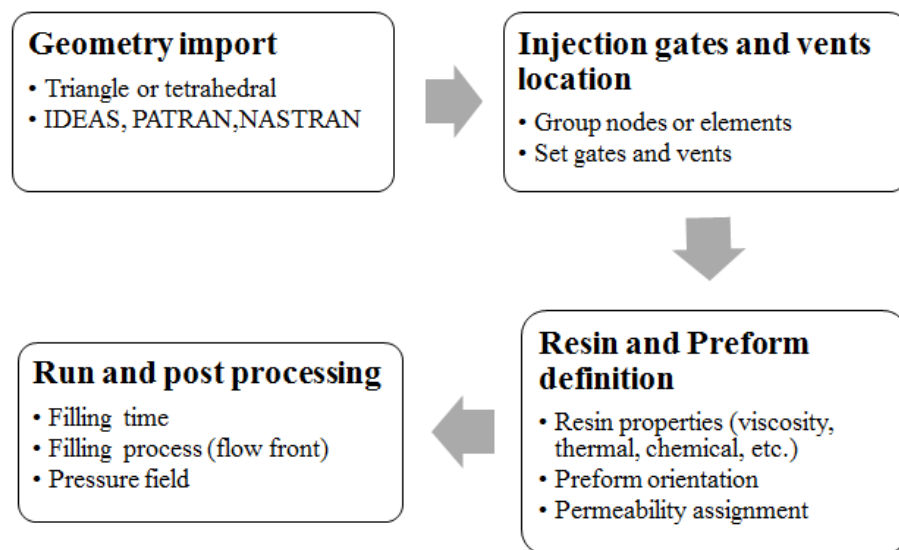


Figure 6.2 Procedure of process modelling with PAM-RTM

6.2.2 Influence of location of injection gates and vents

One essential consideration is the design of mould, mainly related with the proper location of injection ports and vents. The current research is based on the RTM process of manufacturing composite panels. The component is modelled as a square plate with a dimension of 280mm by 280mm; as the assumed mould for producing the composite

panels has a dimension of 300mm by 300mm, there will be runners around the preform. The configuration of this model is illustrated in Figure 6.3. There are resin injection gates and vents distributed at the centre and four corners of the mould. The effect of various injection methods can be studied by changing the position of gates and vents.

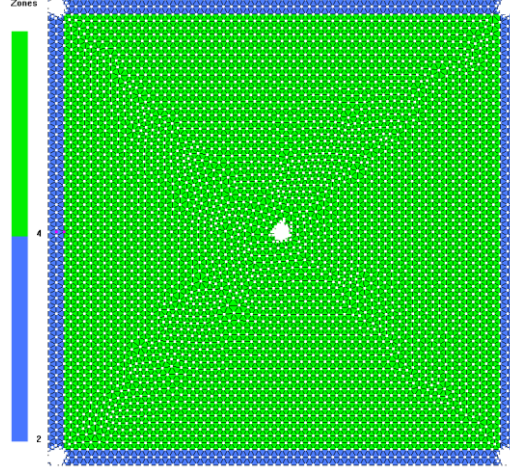


Figure 6.3 2D plate model with runners around the preform (the green elements represent the preform; the blue elements represent the runners)

According to the modelling procedure illustrated in Figure 6.2, the essential steps lie in the assignment of material properties for the flow modelling process. In this current research, the preform is modelled as a 3D woven carbon fibre fabric with a thickness of 3.8mm. The preform's permeability is obtained from the experimental measurements in chapter 3. Note that the runners around the preform can be seen as a material with a high permeability. Thus, there are two separated zones for this model. Based on Poiseuille's flow through pipes with a radius of R , the runner's permeability can be calculated as presented in equations 6.2 and 6.3.

$$Q = \frac{\pi R^4}{8 \cdot \mu \cdot l} (P_1 - P_2) = \frac{k \cdot A}{\mu} \cdot \nabla P \quad (6.2)$$

$$k = R^2/8 \quad (6.3)$$

Thus, the permeability inputs for this flow model are listed in Table 6.1. Note that the current model can be seen as a 2D model, as the in-plane dimensions of this preform are much larger than its thickness. Thus, only in-plane permeability (in warp and weft direction) are applied here.

Table 6.1 Permeability value applied process modelling

Name	V_f	K_1 (weft) (10^{-10}m^2)	K_2 (warp) (10^{-10}m^2)	Runner (10^{-7}m^2)
CF_38	0.59	1.458	0.847	7.81

Another essential material assignment is the applied fluid. Epoxy resin Prime 20LV from Gurit Company is applied here, as it is also the selected resin for producing panels for this project. Note that the processing temperature for this modelling work is assumed as room temperature, the exothermic heat during the mixing of resin and hardener can be ignored. The properties of epoxy resin Prime 20LV at room temperature (25°C) is shown in Table 6.2.

Table 6.2 Resin property

Name	Density (kg/m^3)	Viscosity (Pa.s)
Prime 20 LV	936	0.221

Two specific injection methods are investigated in this work: central injection and corner injection. This can be realized by changing the pressure of the gates and vents respectively. Constant pressure boundary conditions are applied at the gates and vents: 1bar and 0bar respectively. The simulation is assumed as under isothermal conditions, so there is no heat transfer between resin, preform and mould. After the simulation is finished, the filling process can be tracked by post-processing. Figure 6.4 presents the filling state at various time steps for central injection.

It can be seen from Figure 6.4 that, the flow front is presenting an elliptical shape due to the anisotropic permeability in warp and weft directions. Besides, due to the low resistance of the runners around the preform, the resin will flow firstly through these runners when it reaches the preform boundaries. This inevitably leads to entrapped dry area at the four corners, as shown in Figure 6.4 at 652s. Actually, air entrapments can be detected if this function is activated in PAM-RTM in this simulation, as presented in Figure 6.5. Note that the volume change of the air pockets will follow the ideal gas equation.

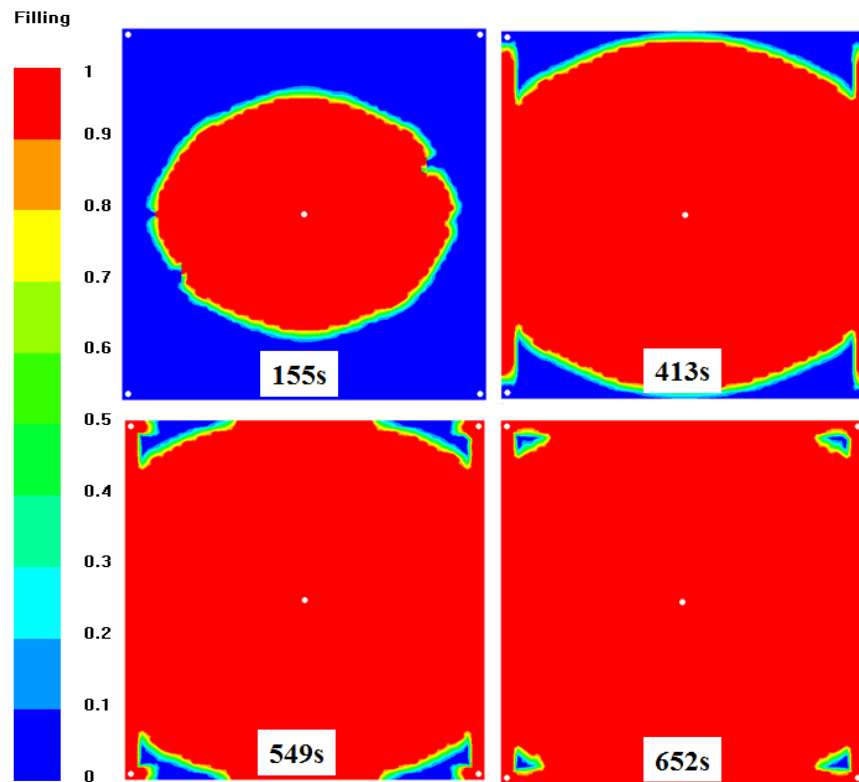


Figure 6.4 Filling process with central injection

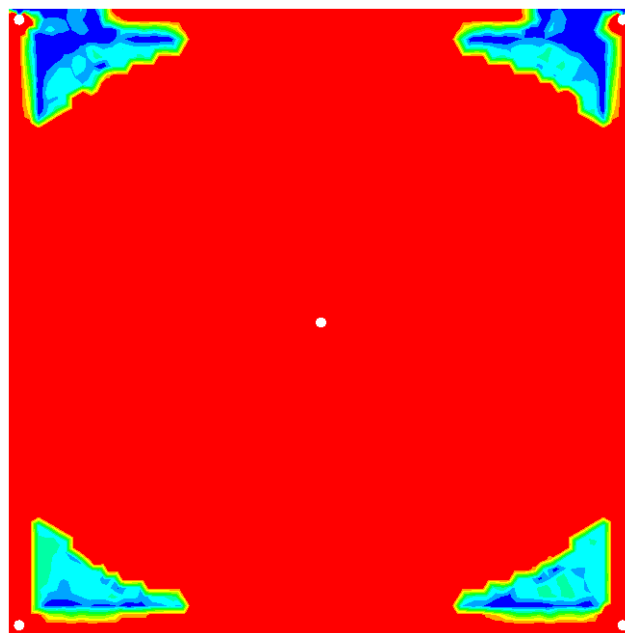


Figure 6.5 Air entrapments with central injection

Figure 6.5 show the overall filling time across the whole panel.

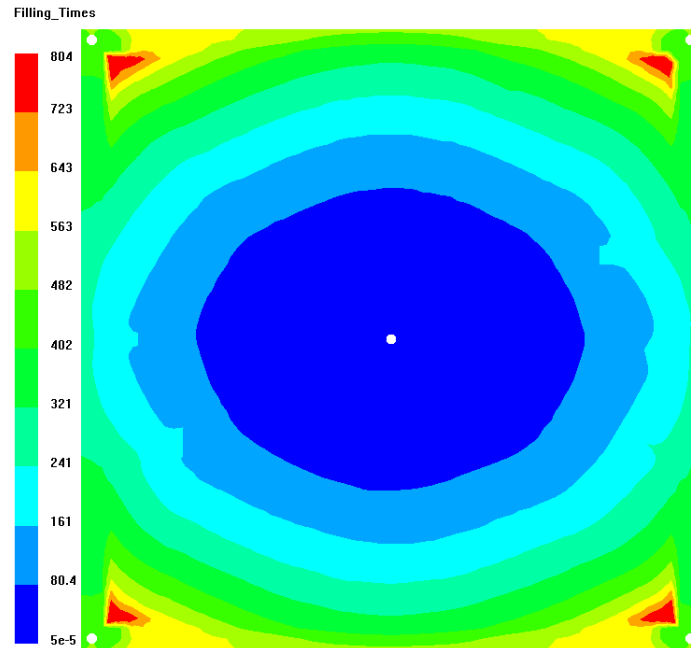


Figure 6.6 Filling time distribution with central injection

To make a comparison, a different kind of injection method was applied: the resin was injected from four corners of the panel, and the vent was located at the centre of the panel. The resin pressure at four gates is the same as that by central injection. It can be seen that the flow front firstly progress through the runners and will impregnate into the preform later, as shown in Figure 6.6. The total injection time is much shorter, and no air entrapments can be found due to the comparatively even flow progress from four injection gates. Note that in this study the four runners around the preform possess the same dimensions, thus the flow fronts from four corners show a symmetric feature. However, air entrapments may occur around the central vent if the four runners possess different dimensions. Figure 6.7 presents the filling time distribution across the whole panel.

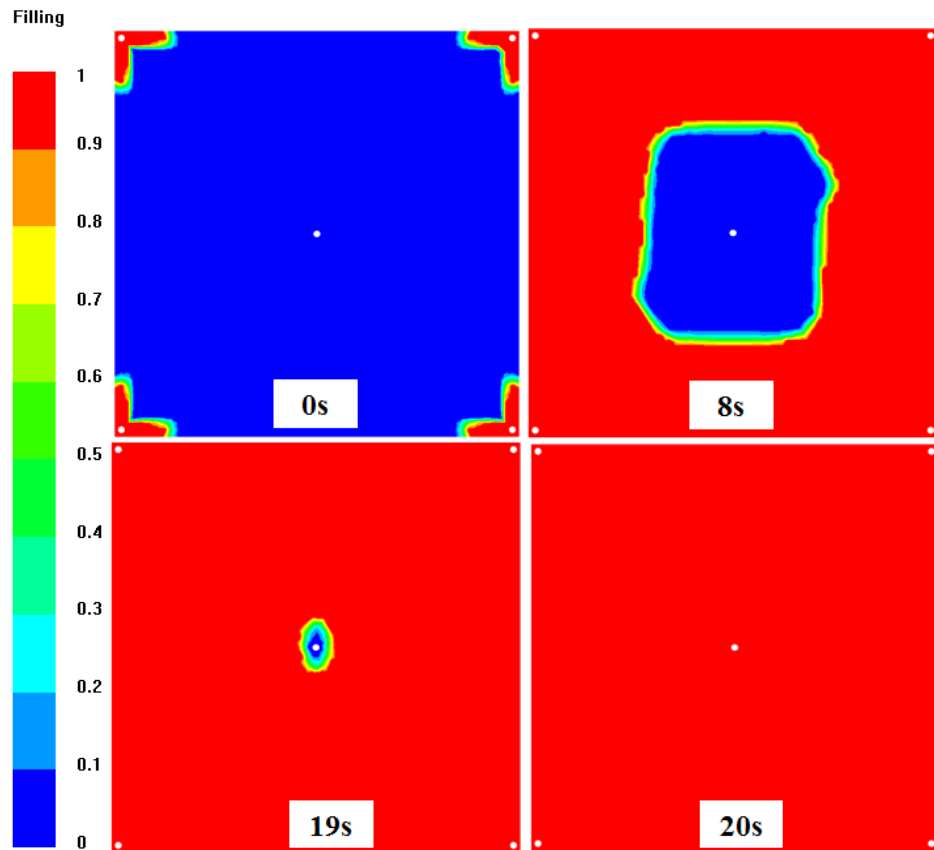


Figure 6.7 Filling process with four corner injection

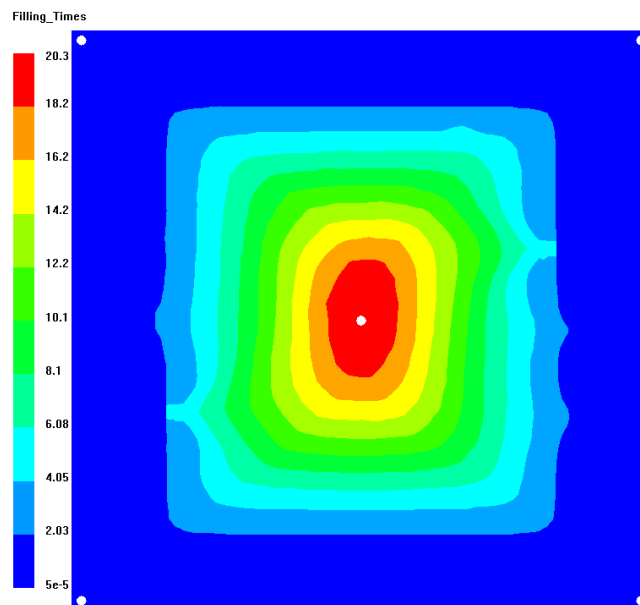


Figure 6.8 Filling time distribution with corner injection

The permeability difference between the preform and the runners determines the flow pattern and the impregnation process during RTM. The flow front also depends on the permeability tensor inherent to the fabric. The uneven flow fronts and merging of different flow fronts may lead to air entrapments or dry spots. Therefore, proper design

of the locations of gates and vents in the mould is required for successful injection. Another influence of different injection methods lies in total mould filling time. The injection should be completed before the resin starts to gel or cure. This is especially essential for large-scale components. In this study, it can be concluded that the corner injection method saves time over central injection.

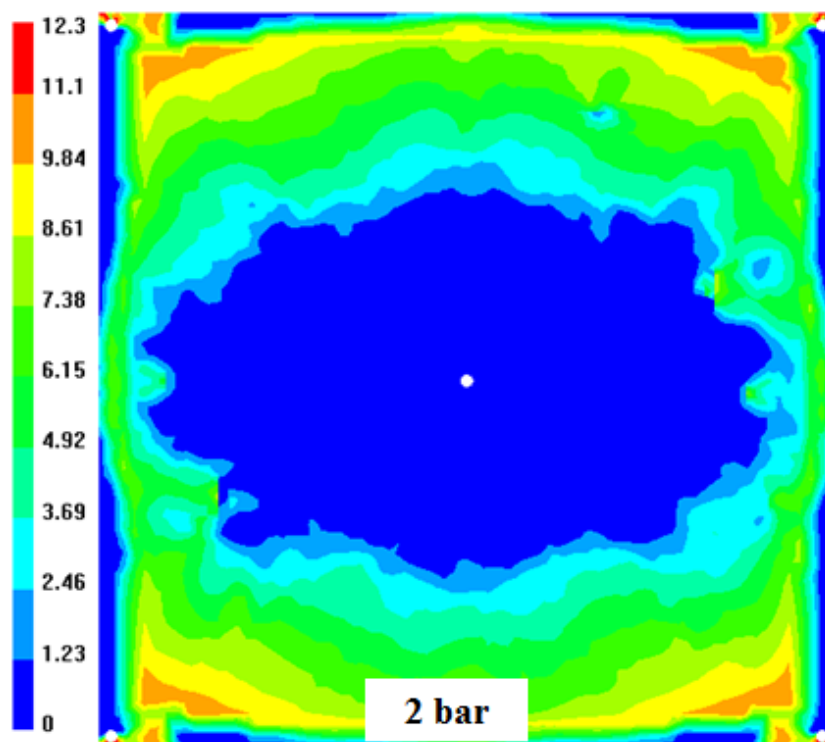
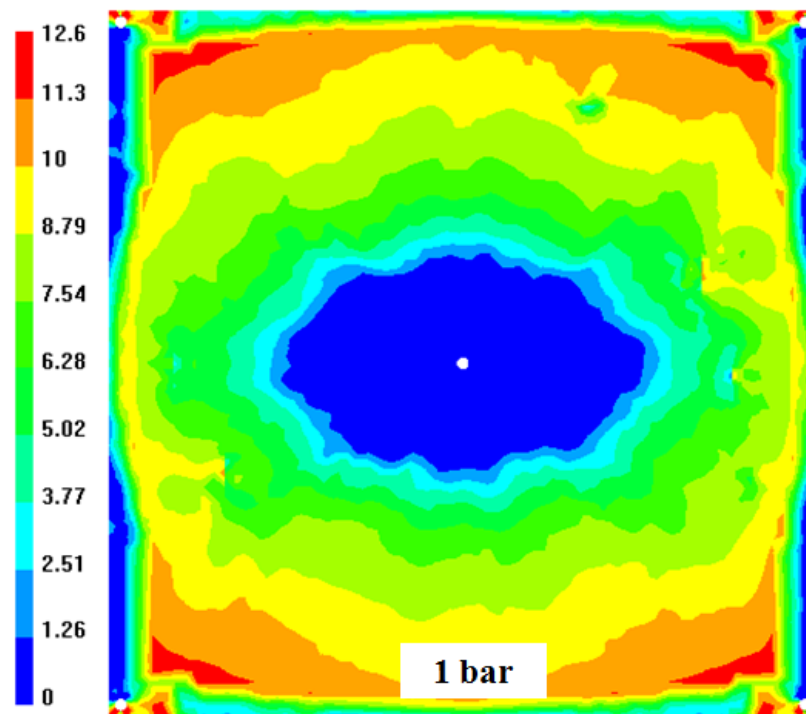
6.2.3 Influence of injection pressure

In addition to macro-scale defects such as air entrapment generated defects such as micro-void should also be eliminated during RTM. It has been addressed in section 2.5 that the generation of these defects are related with the comparative flow rates within or between fibre yarns. Note that the dual flow is driven by the capillary force within fibre yarns and the viscous force between fibre yarns. As summarized in section 2.5, it has been investigated by researchers that the content of void (micro and meso) is related with the varied capillary number. Thus, it is assumed that the void content can be minimized by obtaining the optimized capillary number, which can be achieved by flow rate optimization.

In PAM-RTM, resin flowing through the macro-scale model is solved (or controlled) by Darcy's law. Based on the relation between resin pressure and velocity described by Darcy's law, the above mentioned flow rate optimization process can be realized by changing the injection pressure.

According to the void formation theory based on capillary number, the relation between void content and capillary number should be acquired in advance. Generally this relation can be obtained from experiments [16]. As for this present case, the aim of this study is to investigate the influence of various injection pressure on the void content, void data from the reference [16] is applied here.

In this research, firstly the influence of various injection pressures was selected on the plate with central injection; the injection pressure was increased from 1bar to 4bar; in all four runs were completed. With void functions set in PAM-RTM, macro and micro void content under each injection condition can be predicted and summarized. Figure 6.8 presented the macro void distribution under the four injection conditions (from 1bar to 4bar).



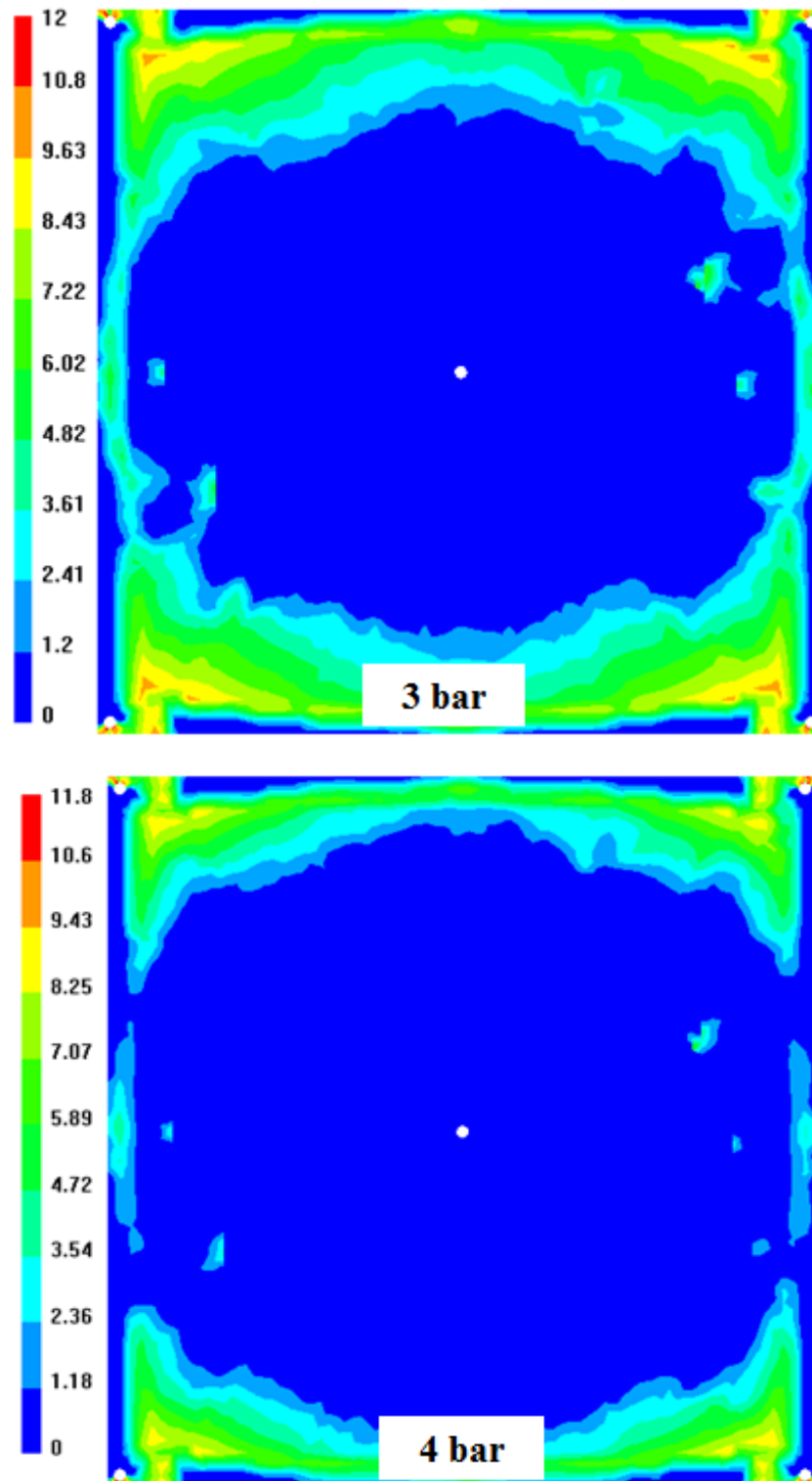
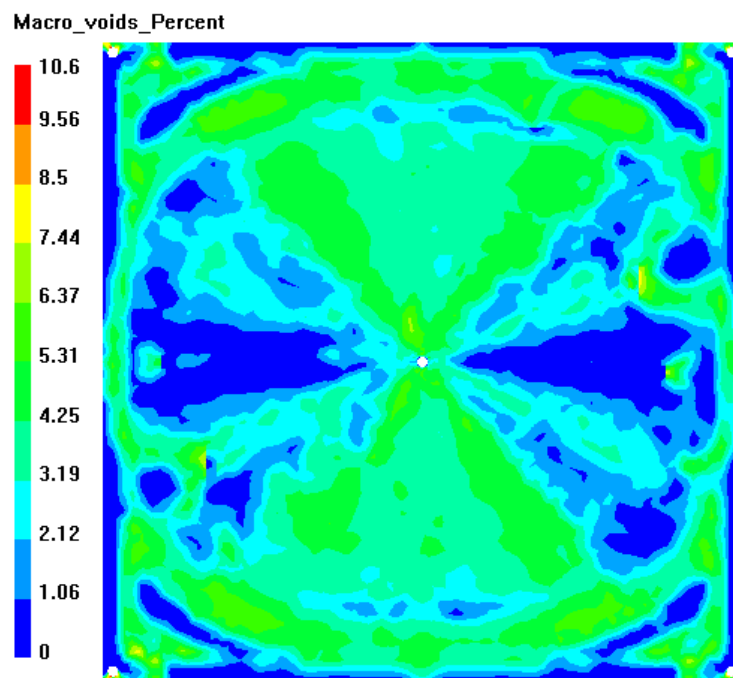


Figure 6.9 Modelling macro void distribution under various injection pressures

It can be deduced from Figure 6.9 that macro-void distribution area decreases with the increasing constant injection pressure; however, in areas near the plate boundaries, void content can reach around 7%-11%; besides, there is a decreasing distribution trend from centre of the plate (or the injection gate) to the corner of the plate (or the vents). Note that the void detection function within PAM-RTM is based on the current single

calculating step; the determination of void generation is related with the exact flow front velocity. Void contents (or distribution) will not change after the flow front passes each element during the simulation. Thus, void transportation and the change of volume of void cannot be simulated with PAM-RTM. Note that in this simulation, micro-void are not presented here as un-expectedly high micro-void contents were obtained under these injection conditions. This may be caused by the inappropriate pre-set void content function related with flow front velocity.

Based on the relation between void formation and capillary number, void contents can be reduced by obtaining the optimum capillary number locally at flow front arrival t . According to the definition of capillary number in equation (2.23), the influencing factors include the viscosity of the resin, the contact angle between the resin and the fibres, and the flow velocities. Thus, the optimization process of local capillary number can be achieved with a velocity optimization function, which can be realized by varying the injection pressure during the flow simulation process.



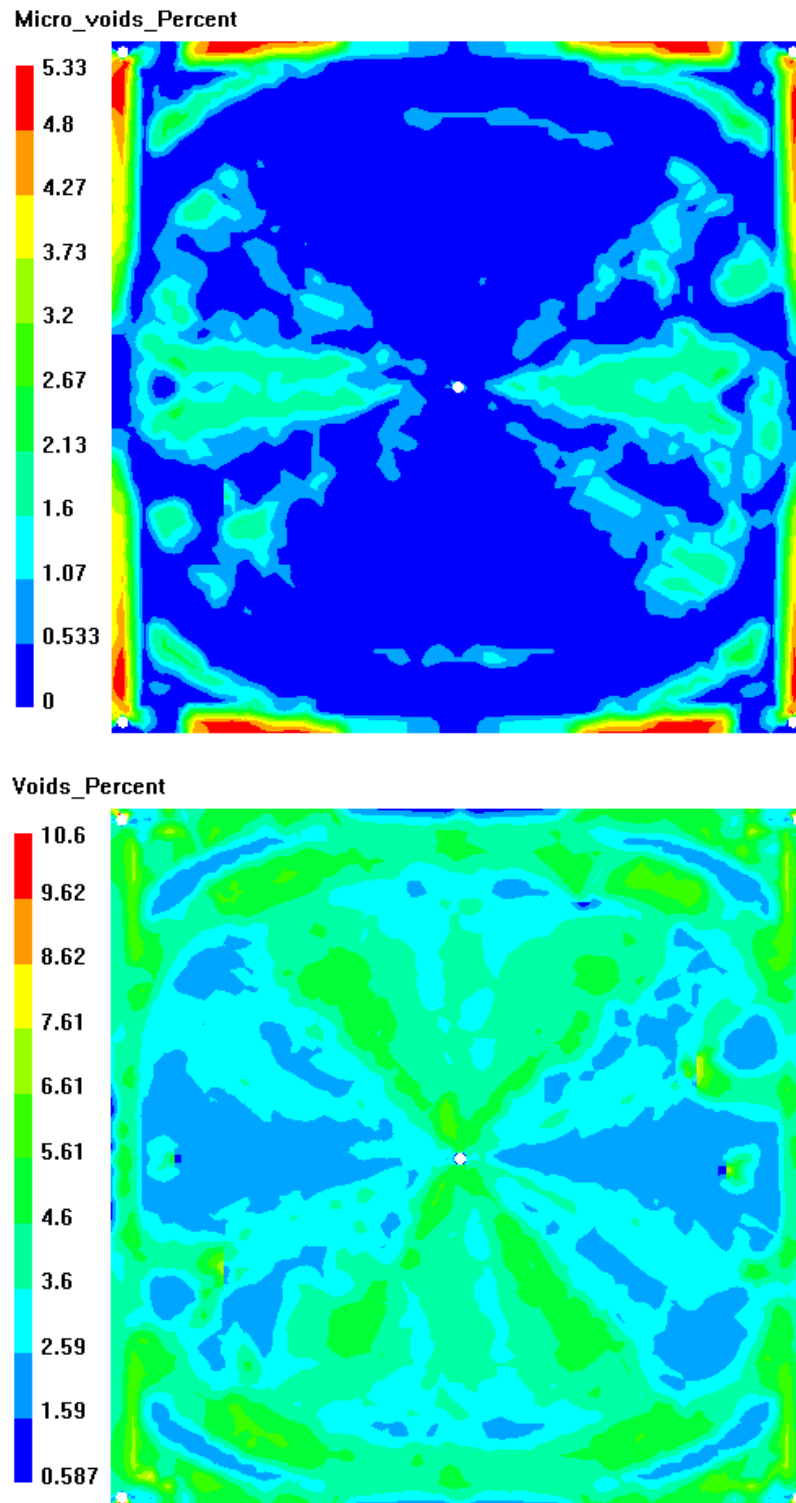


Figure 6.10 Modelling void distribution and content with velocity optimization

With the velocity optimization function on in PAM-RTM, the injection pressure can be adjusted automatically, which is based on the relation between void-velocity function which is pre-set within PAM-RTM. Figure 6.10 presents the macro-, micro-, and total void distributions across the plate after the velocity optimization process. Compared with the original simulation without velocity optimization, macro-void distribute more

evenly across the plate, and the void content is below around 7%. Besides, with the micro-void contents below around 3%, the total void content is around 5% across the whole plate. It can be seen that both the macro-void and micro-void contents are reduced due to this velocity optimization procedure.

Note that the void formation model within PAM-RTM is based on the discretized elements across the plate. The detection of void formation depends on the exactly given velocity when the flow front arrives at element. Thus, only one kind of void (macro- or micro-) can appear at each element. Thus, as the permeability tensor is anisotropic across the modelled preform, the macro- and micro-void distribution also show some kind of symmetric characteristic, just as shown in Figure 6.10.

By inserting a sensor point at the injection gate, the optimized injection pressure can be presented as shown in Figure 6.11.

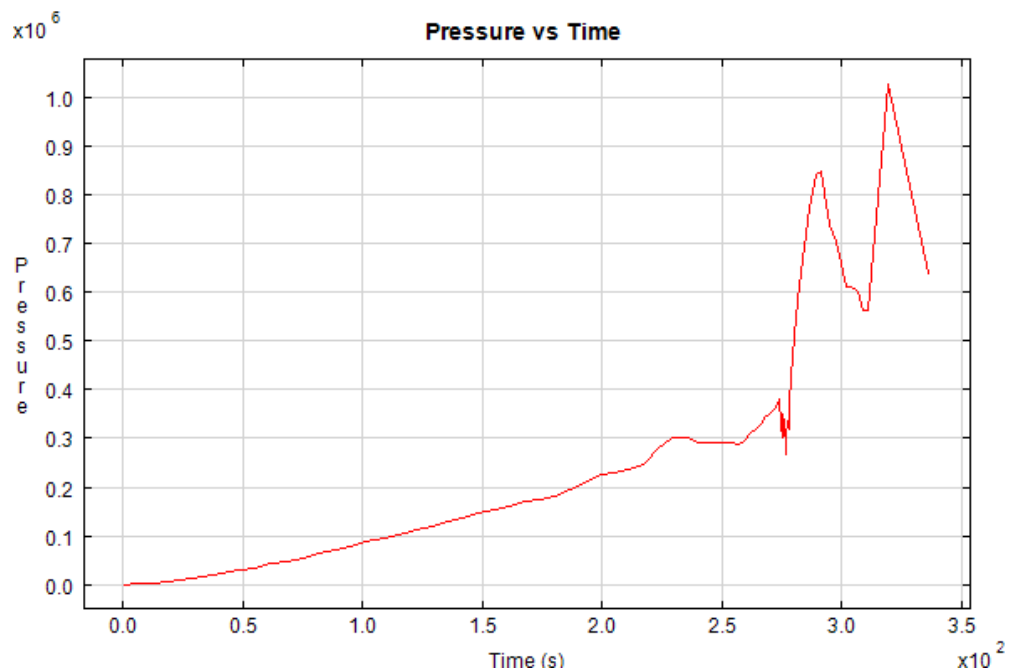


Figure 6.11 Optimized injection pressure

6.3 Experimental characterization of defect generation during RTM

6.3.1 Defects characterisation methodology

The existence of void within composite materials will deteriorate the mechanical properties such as the inter-laminar shear [127] and shear strength [128]. In this study, the content and distribution of void were characterized with an optical microscopy method. Panels with various processing parameters were manufactured. Specimens with in-plane dimension of 25mm x 15mm were cut from the moulded panels. Because

of the inherent geometric anisotropy of the fabric structure, defect formation in warp and weft direction should be analysed, hence the specimens were taken from that panel as shown in Figure 6.12. To study the defects formed inside of the panels, the through-thickness cross-sectional area along the longer side of the specimen was examined under an optical microscope. The cross-sections were ground and polished to obtain a flat and clean surface. The grinding and polishing was performed on several steps, by gradually refining the size of grinding paper (240, 320, 600, 800, 1000, 2500 /grains), followed with alumina powder (grain size 1 μm). To make this process easier, the specimens were placed in a cylindrical pot with casting resin in it, and the cured cylinders were then polished with a grinding machine. A specimen prepared for optical microscopy is shown in Figure 6.12.



Figure 6.12 Specimen prepared for optical microscopy

The cross-sections of the polished specimens were examined with the optical microscope Zeiss Axiolab. Different resolution can be obtained by applying lenses with different magnifications. Due to the different reflections of the incident light, void formed within the specimen can be distinguished from the resin and carbon fibres. The captured cross-section images can be processed with image processing software (e.g. ImageJ).

6.3.2 Experimental design

In the current study, the influences of different processing parameters on the void formation and distribution during RTM process is investigated by manufacturing panels with various conditions. Besides, void distribution is also investigated along the specific directions.

Three panels are made with a thickness of 4.2mm, with the fibre volume fraction reaching around 53%. Central injection with constant 2bar is applied to all the three panels. The influences of mould temperature and vacuum condition on the void content are studied. Table 6.3 presents the various injection conditions.

Table 6.3 RTM process information

Panel	Cavity thickness	Injection method	Mould heating	Vacuum
CF4.2_2A	4.2 mm	2bar central	No	No
CF4.2_2AH	4.2 mm	2bar central	Yes	No
CF4.2_2VAH	4.2 mm	2bar central	Yes	Yes

In order to study void distributions across the panels, specimens are selected at various locations, as shown in Figure 6.13. In this way, void contents along warp and weft directions can be analysed across the panel.

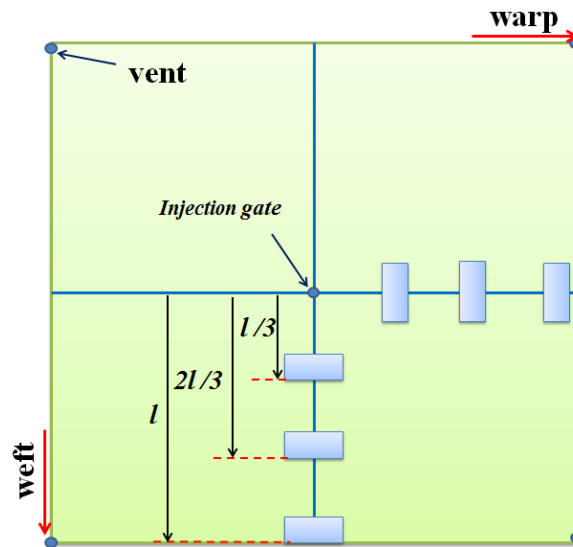


Figure 6.13 Specimen location for the panels made with RTM

6.3.3 Analysis of void content and distribution in weft direction

According to the specimen selection method illustrated in Figure 6.13 and the void characterization method illustrated in last section, void contents and distributions are characterized across these panels.

Figure 6.14 presents the specimen cross sections selected in the panel CF4.2_2A. It can be seen that macro-void are mainly generated at the gaps formed by the intersection of warp yarns and weft yarns, especially at the tips of weft yarns. Micro-void generated within weft yarns shows a random distribution.

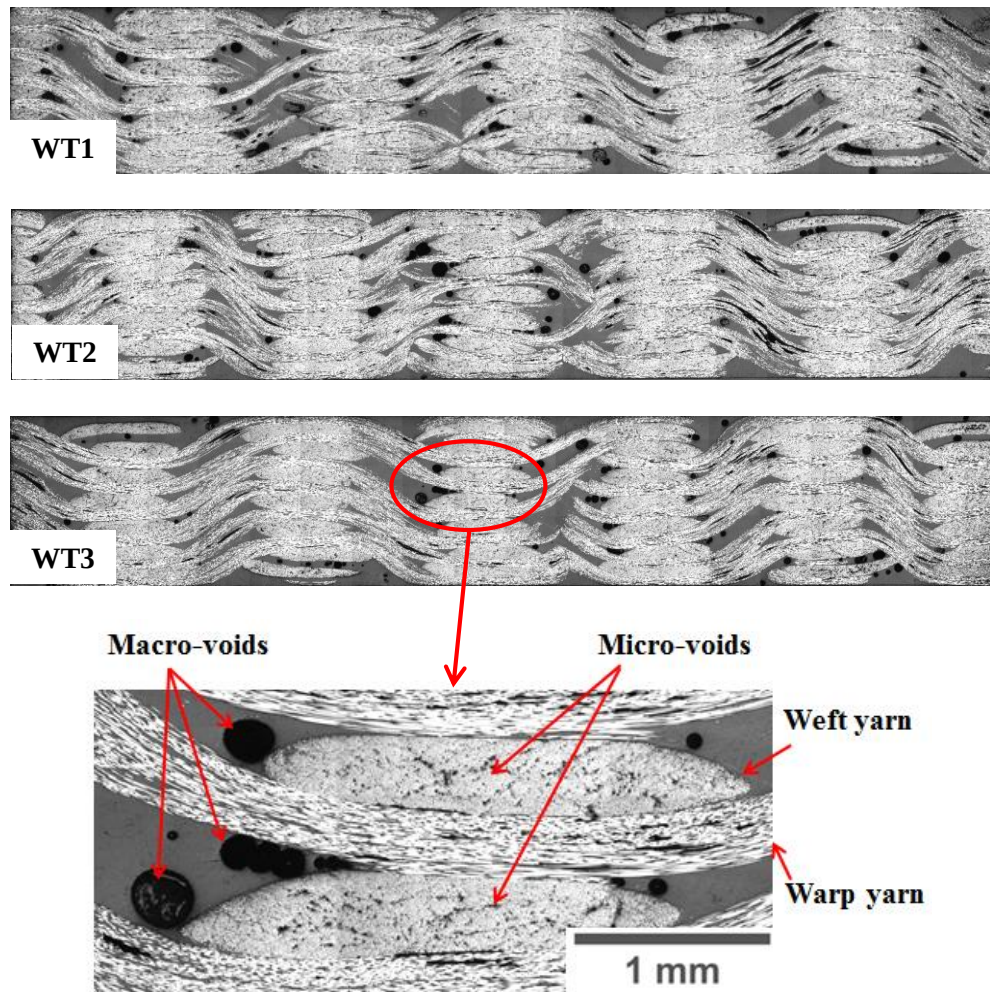


Figure 6.14 Cross sections of specimens in weft direction selected from the panel CF4.2_2A: note that WT1, WT2, WT3 are names for the specimens selected in various locations along weft yarn direction; the bottom image is zoomed-in area from WT3 cross section

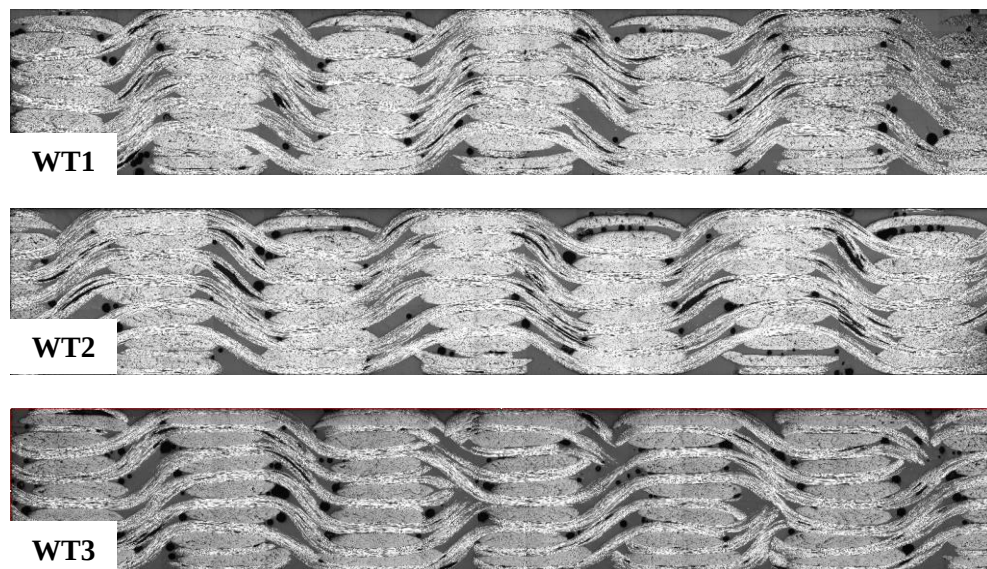


Figure 6.15 Cross sections of specimens in weft direction selected from the panel CF4.2_2AH: note that WT1, WT2, WT3 are names for the specimens selected in various locations along weft yarn direction

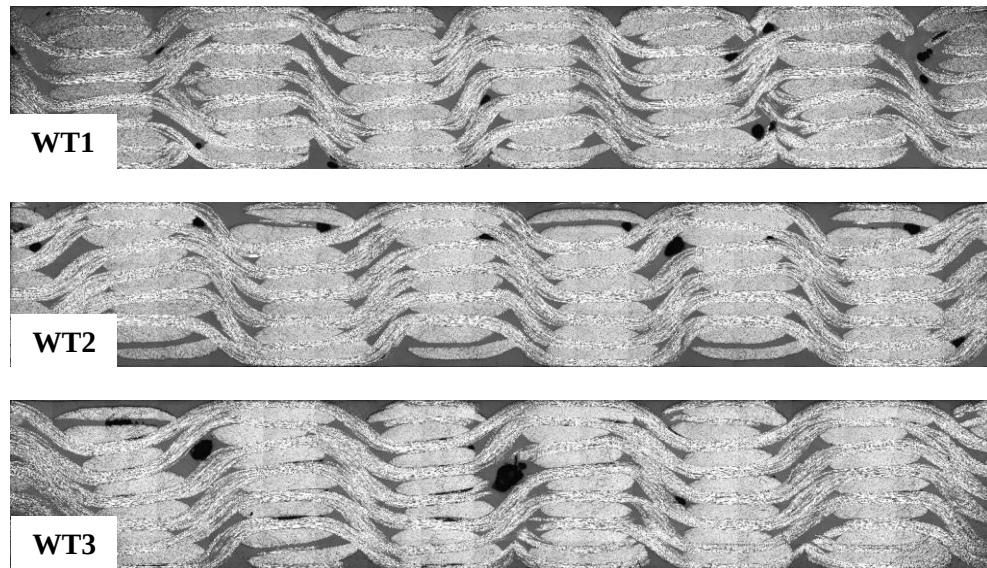
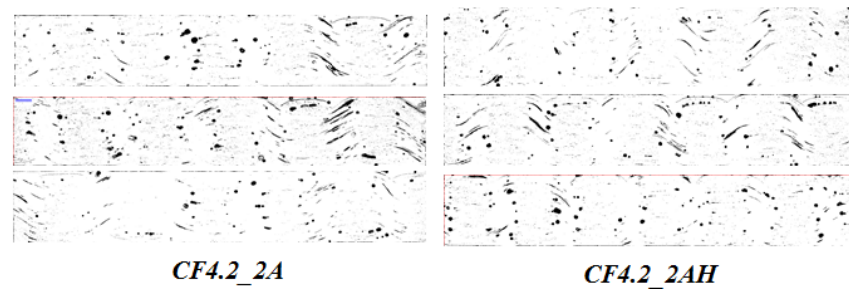


Figure 6.16 Cross sections of specimens in weft direction selected from the panel CF4.2_2VAH: note that WT1, WT2, WT3 are names for the specimens selected in various locations along weft yarn direction

Figure 6.15 and 6.16 present the cross sections of specimens selected from the manufactured panels CF4.2_2AH and CF4.2_2VAH respectively. After catching images of these specimen cross sections with optical microscopy, these images are then processed with the software ImageJ. With ImageJ, firstly the brightness and contrast of these images are adjusted to obtain a clear image from which void, matrix and fibre yarn can be distinguished separately. By setting proper thresholding values for each image, the void can be distinguished and their contents can be calculated automatically with ImageJ, as presented in Figure 6.16. Note that the characterized void with this method are a contribution of macro-void and micro-void.



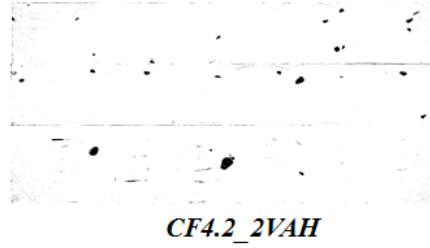


Figure 6.17 Processed images for void characterisation

Figure 6.18 presents comparison of void contents in weft direction from these three panels. It is indicated that the application of mould heating or vacuum condition reduced the possibility of void formation during RTM; especially for the panel produced with vacuum condition (CF4.2-2VAH), the average void content is decreased to around 1%. Besides, there seems a decreasing trend of void contents with the increasing distance from the injection gate. This feature is obvious with the first panel (CF4.2_2A), in which the void content ranges from 3% to 6.5%.

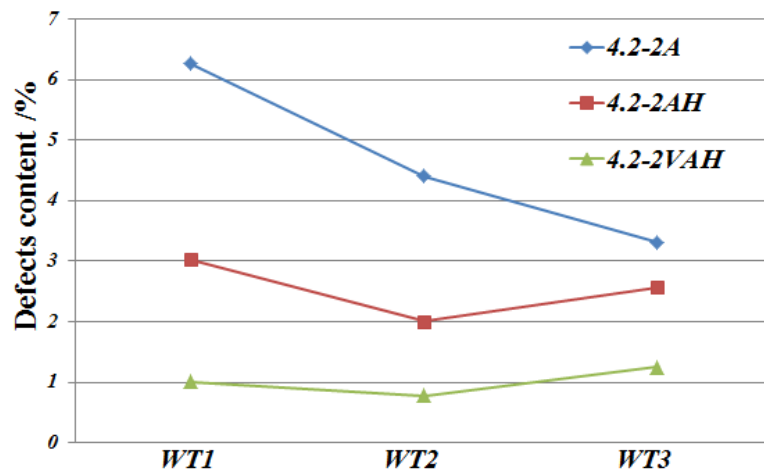


Figure 6.18 Comparison of void contents in weft direction among the three panels

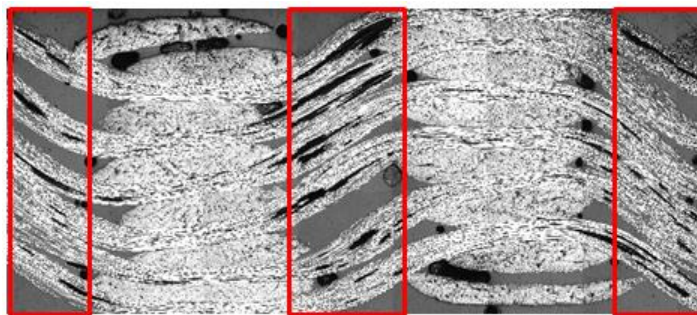


Figure 6.19 Void distribution in warp yarn (within the red square zones) in specimen WT1 from panel CF4.2_2A

Note that although the void can be distinguished by macro-void between fibre yarns and micro-void within fibre yarn, the void characterization from processing the cross sectional images will inevitably show biased results, as this method is based on calculating the void area across the whole cross section. However, this may bring biased results as void within warp yarns will show large area percentage, as shown in Figure 6.19. Thus, this method should be applied carefully. Regarding the vacuum condition, the percentage of macro-void between fibre yarns is obviously reduced due to the evacuation of air from the mould. This can be applied as optimization methods for industrial RTM manufacturing process.

6.3.4 Analysis of void content and distribution in warp direction

Specimens selected in warp directions from these three panels are observed with the same methodology. The observed cross sections of these specimens are presented in Figure 6.20, Figure 6.21, and Figure 6.22.

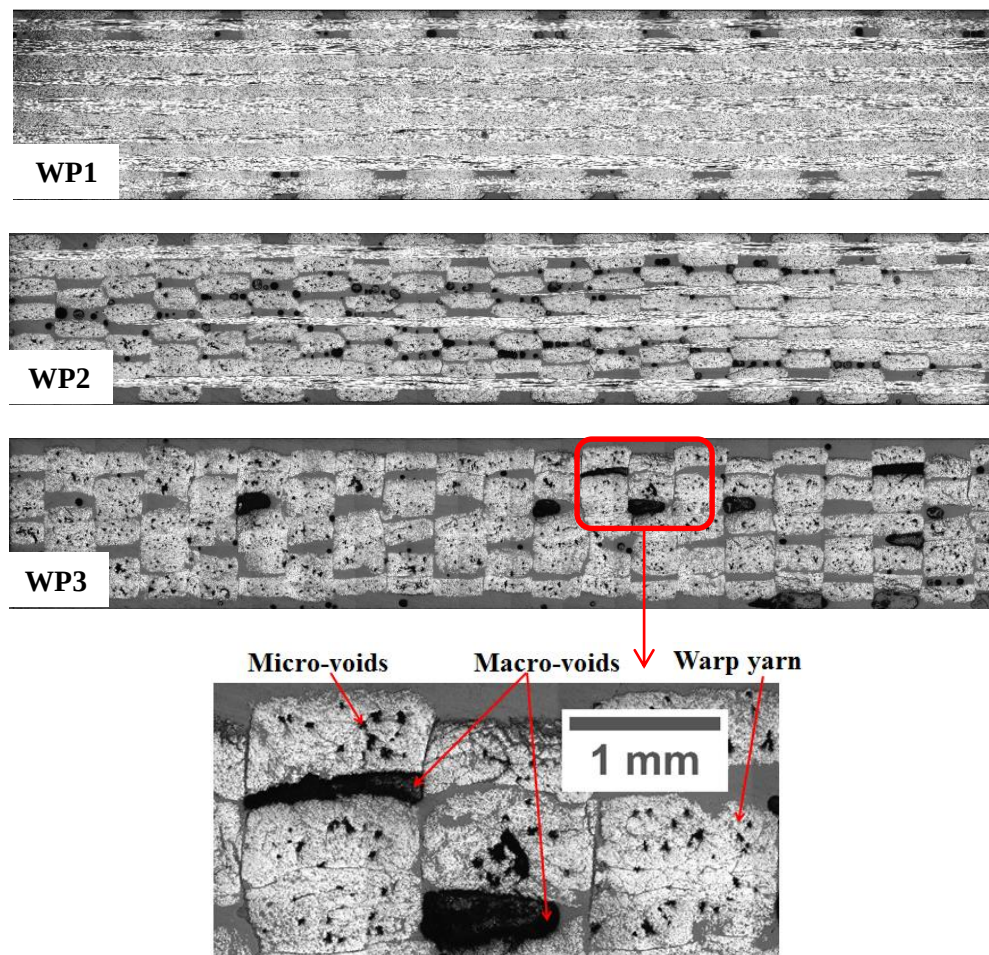


Figure 6.20 Cross sections of specimens in warp direction selected from the panel CF4.2_2A: note that WP1, WP2, WP3 are names for the specimens selected in

various locations along warp yarn direction; the bottom image is the zoomed-in area from specimen WP3

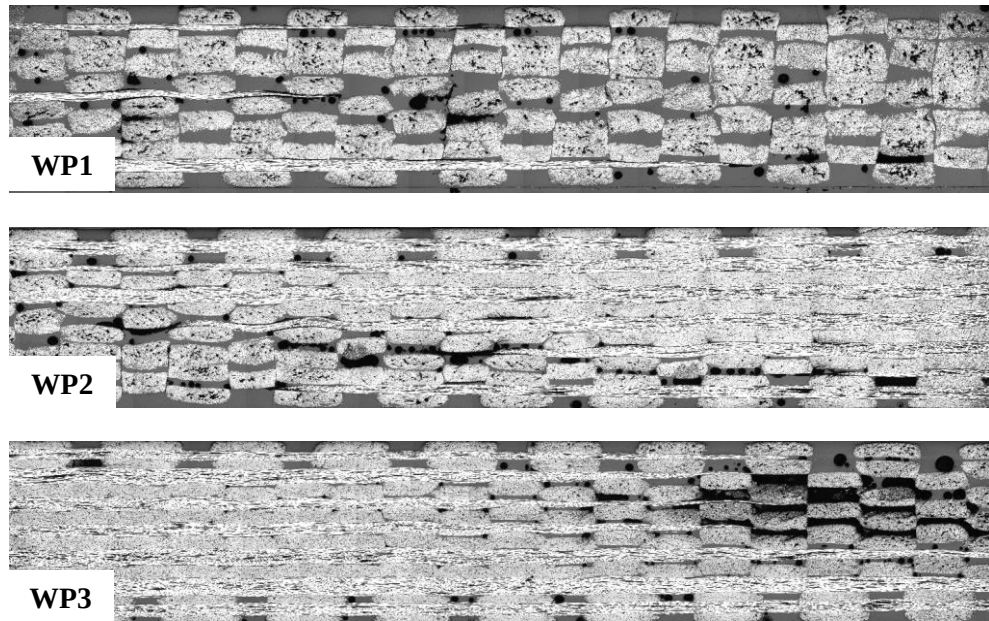


Figure 6.21 Cross sections of specimens in warp direction selected from the panel CF4.2_2AH: note that WP1, WP2, WP3 are names for the specimens selected in various locations along warp yarn direction;

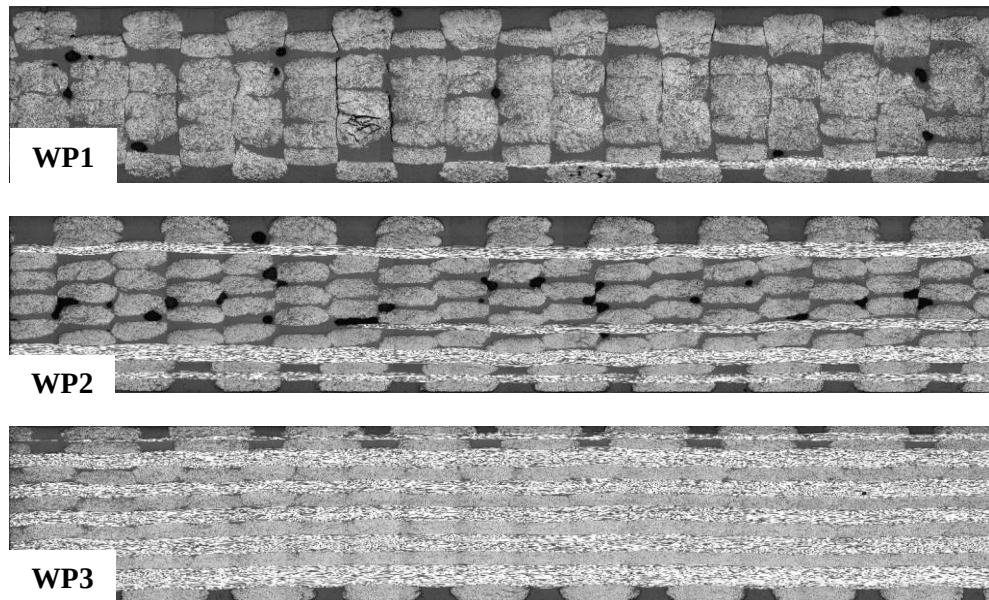


Figure 6.22 Cross sections of specimens in warp direction selected from the panel CF4.2_2VAH: note that WP1, WP2, WP3 are names for the specimens selected in various locations along warp yarn direction;

Generally, both macro-void between fibre yarns and micro-void within fibre yarn can be observed. From the comparison of the zoomed in area between Figure 6.14 and

Figure 6.20, it is indicated that micro-void within warp yarns generally possess a larger dimension than those within weft yarns, as there are comparatively larger pores within the ‘loose’ warp yarn at the ‘bridge’ locations (location A in Figure 6.23).

Besides, due to the internal weave structure of this 3D woven fabric, the selection of specimen location also affects the following void characterization results. As presented in Figure 6.23, as the warp yarns are highly stacked at crossover locations (location B in Figure 6.23), no channels can be found if the observed cross section is selected at this location, therefore, there are no places for macro-void formation either; on the other hand, macro-void can be observed at the ‘bridge’ locations (location A in Figure 6.3. This location related feature will inevitably have an influence on the local void contents.

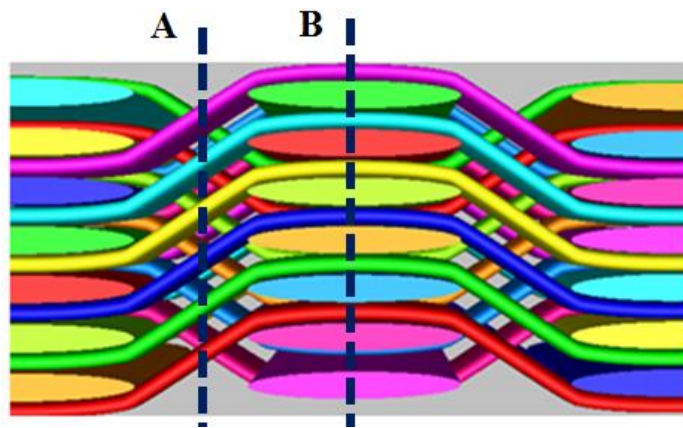


Figure 6.23 Specimen locations

The processed cross sectional images are presented in Figure 6.24. It is indicated that micro-void are almost eliminated with applied vacuum condition (panel CF4.2_2VAH).

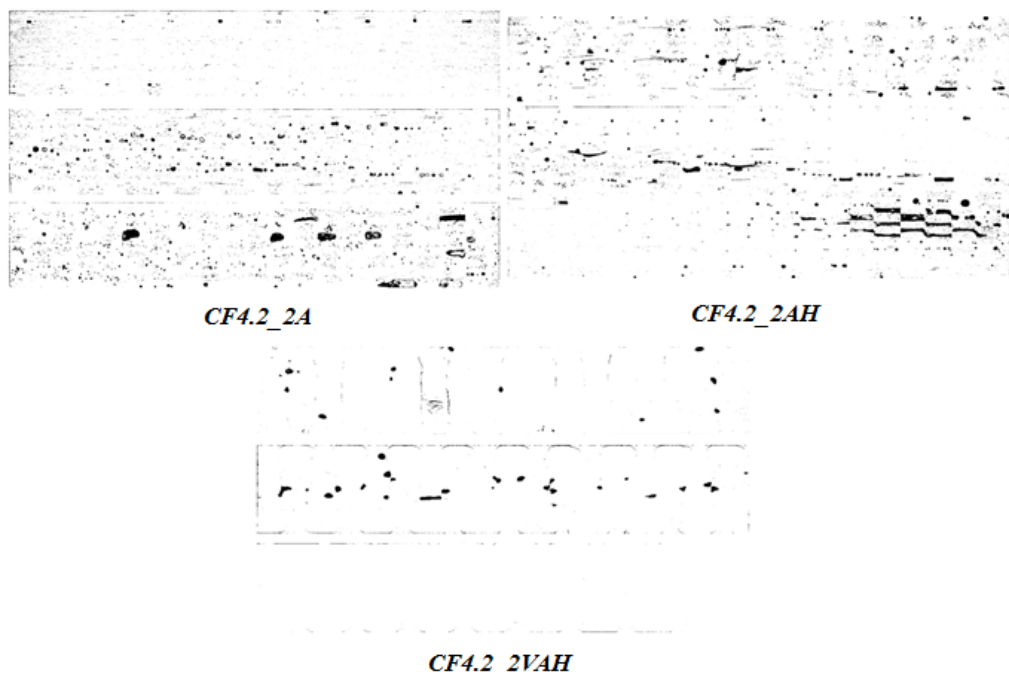


Figure 6.24 Processed images for void characterisation for specimens in warp direction

The void contents in the warp direction among the three panels are summarized in Figure 6.25. It can be seen that for panels CF4.2_2A and CF4.2_2AH, the void percentage in warp direction shows an increasing trend with the increasing distance from the injection gate (from WP1 to WP3). Compared with mould heating, vacuum condition still helps eliminate void formation during RTM.

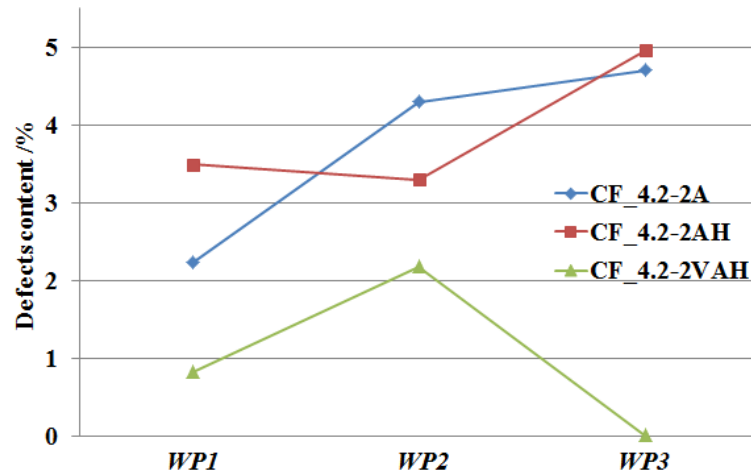


Figure 6.25 Comparison of void contents in warp direction among the three panels

6.4 Discussion and Conclusions

The RTM process modelling theory and technique has been discussed in this chapter. The influences of various injection conditions on the formation of various defects has been investigated based on the macro-scale modelling software PAM-RTM. Specifically, the formation of dry spots within final composite components can be avoided by the proper selection of injection gates and vents. Mould filling time can also be reduced. Thus, the production cost and cycle time can be decreased. Besides, the influence of injection pressure change on the formation of macro and micro void has been modelled based on a capillary theory. With the optimization function in PAM-RTM, defect contents can be reduced to the minimum by changing the injection pressure profile. However, this optimization process can only be applied on the basis of a known relation between capillary number and void contents from experiments.

Experimental characterization of defects contents and distribution was studied on the panels manufactured with various conditions, including the application of mould heating and vacuum condition. The voids contents in warp and weft direction was studied. It is found that macro voids mainly distributing at the channels between fibre

yarns; micro voids within warp yarns possess higher volume than that of in weft yarns. Besides, for various RTM processing parameters, voids contents change with the distance from the injection gate.

It should be noted that the void transport and elimination is not considered in PAM-RTM with capillary theory. There is also still work to do for obtaining the relations between voids contents and capillary number for various materials. Besides, voids characterisation based on observing cross sectional image is sensitive to the specimen location, especially for fabrics with complicated internal structure. Thus, more efficient and reliable characterisation techniques need to be investigated to achieve more precise results.

Furthermore, due to the voids generation mechanism used in PAM-RTM (based on capillary effect), it is not reasonable to compare the experimental results from RTM panels with the predicted voids contents and distribution, as there are different capillary numbers in warp and weft yarn directions respectively. This determination of capillary number in various fabrics will be continued in the future study.

7. Conclusions and Future work

The research work in this thesis is originated from the cooperative project ‘Simulation Methodology for Impact Damage in Composite Components of Aero-Engines - Theoretical Models and Experimental Validation Strategy’, between ACAE (AVIC Commercial Aircraft Engine. Co., ltd) and the University of Nottingham. Due to the work package description, this research mainly consists of textiles permeability characterisation and defects generation during manufacturing of composite components with RTM. Both numerical and experimental methodologies are investigated.

In RTM modelling, textile reinforcement permeability plays an essential role. Usually textile permeability can be determined experimentally with particular tooling, such as the experimental characterisation approach described in Chapter 3. However, due to the variability inherent within the preform, many repeats must be taken to obtain a credible result. To avoid this tedious measurement work, permeability prediction based on a unit cell approach has been developed in Chapter 5. Note that a unit cell is considered as the representative volume element (RVE) within a fabric. To generate the unit cell model with TexGen, X-ray micro-CT is applied to obtain the internal geometric features. The geometric variability is also studied in Chapter 3 and Chapter 5 as it greatly influences the permeability modelling results.

Due to the dual-scale flow characteristic within a unit cell model during flow modelling, the fluid-porous interface boundary condition is investigated in Chapter 4. Micro-scale models with random filament distributions are generated. By comparison of flow simulation results, it is found that in this research a non-slip wall boundary condition can be applied at the tow surface. However, it should be noted that this condition can be varied when there is a high overall fibre volume fraction for the preform.

Regarding defects generation during RTM, Chapter 6 presents a parametric study based on both numerical and experimental analyses. The influence of processing parameters such as injection pressure and gate or vent locations on void generation and distribution are investigated. Experimental characterisation was based on RTM-processed panels with various processing conditions.

Generally the present work is based on a multi-scale study of RTM-related process modelling of 3D woven composites, including the fluid-porous interface boundary condition modelling in micro-scale, permeability modelling with a unit cell model in meso-scale and RTM process modelling in macro-scale. Also, experimental work is

conducted to make a comparison or validate against the simulation results. Note that as part of the whole project, this research fulfilled all the research tasks required: a permeability modelling toolbox and technique for 3D woven fabrics has been developed, and its ability to predict permeability has been demonstrated through experiments; void formation mechanisms and processes have been investigated through parametric studies in macro-scale process modelling with PAM-RTM, as well as with designed experiments.

As this research work is based on the urgent requirement from aerospace industry, the findings present in this thesis can be directly transformed into engineering applications in aerospace composites, including composite fan blade and containment case. Together with other three work packages, this work focuses on the manufacturing process of composite components. The specimen required for whole project are also prepared with the support and knowledge from this present work. From an overall point of view, this work concentrates on the integrated process modelling of RTM technology. The essential part lies in the precise illustration of real fabrics, from fibre distribution within fibre yarns, changes of yarn path and geometry, deformation of fabric in the macro-scale. For RTM process modelling, especially for modelling resin flow within and between fibre yarns, this geometrical sensitivity needs much more attention. The effectiveness of simulation methodology can be validated against experiments. In this present work, permeability measurements are compared with prediction results based on optimized unit cell. Note that the validation of simulation depends on the consistence between the applied model and the real process. Thus, for macro-scale modelling in Chapter 6, as the capillary number for the present 3D woven fabric is not determined yet, parametric study of voids formation between RTM process modelling and experiments cannot be compared directly. This work will be continued in future research.

It can be seen that the present study covers a wide research scope related with RTM-based processes and gives an overall view. However, further study can be carried out as identified below:

- 1) What the fluid-porous boundary condition is like when there is a high fibre volume fraction for the preform: In this case, the flow within the fibre tow may become comparative with the channel flow between fibre tows, so the intra-tow flow cannot be neglected during permeability prediction with a unit cell methodology. Thus, a more precise interface boundary condition should be developed;

- 2) Geometrical variability exists widely across the fabric, and it will have a significant effect on the permeability prediction based on unit cells, as well as the resin flow modelling in macro scale. Note that not all variables are included in this research, such as the effect of yarn path and shape variation;
- 3) Based on defect generation mechanisms during RTM, the capillary number or capillary force needs to be determined experimentally, so this parameter can be applied in macro scale modelling software such as PAM-RTM. Also, the determination methodology of void contents and distribution can be developed, as the optical method used in this research may result in inaccurate results.

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