On the variability of permeability induced by reinforcement distortions and dual scale flow in Liquid

Composite Moulding: A review

M. Bodaghi^a, S.V. Lomov^b, P. Simacek^c, N.C. Correia^a and S.G. Advani^c

a INEGI-Institute of Science and Innovation in Mechanical and Industrial Engineering, Campus

FEUP, Porto, Portugal

b Department of Materials Engineering, KU Leuven, Leuven, Belgium

c Center for Composite Materials and Department of Mechanical Engineering, University of Delaware,

United States

Abstract

A comprehensive review of experimental and analytical studies since 1990 on the variability of permeability induced by fibrous media (reinforcement) distortions across the composite part manufacturing chain is presented. The review covers variability in as-supplied dry reinforcements, which include tow waviness, tow size and tow shape variations, interconnectedness of the pore space inside the tows (tortuosity), and changes during production, handling or storage, affected by the reinforcement deformation (non-uniform shearing, stretching and compression) and nesting of the layers in the laminate. The review clearly indicates that the interdependencies among these parameters is one of the root causes of the spatial variation of the permeability of the preform. This has spurred recent work to quantify flow front and filling time variabilities and development of optimal injection strategies using stochastic flow simulations. State-of-the-art experimental and theoretical approaches and modelling of this stochastic behaviour within numerical frameworks for the design of composite manufacturing processes are introduced and future outlook on the role of such variability at different scales is forecasted.

Keywords: A. Liquid composite moulding; B. Permeability; C. Statistical methods; D. Fabrics; E. Variability

1. Introduction

Liquid Composite Moulding (LCM) technology family includes Resin Transfer Moulding (RTM), vacuum-assisted RTM (VARTM) and, when flexible membranes or shells are used, vacuum infusion (VI) or other resin infusion techniques under flexible tooling (RIFT) variants. Experience with this technology has shown that it is possible to manufacture autoclave-quality components of complex shapes with medium scale production volumes [1]. LCM processes have been used to manufacture aircraft components such as the co-cured Wing Test Box [2], MRJ empennage box structure [3] and automotive components such as doors, roofs and side panels [4].

In this family of processes, a dry fibre preform is placed in a sealed mould cavity and either atmospheric pressure pushes the resin from its reservoir into the mould that is under vacuum, or the resin is injected into a rigid mould under positive pressure. Thermoset resins are commonly used in LCM due to their relatively low viscosity range from 0.1 to 0.5 Pa·s, which makes filling of small pores between fibres and between fibre tows possible within a narrow processing window. As thermoplastic resin viscosity is orders of magnitude higher than that of thermoset resins, the use of thermoplastic resins requires very

high injection pressures (>20 bar), creating a new challenge of fibres being displaced during the impregnation process [5] [6]. The goal in LCM is to have the resin fill all the empty spaces between and within fibre tows reliably and in the shortest time.

The fluid mechanics of the resin impregnating the preform, and the heat transfer phenomena associated with resin curing are two of the most important physical mechanisms in LCM processes, playing a key role in mould filling. Race tracking occurs when there are unplanned gaps usually near the edges of the mould or around inserts, reducing the resistance to flow through these channels, and leading to unbalanced flow paths. Race tracking and/or material variability can result in unsuccessful mould filling creating dry regions resulting in rejection of the part.

Over the last three decades, commercial LCM flow simulations have advanced and incorporated important process phenomena models. Such simulations do provide helpful guidelines for creating and improving tooling design. These commercially available process simulation packages like RTMflow [7], PAM-RTM originated from RTMflow by ESI Group, RTM-Worx developed by Polyworx [8], LIMS by the University of Delaware [9] [10] or SimLCM [11] are based on an approach that combines the quasi-steady finite element solution of the pressure field equations and a finite volume approach for the advancement of the flow front. Crucially, the calculations of the pressure field (and consequently flow front positions in time) are highly dependent on the quality of the permeability inputs that are provided. Hence, comprehensive characterisation of textile reinforcements along with its variability is essential. Due to a significant effect of the permeability field on mould filling predictions from simulations, the determination and characterization of permeability and its variability is therefore an object of continuous intensive research for the scientific community.

By using computer simulations of mould filling and curing stages [12][13], one can avoid time-consuming and expensive trial and error in the design, optimization and control of the LCM processes. An important factor which affects the reliability and validity of these simulations is the stochasticity and variability of the reinforcement geometry which is inherent to fibrous materials. The local variability of the textile geometry affects the local reinforcement permeability which influences the local resin filling pattern and cause voids if the resin prematurely reaches the final vent location before covering all the empty spaces between the fibres.

Flow simulations in LCM are based on flow of an incompressible fluid through rigid homogeneous porous medium and is modelled using the empirical Darcy's law (Eq.1) coupled with the mass conservation principle (Eq.2).

$$-\nabla p \quad (1)$$

$$(2)$$

where $\bar{u}$ is the (volume-averaged) "Darcy velocity", μ is the viscosity, p is the (volume-averaged) pressure, and $[K]$ is the permeability tensor of the fibrous porous medium.

Substituting Eq.1 into Eq.2 results in a governing equation for resin pressure:

$$- \quad (3)$$

Flow simulations solve the governing equation for pressure (Eq.3) in the domain of interest. The inputs include the mesh of the part geometry, location of gates for resin entry into the mould, boundary conditions of resin pressure or the pressure gradient (flow rate) at the gates and the values of resin viscosity and the permeability tensor. Note that in a finite element framework, one can specify a different permeability value for each element allowing one to evaluate the effect of permeability variation. Justification for the use of Darcy's law has been confirmed in many previous works. Bear [14] defined an upper limit for a Reynolds number (less than one) for the validation of Darcy's law. It has been shown that the Reynolds number (based on the diameter of assumed circular fibre tow) for the LCM family of processes to be of the order 10^{-1} , confirming the validity of Darcy's law [15]. As the shear experienced by the resin during the flow is not very high, one can treat the resin to be Newtonian.

Permeability tensor $[K]$ has units of $[m^2]$ which is defined by the geometry of the reinforcement, and is proportional to the square of the characteristic length of the reinforcement. In relation to this scale, one can broadly classify two basic types of textile reinforcements. One type or class would be the permeability of as "random mat"-like materials (Figure. 1A), which have no ordered meso-scale arrangements of fibres, and the average pore size is of one length scale. The other two are fabrics, which are produced by weaving (Figure.1B), stitching (Figure.1C) or braiding [15] or other textile manufacturing processes.

(Figure.1)

Each tow in these fabrics contain thousands of fibres. Channels between tows (as seen in Figure.1B and 1C) have widths from tens to few hundred micrometres; as the fibre diameters are about 5 to 7 μm (carbon fibres) or 10 to 20 μm (glass fibres), the spacing between the fibres is of the order of nanometers to a few micrometres [16]. Thus such textile reinforcements exhibit dual scale porosity: Channels between tows form the mesoscale porosity (inter-tow porosity) (Figure.2A) while spaces between fibres create the microscale porosity (intra-tow porosity) (Figure.2B) [17]. The intra-tow porosity is defined as the ratio of the channel volume (empty space) within a tow to the total volume of the tow. The inter-tow porosity is characterized by the ratio of the channel volume between the tows (by considering them solid and impermeable) to the total volume of reinforcement.

(Figure.2)

Thus for such fabrics, an identifiable network of dual scale porous media exists. Equations (1-3) describe the flow of a fluid assuming a single scale porous media. The phenomena occurring during a preform impregnation are more complex and include dual scale impregnation, progression of the flow front, capillary effects, and formation and transport of voids due to air entrapment. The reader is referred to Mehdikhani *et al.* [18] for a detailed analysis of the literature on the formation of voids and their influence on the mechanical properties of composites. Void formation itself, and the flow peculiarities that lead to it, are caused by the variations of and within the fibre reinforcement structure.

The sources of these variations reflected as variations in permeability values, which may be classified into two categories: First, variations of the measured values of permeability can be due to measurement errors. As permeability measurement is not standardised, the reported permeability values show a large scatter

between different methods and laboratories. This source is being addressed in a series of international permeability benchmark exercises [19][20][21][22]. A second possible source of variability is the inherent variation of the structure at the meso- and microscale of the fabric material which may not be immediately obvious to the naked eye. Moreover, the laminate is made by stacking multiple layers and their nesting could be different from one layup to another which will definitely change the overall architecture at these small scales and result in variations of the measured permeability values. Also all experimental measurements assume that the permeability is uniform across their preform sample and hence calculate a single permeability value which usually is not the case.

Figure 3 presents an overview of the different causes of variability in permeability which lead to variation of flow dynamics which can cause voids in LCM processes. During preforming step (Figure.3), draping and compaction of the fabric account for the geometric variations, which changes the fibre architecture and the cross-section shape of the tows. The absence of resin during the preforming leads to an increase in the magnitude of fibre movement as compared to prepreg processing where the resin acts as a binder. As the level of compaction increases, the interaction between adjacent fabric layers intensifies, resulting in nesting of these layers, which directly affects its permeability [23].

Variations in permeability influence the mould filling stage and consequently the quality of the final composite part (Figure.3), leading to two undesired manufacturing consequences [13]. First, to avoid compromising performance of the composite due to unavoidable defects due to this variability, one usually uses more conservative designs, with a factor of safety, making the composite part thicker and hence more expensive and heavy. Second, defects (e.g. dry spots) can lead to higher scrap which increases the cost of production.

(Figure.3)

The reproducibility of permeability values from one part to the next is not possible due to the intrinsic variation at the micro and meso scale of the reinforcements due to placement as well as nesting [21-26]. Therefore, identifying the significance of various uncertainty contributors to the statistics of permeability and introducing these inputs into the resin flow simulations can be the path to explore robust processing conditions despite the presence of these variations.

In an attempt to address the origins of the scatter in measured permeability values, Hoes [24] developed a special textile in which different layers were stacked together to constrain nesting and the layers was fused together in a way to restrict uncontrolled nesting and to prevent the low shearing resistance which frequently happen to woven glass fabric. The results showed that the scatter in permeability measurements almost completely disappeared when the effect of the nesting of layers is eliminated. The issues of reproducibility and repeatability of permeability measurements were addressed by the worldwide permeability benchmark exercises II [21]. It has also been shown that there is a strong correlation between tow architecture variability and the broad scatter of the fabric permeability values [25][23]. When the tow cross-section shape and the tow undulation path in the fabric change, the orientation of the plane in which the fabric layer stacks also changes. These changes in fabric architecture are responsible for the scatter in the permeability components. All textile reinforcements usually shows some degree of internal geometry variations, which affects the local permeability and contributes to the uncertainty in measured global permeability values. The contribution of geometrical variation of a textile

to the scatter of permeability was recently addressed by Bodaghi et al. [26]. They looked into the same fabric (2×2 twill woven carbon) that was used in the benchmark II exercises [20] and their results indicated that the intrinsic variability of the textile reinforcement is a major contributor to the scatter measured in permeability.

Advani et al. [18] pointed out in 1994, that the state of the art of flow modelling is much more advanced than the techniques to determine textile reinforcement permeability. In our opinion, this statement is still valid today; one of the most important, yet little understood, areas of composite manufacturing is the interaction between the heterogeneity of a textile reinforcement and resin flow behaviour through it. It may be worth noting that this more advanced modelling assumes a deterministic permeability value. There is also the question of how one could experimentally determine the fabric heterogeneity which could serve as input in a stochastic model for flow. To the best of the authors' knowledge, not much work has been published in stochastic flow modelling or characterizing the heterogeneity in fabric architecture after being placed in the mould before injection for LCM process models.

Most investigations have been limited to local features, neglecting the spatial dependency of permeability (permeability variation within a mould cavity) in the textile reinforcement which is necessary to adequately simulate fluid flow. Analysts usually impose a number of assumptions regarding the statistical characterisation of the permeability, which result in inaccurate approximations of the actual variations in the textile properties. However, spatial variability is well analysed by advanced methods of stochastic structural mechanics. Therefore connecting the micromechanical characteristics with the spatial randomness of material properties at the macroscale has attracted attention of some researchers.

In recent years, the microstructure characteristics of random heterogeneous materials have been quantified and a co-relation between material properties and the microstructure has been established for several cases [27]. Frantziskonis [28] proposed a process for the evaluation of stochastic formulations for modelling the constitutive behavior of heterogeneous solid materials. Starzewski and Wang [29] used stochastic finite elements to model microstructural material randomness in a RVE to bridge it with the global response. A moving-window micromechanics methods was applied in [30] and [31] to produce elastic and inelastic material property fields to account for the random microstructure of a composite material. In order to determine the effective elasticity tensor with stochastic material characteristics, Kaminski and Kleiber [32] applied the second order perturbation and stochastic second central moment technique to solve the homogenization problem. The random field characterisation of elastic properties is estimated by a simple stochastic micromechanical model and homogenisation. An analytical functional perturbation method was developed in [33] to compute the average deflections and reaction forces of stochastically heterogeneous beams. To determine the length scale of inhomogeneity, the correlation length for a mesoscopic model of an anisotropic polycrystalline material was estimated by Simonovski *et al.* [34]. Stochastic cohesive zone elements were used in [34] to investigate the effect of microstructural randomness on the fracture behaviour of composite double cantilever beams. The Monte Carlo based generalized variability response function methodology were computed to estimate the displacement response and the effective compliance of linear plane stress systems [35]. Sakata *et al.* [36] studied the influence of a microscopic random variation of the elastic properties of component materials on the mechanical properties of a laminated plate. However, no systematic method has been developed to apply

internal geometry variations of textile reinforcements for flow simulation procedure in combination with experimental data.

Number of published papers on a topic is one metric for evaluating its importance and timeliness. By searching for “Liquid composite moulding” in Scopus, 1419 papers contained this term in their title, abstract, or keywords. Figure.4 provides a broad breakdown of 1419 papers with more than 150 authors from 1991 through 2017. From analysis of 1419 papers published in more than 20 journals and three conference proceedings of composite manufacturing from 1991 to 2017, Figure.4 shows that papers related to permeability variability has been seldom addressed as the focus, with fewer than 10 papers per year, and it is only recently that its importance has been recognized. The same trend was found in the flow models until 2002 before increasing to five times that number by 2017. However, the flow modelling uses a deterministic permeability value but in recent years has shown the effect on mould filling patterns and void formation if the permeability values are stochastically assigned to finite elements in the model and high permeability values are assigned along edges and inserts where one would expect race-tracking.

(Figure.4)

Review structure

This review paper will summarise and synthesize previous literature on the variability of reinforcement permeability induced by the reinforcement distortions with three primary goals: (1) to compose and organise existing knowledge and state of the art, (2) to describe the inter-dependencies between the different sources of reinforcement variability, (3) to highlight permeability scatter on manufacturing-induced defects. The sensitivity of permeability statistics to these sources of uncertainties and incorporating their influences into the statistics of permeability data will also be addressed.

First, we describe the heterogeneous nature of textile reinforcements and dual scale architecture. Then, we review the literature on several aspects of fabric variability induced during composite manufacturing steps including draping, nesting, tow deformation, and fibre packing and discuss mechanisms to generate statistically accurate permeability estimates. The third part of the article focuses on the need for stochastic flow simulations to incorporate the textile heterogeneity (the micro/meso scale variabilities) into the commercially available global flow simulation packages.

2. Textile Factors Contributing to Variability of Preform Permeability

2.1. Dual-scale channels

When resin is injected at a constant flow rate along a line gate into a mould containing a fabric, the one dimensional flow in the x direction according to Darcy’s law should dictate a linear increase in the pressure at the inlet gate with the impregnation time (t) which has been shown to be the case for single scale porous medium such as a random fibre preform shown in Figure.1A. The dual-scale textile reinforcements shown in Figure.2B form distinct bulk- and micro-flow zones, resulting in high permeability (inter-tow) and low permeability (intra-tow) regions. Many researchers have found that a linear time-pressure relationship often does not exist for a dual-scale porous medium (such as woven, stitched, or braided textile reinforcements) (Tables.1 and 2). There are some analytic/semianalytic

solutions suggesting that the compliance does not have this effect [37]. Nonetheless, the work of Lopatnikov *et al.* [37] assumes elastic behaviour of fiber bed which might be a oversimplification [38]. Lopatnikov *et al.* [37] derived analytical solutions of vacuum-assisted resin transfer moulding (VARTM) under the assumption of a deformable porous medium with constant elastic modulus. However, the preforms in LCM processes shows non-linear elastic or even elasto-visco-plastic behaviour [39].

As opposed to resin transfer moulding (RTM), VARTM uses a single sided mould and the reinforcement is sealed by a vacuum bag. As the vacuum bag provides the minimal rigidity, the preform thickness will vary relative to the resin pressure inside the cavity [40][41][42], and so will the preform permeability which depends on the preform porosity [43] and fluid saturation[44]. During the mould filling, within saturated zone defined as the ratio of pore volume occupied by resin; the applied compaction pressure is shared by the resin and the preform. Modeling of liquid media undergoing compaction has been attempted [45][46]. However, viscous resin infusion simulations are usually performed neglecting the fabric deformations. Several approaches have been suggested to improve the accuracy of these simulations. Preziosi *et al.*[47] and Ambrosi *et al.*[48] proposed a modified momentum balance equation for the fluid and the solid phase to deal with the one-dimensional problem of injection in an elastic preform. Other studies adopted Terzaghi's model to account for the deformed saturated preform through its hydrostatic pressure [49][43]. Therefore; as the local hydrostatic pressure (fluid pressure) increases; the compaction stress on the saturated part of the preform decreases (wet unloading), and hence the local permeability increases. As the permeability is governed by the local reinforcement architecture, accurate viscous liquid infusion simulations requires a realistic model of the reinforcement compaction behaviour. To characterise the preform compressibility, Gutowski *et al.*[50] were among the first propose a model for fabric deformation under a load but their study was based on a two part rigid mould. Several studies [51] [52] [53] [54] [55] have performed to correlate part thickness variation and pressure profile for the one dimensional flow in the VARTM process. Correia *et al.* [40] and Park *et al.* [56] unified these formulations to derive analytical models to solve for the resin flow in VARTM and resin film infusion processes. These authors also studied the influence of preform compressibility on filling time and thickness variations. However, the main limitation of the analytical formulations is their inability to take into account preform thickness variation in the saturated region.

The concept of saturation helps to describe why a fluid resin progressively impregnates a porous preform. From a physical point of view, Spaid *et al.* [57] related the pressure gradient and degree of saturation with surface tension effects. Therefore, a further relationship between the pressure field and the degree of saturation has to be governed based on saturated and unsaturated flow regime in porous media [58]. Formulation of a complete model of deformation/infusion requires three characteristics properties: (1) the dependence of the saturation level on the local pressure: flow modifying the mechanical response of the saturated preform, (2) the stress-strain behaviour of the preform, and (3) the permeability as a function of the degree of saturation.

Currently, the lack of information about the relation between the pressure and saturation leads to the assumption that the resin advances filling homogenously the entire porosity of the preform (slug-flow assumption) [59][60][46]. The reader is referred to Michaud [61] for a detailed analysis of the literature

on the slug-flow. However, many authors [62][63][64][65] have found significant deviations from the slug-flow behaviour, together with nonlinear pressure gradients for a dual-scale porous medium.

On first glance, it may appear that the flow deviates from Darcy's law but one can explain this behaviour by considering Darcy's law at the macro scale and at the tow scale with two different permeability values because the resin is drawn from the inter-tow channels and into the dense fibre packing of tows. The non-linear relationship is attributed to the local changes in flow where the fibre tow serves as a sink [66]. As the channels inside fibre tows are much smaller than the channels between the tows and in LCM the flow is usually pressure driven, it has been observed that the resin will first impregnate the inter-tow channels before the intra-tow channels. Consequently, tows are unsaturated or partially saturated near the macro flow front. Capillary action may play a role. The rationale behind this is that at low capillary number (C_a), the capillary effects may dominate, flow within tows will be faster than in between tows, and hence void may be formed between tows. At higher C_a , the viscous effects dominate, flow between tows is faster and hence void may be entrapped among fibres within tows. $C_a = \mu u / \gamma$ (μ is the resin viscosity, u is liquid velocity, and γ the surface tension between the resin and the ambient atmosphere) for polymer resins are within a range between 10^{-3} to 10^{-1} [61]. There is an optimal capillary number (C_{aopt}) for infiltration to reduce the occurrence of void formation. Patel and Lee [67] found C_{aopt} on the order of 10^{-1} to 10^{-2} for an unsaturated polyester resin impregnating bidirectional stitched fibre glass mat [67]. Zingraff *et al.* [68] found C_{aopt} value around 0.004-0.006 for low-viscosity reactive thermoplastic resin. C_{aopt} of 0.008 was reported by Leclerc and Ruiz [67]. Park and Lee [67] reviewed the values of C_{aopt} estimated by previous studies and concluded that C_{aopt} is approximately 10^{-3} for a resin velocity in the range of 0.1–1 mm/s. However, to achieved the required cycle time in most cases of industrial relevance, fluid velocities are much higher than those corresponding to C_{aopt} . Even after the flow front has moved downstream, the tows upstream continue to saturate, and the rate of liquid volume entering the tows serves as a sink, s , in the mass conservation equation as shown below (Eq.4).

$$- \quad \quad \quad (Eq.4)$$

As long as s is non-zero, it can explain the non-linear relationship between Δp and t .

(Table.1)

(Table.2)

This non-linear behaviour induced due to dual scale of porosity influences the overall permeability of the fabric [75]. Pillai and Advani [62] suggested that there is a certain value (0.1 at $V_f=50\%$) for the ratio of low to high permeability zones beyond which the flow in intra-tow porosity region cannot be neglected for the calculation of the global permeability. Senoguz *et al.* [76] observed that intra-tow flow is the dominant phenomenon that accounts for the differences in saturated and unsaturated permeabilities. Dungan and Sastry [77] included the physics of intra-tow flow in the flow model to obtain reasonable results for unsaturated flow in woven fabrics. Huber and Maier [78] developed a model to account for the ratio of saturated permeability to unsaturated permeability by the combination of the inter-tow and intra-tow permeability. Similar works by Parnas and Phelan [79] show the characteristics of flow exchange in inter-tow porosity need to involve tow-level effects.

Simulations of fluid flow in dual-scale porous media capture simultaneously the flow through both the intra-tow and inter tow channels. The simplest geometric form of porous media has been studied is an unidirectional array with permeable tows (Table.3). Phelan and Wise [80], Sadiq *et al.*[81], Ranganathan *et al.*[82], Papathanasiou [83] [84], and Shou *et al.* [85] studied the flow around solid and permeable cylinders with square and hexagonal arrangements. These studies showed that intra-tow permeability has an increasing influence on global permeability as the overall fibre volume fraction increases.

Due to the dual-scale nature of weave and tow structures, fluid flow in the woven fabrics was also simulated to study the combined interaction of the intra-tow permeability and the inter-tow permeability on the global permeability (Table.3). Tung *et al.*[86], Belov *et al.*[87], Wang *et al.*[88], Nedanov and Advani [89], and Nabovati *et al.* [90] reported the difference in the computed global permeability of woven fabrics for the cases of permeable and impermeable tows to be in the range of 10% to 30%. However, the values of inter- and intra-tow porosity used in many of the studies are outside of these ranges because of the issues with geometry generation. For example, the actual values of inter- and intra-tow porosity in the actual 2×2 twill carbon textile reinforcement are in the range of 22-26% [26] and 30-60% [16], correspondingly.

(Table.3)

In the table, K_p is permeability of dual-scale flow; consisting of intra- and inter-flow (Meso-scale+micro-scale), K_s is permeability of flow between tows neglecting the intra-tow flow (meso-scale) and K_t is the permeability of the tows (micro-scale). Here V_f is fibre volume fraction of a porous medium. ϕ_t is porosity fraction inside a tow, ϕ_s is porosity fraction between tows.

It is also interesting to notice that the plot of K_p/K_t versus K_p/K_s in log-log coordinates reveals two distinct zones (Figure.5); for $\log(K_p/K_s) < 0.15$ (that is $K_p/K_s < 1.41$) shows that the permeability of the tow and the ratio of K_p/K_t does not have a significant influence on the global permeability, where as for $\log(K_p/K_s) >> 0.15$, tow permeability plays an important role in determining the permeability, K_p .

(Figure.5)

K_p/K_t also increases with increasing of ratio of ϕ_s/ϕ_t as seen from Figure.6. This is because as the overall fibre volume fraction increases the inter-tow channels continue to become smaller and eventually close. This may, of course, depend on the type of the fabric (woven, 0/90 non-crimp fabric or +45/-45 non-crimp fabric).

(Figure.6)

Dual scale flow: Summary and Outlook

- Models, which assume solid tows, were found to underestimate the predicted overall permeability particularly at high fibre volume fractions.
- The variations of macroscopic permeability, which is determined in macroscopic flow experiments, can never completely replicate the actual local inhomogeneity.
- Dual-scale flow effects create difference between inter-tow permeability and the overall permeability in the range of 10 to 30%. This can be considered as an upper limit for possible contribution of intra-tow permeability to the overall flow.

(Table.5)

Figure.7 shows the graphs of different correlation K_T/d_f^2 with ϕ_t over the range of 0.37-0.9. It is observed that the difference in the values of K_T/d_f^2 is large at high values of ϕ_t (lower fiber tow volume fractions) and as ϕ_t decreases the differences seem to converge. This may be due to more possible arrangements for fibres in a tow when the fibre volume fraction is low. As the ϕ_t decreases, the fibres will move closer together and will be constrained in their arrangement. Further decrease in the ϕ_t pack the fibres together. This packing provides a less tortuous path for liquid flow. Thus, the difference in the values of K_T/d_f^2 from different correlation function decreased with decreasing ϕ_t . This indicates that the variability of permeability decreases with increasing domain size [111].

(Figure.7)

All of the previous numerical studies were aimed at addressing the effect of the details of fibre packing in the tow on intra-tow permeability along and perpendicular to the fibre tows. Lundstrom and Gebart [112] investigated the influence of quadratic and hexagonal fibre packing arrangement inside tows and non-uniform fibre diameter on longitudinal intra-tow permeability at constant ϕ_t . Their results showed that the longitudinal permeability of hexagonal fibre packing is higher than the quadratic fibre packing for fibres of the same diameter. Similar behaviour was observed by Loendersloot and Akkerman [113]. Their results showed that the longitudinal permeability is two times larger for the circular tow cross-section as compared to the square tow cross-section. For the transverse permeability, Huber and Maier [78] found a decreasing trend of the transverse permeability as the degree of randomness of the fibre packing increased. Similar conclusion was reached by Bechtold and Ye [114] who studied the effect of the fibre packing bundle and observed a significant influence for the intra-tow permeability components. DeValve and Pitchumani [20] obtained similar results for the influence of fibre packing on the magnitude of longitudinal permeability. They showed that the longitudinal permeability of 3D staggered packing is one order of magnitude lower than 3D rectangular packing.

2.2.3. Randomised fibre rearrangement

The influence of random fibre arrangements on the resulting intra-tow permeability was investigated by Cai and Berdichevsky [115]. They considered two random effects for the flow around a set of square unit cells: (1) random packing pattern, in which the fibres randomly fill the cells or are completely removed, (2) fibres are randomly positioned at off-centre locations of the cells. Then, finite element simulations on permeability scatter of an ideal fibre tow was done to relate the permeability values to V_f^{max} . Even though the periodic unit cells were used for their randomisation modelling method, their results showed substantial variations around 10% to 30% in permeability values in transverse direction and 20% in longitudinal direction for the same overall V_f (50%) as a function of the micro-scale fibre arrangement. Bechtold and Ye [114] determined the stochastic distribution of fibres in fibre tows. They found the degree of agglomeration in fibre distribution increases with increasing injection pressure, suggesting change in fibre positions and the formation of local flow channels. They compared this observation with five additional different degrees of fibre clustering for the same overall $V_f=52\%$. Their results showed

increasing trend of transverse permeability with a decreasing degree of irregularity. However, the comparison of their predicted intra-tow permeability and experimentally determined overall permeability is inconclusive; the influence of random arrangements of fibre on permeability scatter was ignored. In addition the unit cell size containing only 15 fibres was significantly smaller than the size of representative volume element (RVE) recommended by previous studies [116]–[121][122] and hence their results may not be representative. Large RVEs with high fibre volume fraction can be generated using method of Melro *et al.*[123] , validated in [124].

An interesting concept in relating the microscale to the macroscale is to correlate the normalised transverse permeability to some statistical descriptor of microstructure. This was considered by Chen and Papathanasiou [125] and Yazdchi *et al.* [116] for two-dimensional random packing of fibres. In [125], the influence of UD random array of fibres on transverse permeability was also computationally investigated. They generated the random array of fibres using a Monte Carlo method (MCM) to perturb fibre packing in square arrays. The degree of randomness was influenced by the number of distorted iterations. Their results showed that as the heterogeneity of the micro-structure increases, a higher average permeability was observed for the same fiber volume fraction, V_f . The flow behaviour is dominated by the formation of large channels as a result of random fibre arrangement. This observation therefore contradicts the previous transverse permeability simulations. The permeability values were also correlated with the average nearest inter-fibre distance by a power law equation. Due to the use of MCM algorithm, the V_f ranged between 10% to 55% which is not representative V_f of tows within a composite laminate. A similar method for prediction of transverse permeability for porosity fraction range of 30% to 90% in random array of fibres was used by Yazdchi *et al.* [116]. Matsumura *et al.* [126] extended the work in [116] and studied the effect of fibre's size on the transverse permeability. Their result showed that the permeability can be correlated with the second nearest inter-fibre spacing by a power-law equation as already pointed by [116]. In addition, they suggested a Weibull distribution for the statistics of micro-scale permeability. Their simulation results showed that the most volume of fluid transports through a few major flow ducts. This observation is confirmed by Gommer *et al.*[127] for actual fibre arrangements in tows [128]. A power law correlation was found between intra-tow permeability and shortest Delaunay edges of the micro-structural domain. The micro-structural domain was generated with four random generator algorithms.

However, all these algorithms were not correlated to actual intra-tow microstructures. In addition, these models do not allow one to include the location dependent fibre volume fractions. Realistic fibre tows were shown to exhibit a stochastic distribution of fibre spacing [111]. Endruweit *et al.* [111] showed that the transverse permeability of fibre tows tends to be lower in case of non-uniform distribution of fibre than for fibre tow with regular arrangements of fibres, whilst the axial permeability of tow permeability is higher [111][129]. These finding indicate that permeability is a stochastic parameter and hence a proper characterisation of permeability requires a large number of experiments [130] as the fibre tow-cross section has to be statistically processed.

Regular fibre packing; Summary and Outlook

From the foregoing list of parameters affecting intra-tow permeability:

- All the reviewed RVE models only use numerical method to predict intra-tow permeability in random packing fibre arrangements.
- It is clear that the accurate description of intra-tow permeability by the given analytical models as listed in Table.3 is significantly influenced by fibre packing arrangements, tow waviness and tow cross-section shapes.
- These models frequently require the determination of coefficient through extensive experimental work, and but still generate permeability values that can differ by one to two order of magnitude from the experimental results.
- Although different degrees of fibre clustering are studied, the validation of actual fibre arrangement within a composite laminate is not performed or only carried out with inadequate geometric details.
- The models have omitted the fibre misalignment by the assumption of parallel alignment of the fibres. Influence of longitudinal tortuosity is ignored.
- The permeability of ideal fibre distribution underestimates the axial permeability with actual non-uniformity [111].
- Because of nonlinear correlation of permeability and fibre volume fraction, using their average values may not adequately represent the stochasticity of fibre spacing.
- Applying the statistical distribution of fibre spacing allows us to predict the multi microvoid formation within fibre tows which can be at different location for the same fibre volume fraction as observed in many micrographs of the manufactured composite [130] [131].
- RVEs with thousands of fibers need to be tested to mimic realistic distribution of fibres within a fibre tow

2.2.4. Tow cross-section shape

Accurate modelling of tow cross-sections is a crucial step in permeability prediction. The shape of tow cross-sections can differ from the most often assumed elliptical shape as, for example, done by Phelan and Wise [80] and Vanaerschot *et al.* [132] for a 2×2 twill woven carbon fabric. Lundström *et al.* [133] discussed the meso-scale permeability of non-crimp fabrics and developed an analytical model for inter-tow permeability with different tow cross-sections, including elliptical and parabolic. Dasgupta and Agarwal [134] observed that the cross sections are lenticular and the tow undulations are same for both warp and weft direction of plain-weave glass fabric. Later, Binétruy *et al.* [75] assumed rectangular cross-sections to study tow impregnation of woven fabrics and the mechanisms of void formation in RTM process. The shape of tow cross-section may also be described by circular cylinders (Peirce) [135]. Nevertheless, for many textile reinforcements, these assumptions are not perfect, but they allow us to obtain useful information about the tow cross section. Badel *et al.* [136] observed that the cross-sections of twill woven carbon fabrics are not symmetric due to the rearrangement of fibres in the tows, and it can change depending on the compaction load on textile reinforcements. The determined variability of tow cross-sections of non-crimp orthogonal woven carbon fabric by Karahan *et al.* [137] also showed the deviations from the rectangular shapes. Marburski *et al.* [138] showed that the tow cross sections of carbon woven fabrics change from an ellipse in a non-deformed state to a more complex shape in a sheared state. They observed a polygonal shape of the weft tows for the shear angle $>30^\circ$. Wong *et*

al.[139] used a generalised power ellipse which is derived by Crooksen [140] to approximate tow cross-sections. Their results [139] showed that the equivalent permeability can increase by a factor of up to 2 as the tow cross-section shape changes from a rectangular to an ellipse. Similarly, Endruweit *et al.* [133] showed that higher global permeability can be obtained for inter-tow spacing with near-rectangular cross-section than by tows with lenticular cross-section.

Summary and Outlook

Even in the ideal case (no deformation),

- Tows have a wide variety of cross-section shapes depending on the tow location inside the fabric.
- This may contribute to large variation in experimentally determined permeability values for textile reinforcement, and hence the accurate permeability prediction is elusive even with known global fibre volume fraction (V_f).

2.3. Textile Deformation

2.3.1. Shear deformation

Permeability variation due to draping is not an issue for flat structures. However, in geometries with double curvature when the preform is draped over the surface, the fabric may undergo significant shear deformation during the lay-up process. Shear deformation can locally change the structure of the fabric making it denser in some regions, decreasing the tow spacing and changing tow cross-sections to a distorted ellipse or quasi-rectangular shape [141] (Figure.8) and hence causing extensive local variations in permeability [142] [143].

(Figure.8)

The effect of shear deformation on fabric permeability has been widely studied. Hammami *et al.*[144] considered two relevant factors during experimental flow in sheared stitched, bidirectional, non-crimp fabrics; the ratio of principal permeability components (K_1/K_2) and their direction of principal axes with respect to the shear deformation of the fibre reinforcement. They found K_1 linearly increases by increasing the shear angle from 0° and 30° and K_2 showed a monotonous decrease as the shear angle increased, resulting in a four-fold increase in the anisotropy index (K_1/ K_2). Similar observations were found by Slade *et al.* [145] for both woven and stitched bi-directional fabrics for the shear angle between 0° and 35° . Endruweit *et al.* [146] reported similar changes in permeability components with changing shear angles for different types of woven fabrics and stitch-bonded non-crimp fabrics.

However, a decrease in permeability is not always the case, and in some cases the high fibre volume fraction regions caused by shear deformation during draping process may lead to higher permeability values [147]. Bickerton *et al.* [147] measured the local tow angle of a non-woven, stitched fabric draped over a hemispherical cone and studied its influence on permeability. The permeability components of preform were calculated by solving Stokes flow between tows and Darcy flow within tows at various angles of shear up to a maximum 36.9° and beyond which a linear interpolation was applied between 36.9° and 90° . Their experimental results showed that draping significantly alters fibre orientation, local fibre volume fraction, permeability of the preform, and hence filling time. Bickerton *et al.* [147] described

two contributing draping parameters that influenced the variations of permeability. They showed that there was (1) reduction of local permeability due to high local fibre volume fraction in high shear regions and (2) change of fibre direction in the tows in these regions changes not only the magnitude but also the direction of the permeability components. Hence, the permeability value in certain direction will increase if the increase due to the reorientation of fibre is more dominant than the decrease due to the increase in fibre local volume fraction.

The same observation was found by Endruweit and Ermanni [148] for the in-plane permeability of various bi-directional glass fibre fabrics experimentally measured by radial injection experiments. Regardless of the type of the textile architecture, they observed that the permeability in fibre direction slightly increases up to a maximum with increasing shear angle as the fibres are aligning and then decreases because the increase in fibre volume fraction reduces the permeability more than the increase due to alignment. However, transverse permeability decreased continuously with increasing shear angle due to increase in fibre volume fraction. These observations agree well with Smith *et al.*[149] and Heardman *et al.* [150] for a variety of woven fabrics. Similar trend was observed by Aranda *et al.*[151] for the in-plane permeability of non-crimp fabrics.

These two concurrent effects of fabric shear were also numerically observed by a number of studies. Wong *et al.*[139] found a significant reduction in K_l when sheared to $\pm 60^\circ$ and a maximum K_l at shear angle of $\pm 45^\circ$ for a 2×2 twill woven fabric. Loix *et al.* [152] proposed a numerical method to quantify the permeability of highly deformed woven fabric for the shear angle between 0° and 50° . Their numerical results showed a monotonous decrease with the shear angle in K_2 . K_l increases for shear angles ranging from 0° to 30° . The similar trend was recorded by Verleye *et al.* [153] who investigated the influence of deformations caused by shearing and compression on the undeformed unit-cell model of the plain woven mono-filament fabric. The modelling of shear on the textile was done by WiseTex software [154]. As their periodic boundary conditions were parallel to the direction of shear, and not parallel to the orthogonal coordinates, it showed that the permeability is only a function of fibre volume fraction regardless of the type of deformation.

Beside the influence of draping on global permeability components in the local regions, the influence of fibre tow deformation due to draping on mould filling time also needs to be accounted. Badel *et al.*[136] showed that the geometry of fibre tow of three types of woven reinforcements (plain weave, 2×2 twill), and interlock) is altered during fabric shearing. This change in tow geometry will result in the local variation of tow fibre volume fraction and permeability, and hence changing the tow permeability and the fibre tow filling time and thus the processing characteristics of the textile reinforcement. It has been numerically shown by Walther *et al.* [155] that tow shearing of orthogonal woven textiles has a significant contribution to mould filling time at shear angles above 20° . This confirms that the tow in high shear regions has a very low permeability, and it requires either very high inlet pressure, or very long filling time to completely impregnate these regions.

Summary and Outlook

- For parts that have double curvatures in their geometry, the draping of the preform along the mould surfaces will change the local fibre architecture in a complex way depending on the shear angle, fibre tow geometry, type of stitching, locking angle, etc.
- It will increase the local fibre volume fraction which reduces the permeability in that region. This is the main factor of permeability change with shear which can be approximated by Kozeny-Carman relation in which the unsheared fabric Kozeny coefficient is used.
- As the fiber tows align it will increase the permeability. The tow compaction can also change during the draping processes. So draping changes the permeability value in magnitude and direction.
- Such variations in permeability will influence the mould filling and can lead to unfilled and unsaturated regions during the manufacturing process. Consequently, the effect of shear on the permeability of textile preforms need to be considered during mould design to reflect the changes introduced.

2.3.2. Nesting

Regardless of fabric type, one of the most important deformations modes in the LCM family of manufacturing processes is out-of-plane compression, in which the textile preform is compacted to a desired thickness. The transverse compression reduces the thickness of the textile preform, causing a modification of the fabric architecture. Nesting is the phenomenon of how various fabric layer interfaces mesh with each other. In general, nesting reduces the laminate thickness, increase the fibre volume fraction, and changes the porosity pattern. There are many possible ways of how adjacent layers will mesh because the peaks and valleys of the interfaces of the layers are not always going to mesh exactly (perfect nesting). This introduces a significant spatial scatter in permeability depending on the degree of meshing (nesting) [26] [23].

Compressibility studies of textile reinforcement have shown that as the number of layers increase in the laminate, nesting decreases the thickness per layer [156]. Saunders *et al.* [157] experimentally studied the microscale compressibility of dry and resin impregnated plain woven fabrics. They concluded that nesting, tow waviness and the deformation of tow cross-section jointly contribute to the distance between adjacent layers. A similar conclusion was reached by Luo and Verpoest [158] for woven, knitted, and random mat reinforcements. Lomov and Verpoest [159] observed the same trend for the compression of woven glass reinforcements due to the local shift of layers. Chen *et al.* [160] identified the distance between layers in woven fabrics was controlled by nesting. Generally, nesting reduces the thickness of laminates and porosity distribution over a textile preform. However, the compression experiments of Pearce and Summerscales [161] declared that the thickness per layer increases as the number of layers increases. They attributed it to larger friction between the two adjacent fabric layers than the mould surface-fabric, preventing the occurrence of nesting.

Nesting can show significant scatter associated with several parameters. Lomov *et al.* [162] demonstrated the influence of a shear deformation on the nesting in a woven reinforcement. Particularly, a textile reinforcement was less sensitive to nesting when sheared. Hence, for highly sheared textile reinforcement

the scatter due to nesting become less prominent. Furthermore, nesting can be limited when the tightness of the textile reinforcement increases. When the tows are positioned more tightly, the hills and valleys of the textile tows become steeper and variability in nesting reduces. Inter-tow spacing also influences nesting. As tow spacing increases, the tightness of the textile decreases, and hence the nesting variability from one layer to the next increases. The same trends were observed by Yousaf *et al.*[163]. It was observed that plain weave fabrics are easier to nest compared to twill and satin fabrics because of shorter tow diameters in the weave.

Nesting or absence of nesting can have a large effect on permeability and porosity which has been confirmed with several experimental and numerical studies. Dugan *et al.*[164] and Senogus *et al.* [76] studied the effect of two extreme cases of maximum nesting and no-nesting of woven fabrics on the permeability scatter. They developed a fully three-dimensional geometric model for plain weave fabric, and a variable gap model for permeability calculation. They demonstrated that the permeability values can differ by an order of magnitude between maximum and zero-nesting cases. Similarly, Belov *et al.*[87] using Lattice Boltzmann modelling for a woven fabric demonstrated that permeability values for different configuration of nesting range between $1.5 \times 10^{-10} \text{ m}^2$ and $7 \times 10^{-10} \text{ m}^2$ for $V_f=41.7\%$. Similar conclusions were obtained by Grujici *et al.*[165] by combining a lubrication model for inter-tow resin flow and Darcy's model for the intra-tow flow model in a two-layer orthogonal plain-weave fabric. Hoes *et al.*[23] used nesting between fibre reinforcement layers to explain large scatter in permeability measurements (ranging between $0.588 \times 10^{-10} \text{ m}^2$ and $2.165 \times 10^{-10} \text{ m}^2$) of 5-layered balanced glass woven fabrics with $V_f=41.7\%$ resulting from 80 experiments. This observation was also confirmed by Delerue *et al.*[166] using the random sampling of X-ray CT image of a glass woven laminated and calculated corresponding local in-plane permeability. Ramakrishnan and Pitchumani [167] provided estimations of inter and intra-tow gaps for woven laminates using fractal geometry model with different nesting configurations. Endruweit *et al.*[146] observed that nesting for woven fabrics with high ratio of gap between tows to in-plane size of tow had a significant influence on the permeability scatter along 0° direction, (the ratio of standard deviation to mean values equal to 29%). Similar conclusions were drawn for triaxially braided reinforcements, and the comparison of results obtained for zero and maximum nesting cases showed that this effect had a significant influence on the in-plane permeability components, particularly along the perform 0° direction [168].

Reflecting the textile geometry in the braided preforms, Swery *et al.* [169] used textile modelling techniques (TexGen developed at the university of Nottingham [170]) along with numerical simulations (FlowTex solver developed at KU Leuven [171]) to predict permeability when four layers are stacked either with zero nesting or with maximum nesting. It was shown that K_x significantly decreases for stacks with maximum nesting. In addition, the filling time was significantly higher for the stacks with maximum nesting at constant injection pressure. In addition to the significant influence of nesting on in-plane permeability scatter, Fang *et al.*[172] studied the effect of two extremes cases of nesting (zero and maximum nesting) on the out-of-plane permeability of unidirectional fabrics. They identified that for the same fibre volume fraction (V_f), the out-of-plane permeability values were two order of magnitude larger with zero nesting case as compared to maximum nesting case. However, as V_f increases, the differences between zero and maximum nesting decreased. Grujicic *et al.* [165], [173], Lekakou *et al.* [174] (in-plane

permeability components) and Fang *et al.* [172] as well as Jiang *et al.* [175] (out of plane permeability) developed numerical models to predict the permeability with nesting.

Summary and Outlook

- Permeability of the preform can be significantly affected by the degree of nesting and such variations need to be accounted for into existing commercial flow simulation packages.
- As the resin impregnates the textile reinforcement, the nesting interface gets lubricated and may improve the degree of nesting changing the dynamic value of permeability. This is definitely the case for VARTM and other compliant mould processes of the LCM family.
- It was found that if compaction tests were carried out for a wide range of textile layers, the nesting effect could be estimated and their contribution on permeability characterised. However, limited experimental data exist regarding permeability variations due to nesting.
- Furthermore, nesting has not been clearly characterised; the results presented in the literature were achieved using conceptual values for the input nesting rather than experimental data. Therefore, further investigation should be carried out towards statistical characterisation of permeability in light of crucial influence of nesting.

3. Addressing Permeability Variations in Flow Simulations

All flow models require permeability input to predict the flow progression of resin in the mould. Permeability tensors could be different in magnitude and direction in different parts of the mould. The flow simulation provides the fill time and the last regions to fill which is where most likely dry spots or voids will occur if there is no vent to displace the air out of the mould. Local variations in permeability usually will not significantly influence the fill time but can dramatically change the flow front progression and hence the void formation during the filling process [176]. Therefore, it is important to address the preform variability in flow simulations in order to explore a process design that will make the process robust despite the presence of permeability variations within the mould and from one part to another.

3.1. Flow Simulations and Preform Variability

Void formation occurs at macro, meso and micro scale. Macro scale voids are formed when the resin fails to impregnate a low permeability region. This type of void is visible by naked eye as a dry spot and usually one must scrap the part. Even two decades ago, flow simulations could predict such macrovoids by tracking the flow front progression and when the flow front reached the last vent, the region not covered by resin was judged to be a macro void [12]. Mesoscale voids are formed when air is entrapped between fibre tows due to different rate of filling within the fibre tows and around the fibre tows and the same phenomenon is responsible for microvoids which are formed by air trapped within the fibre tows due to their low permeability. Dual scale flow simulations such as LIMS can predict micro and macro voids once the input of dual-scale permeability, viscosity and geometry is provided along with injection gate conditions and vent locations [177][178].

The macroscopic resin flow can be treated with an average permeability by using the solution of Darcy's equation. Such a solution, involving average permeability, in which the textile preform is considered as a homogeneous medium, does not introduce local permeability values. Thus, it is desirable to take into

account the textile heterogeneity in the global resin flow simulations [176]. Information about the microscopic structure of textile reinforcements would therefore help the optimisation of a typical LCM process designed to minimize voids and obtain adequate fibre wetting.

A flow simulation should take into account such inevitable variations and therefore reflect the uncertainties associated with permeability with stochastic modelling. Stochastic analysis can mimic LCM manufacturing process in practice and identify robust injection strategies that increase consistency in the properties of final composite parts. When a stochastic model of permeability is included, one can anticipate this effect. However, coupling these two phenomena in the computational domain is formidable due to the need to represent the preform on micro and macro scale. LIMS [179] can currently address this issue with computational efficiency, however, accurate stochastic models that reflect actual variability of preforms are necessary before one can derive any useful inference from such simulations.

Summary and Outlook

Up to now, to deal with this extreme computational effort, many researchers have made simplifying assumptions about the tow geometry and about the resin pressure gradient experienced within the fibre tow [180].

- Information on global resin pressure is used to model tow saturation. However, there is a fundamental gap between the global resin flow modelling and practice.
- In practical manufacturing process, there is uncertainty associated with permeability of textile reinforcement from one location to the next and from one part to the next and one needs to forecast and quantify this variation and include it in numerical simulations to improve robustness.
- The available resin flow models are deterministic as they do not address the micro and meso scale variability in the textile reinforcement. While textile permeability is dependent on fibre arrangement within tows at the microscale level, as well as tow spacing at mesoscale, the flow front pattern is locally controlled by average value of permeability in the finite element models [181].
- Future models and simulations need to create a framework in which these issues can be addressed and their effect on the manufacturing process quantified.

3.2. Stochastic Flow Simulations

A robust resin flow modelling needs to address the effects of textile heterogeneity on the occurrence of void formation. Previous studies [182] [183] revealed that the tow paths in textile composites are stochastic rather than deterministic, and fluctuate around their mean; other parameters of fabric internal structure, such as tow spacing and dimensions [181][184] and in-plane tow waviness [139] also vary. This suggests that introducing the stochastic variation of fabric geometry into flow simulation provides a reasonable estimate of filling time [180] but more importantly they will provide a distribution of macro, meso and micro level voids which will be more sensitive to these permeability variations.

Stochastic simulation of mould filling stage in LCM process has been done by using both some probability distributed spatially uncorrelated geometric variability and a random field in which spatial structure and correlations of permeability imposed by it are taken into account [136] [185]. In the

uncorrelated random case, the value of uncertain permeability follows a specific probability distribution, characterising the randomness of the property. In the case of random field, the value of the permeability varies over the porous domain in accordance with a correlation length and the resulting flow pattern can be analysed in a stochastic fashion; the specified probability distribution to the permeability does not refer to a single random permeability, but to several random permeability values required to adequately represent the random field. The scientific community has devoted more attention to the stochastic simulation of resin flow during LCM processes in order to explore the role of inherent fabric geometry variabilities on void formation. Clearly, the stochastic method allows one to incorporate more detailed description of uncertainties rather than the use of uncorrelated random variable.

For a stochastic simulation of 1D non-isothermal mould filling, Padmanabhan and Pitchumani [186] assumed the random permeability as one of the uncertain input parameters. Unlike Pan *et al.*[187] and Hoes *et al.*[130], they assumed a lognormal distribution for permeability and a normal distribution for porosity. They showed how uncertain material parameters, in fabric and resin alike, can combine in such a way as to reduce process output variabilities. Sozer [188] applied uncorrelated local random permeability in 2D flow simulation to observe the effect of textile reinforcement non-homogeneity on mould filling. In this case, permeability variations are not locally confined by a correlation function. He observed that uncorrelated local variations of permeability up to $\pm 35\%$ have insignificant effects on the mould filling but that if the variations happen in a correlated way, they have a more significant effect on mould filling.

To compare the effects of uncorrelated and correlated local permeability on global permeability, Desplentere *et al.*[189] divided a fibrous medium into number of square zones. They assigned the local permeability for each zone in the principal flow direction in two ways: (i) an uncorrelated normal distribution of permeability (ii) assigning the local permeability in a correlated way, limiting permeability variations between adjacent zones by a correlation function. They demonstrated that uncorrelated approach leads to a strong dependency of the scatter of the global permeability on the size of the discretised zones; hence the uncorrelated approach is not physical. The correlated approach was free from the discretisation size effect, and gave scatter predictions consistent with early works in [130][15].

3.2.1. *Spatial distribution of permeability*

It is obvious that the local permeability variations are determined by the variations of the local textile geometry. Endruweit *et al.*[146] used random sinusoidal shapes of tows and calculated the permeability in correlated fashion. They observed that increasing textile non-uniformity increases the local variation of porosity and permeability values. Hence, the actual dual-scale flow behaviour during resin injection into textile preform is influenced by the intrinsic meso-scale non-uniformity of the textile reinforcement and by the local variations of the macro-scale fibre arrangements. Parseval *et al.*[15], modelling permeability variations introduced by the presence of dual-scale flow, proposed that the spatial harmonic mean of the local permeability values can properly represent the average global permeability. However, they accounted only for variations of intra-tow permeability based on the aspect ratio of yarns cross sections, neglecting the effect of tow spacing and distortions of the tow centrelines. Lundström *et al.*[190] calculated inter-tow permeability at meso-level (unit cell) textile from the dimensions of flow channels with variable gap size between fibre bundles. The results showed that with uncorrelated random

distribution, overall permeability decreased with the maximum gap size at the mesoscale level. Meanwhile for a correlated distribution, overall permeability could either increase or decrease depending on the type of deviations such as tow dimension and tow centroid distances as compared to an ideal unit cell. The results of their study allowed them to include the local randomness in ordered fabrics such as non-crimp stitched fabrics. Wegh *et al.*[191] predicted permeability at mesoscale by employing unit-cell model associated with local variabilities due to shear angle, and compression and, subsequently, they carried out 3D flow simulations. However, the unit-cell model was simplified to a brick-model with a rectangular cross section, which does not adequately represent a real fabric. Loendersloot and Akkerman [192] employed internal geometry variations induced by the distortion of yarns in their analysis of the inter-tow permeability variations of non-crimp fabrics. They found that both the amount of the variation and the spatial distribution of a fabric needs to be taken into account for a proper representation of permeability variation. Similar conclusion was reported by Swery *et al.*[193]. They observed the significant contribution of tow spacing and nesting on the variations of in-plane permeability.

In addition, the presence of pinholes around the crossover points of tows in through thickness direction adds variability to the through thickness permeability. Unlike in-plane permeability (K_x and K_y) variations, limited data exist regarding variations in through the thickness permeability (K_z). Markicevic *et al.*[194] did early work numerically on the through thickness variations in a VARTM process. They studied the influence of the spatial distribution of the through thickness permeability on the formation of void content for a heterogeneous preform formed by woven reinforcements coupled with a homogenous distribution media. The heterogeneities of the preform were modelled by using even distribution of pinholes throughout the thickness in the preform. The influence of the spatial distribution of pinholes permeability on dry spot content was estimated by a random permutation of pinholes permeability. High standard deviation of dry spot content suggested that the formation of dry spot is dependent on the spatial distribution of the permeability of pinholes. Unlike Markicevic *et al.*[194], Yun *et al.*[176] characterised and modelled the effect of experimentally captured pinholes data with assumed cylindrical shape on dry spot formation by assuming maximum nesting. The spatial correlation of pinholes permeability was also addressed in the numerical simulation for a rectangular domain. Their results helped reveal the essence of addressing the stochastic nature of the pinholes for the prediction of dry spots formation.

Summary and Outlook

- Previous investigations have shown that introduction of heterogeneity at the local scale in the fabrics do influence the permeabilities on the local scale which changes the filling pattern during impregnation of the resin into the mould and cause micro voids and dryspots.
- Instead of random assignment of uncorrelated permeability field in a flow simulation, it has been shown that correlated permeability field based on correlated variations of fabric anomalies such as tow size, tow length, tow waviness and pinholes will lead to more realistic predictions of resin flow patterns. However, the coupling of microscale variabilities with the spatial variability of the preform permeability at the macroscale in a meaningful way is a challenging issue.

- Variation within the preform at every scale contributes to permeability variation but there is not yet any model which allows us to establish a complete link between microscale models and stochastic preform permeability at the macroscale.
- Use of statistical data extracted from experimental characterisation of textile reinforcements within mould filling simulation software may be a useful way to characterize the robustness of the process based on heterogeneity of the preform. Nevertheless, as the stochastic modelling introduced above still runs on macroscale, the ability to predict meso- and micro-scale effects without proper scale down remains low, despite the ability to show some effect on the macro- (integral) flow.
-

3.2.2. *Assumptions for stochastic flow modelling*

Permeability shows random variability in spatial distribution and may be modelled as random fields rather than random numbers [195]. Since internal geometric variations extend to adjacent locations in the textile reinforcement, the in-plane tow spacing can be modelled by continuous random fields. Random fields correspond to spatially varying permeability over the scale of a millimetre [16][26]. This leads to stochastic volume element global flow modelling for which the permeability data are stochastic.

There have been very limited stochastic finite element method studies for the prediction of dry spots and voids during mould filling stage by incorporating the random permeability field into the deterministic finite element method. Existing studies do not cover the rigorous modelling of stochastic properties of the permeability field. When establishing models for flow simulations, an understanding of the spatial distribution of local permeability and its effect on global permeability is necessary. Uncertainty propagation that would take these effects into account need to be based on the spatial modelling of permeability which would allow one to quantify the local variability of permeability as a function of fabric heterogeneity. Hence, there is a need to develop systematic methods to apply internal geometry variations of textile reinforcements to flow simulation procedure in combination with realistic experimental data. Only after dependencies between permeability and geometrical properties of a textile reinforcement are adequately correlated, we will be able to realistically simulate flow advancement in a fibrous medium for liquid composite moulding.

Due to the lack of experimental data, analysts have to impose a number of assumptions regarding the statistical characterisation of the permeability, leading to inaccurate approximations of the variabilities of textile reinforcement properties. These assumptions are further discussed in the following subsections.

3.2.3. *Correlation length*

Correlation length is the stochastic parameter which is used in parametric stochastic flow simulations. Since the permeability is required to adequately represent the heterogeneity of a textile preform, it is usually a function of the correlation length. Hence, guessing a value for the correlation length of permeability may lead to the misunderstanding of stochastic flow behaviour in a typical textile preform. The number of random variables are required to adequately represent a permeability field as a function of the correlation length. Matsuzaki and Shiota [196] showed a considerable difference between true permeability distribution and the one assumed in the stochastic simulation. One should, therefore, first

collect experimental data on the spatially correlated random fluctuations of uncertain properties and subsequently use these properties to derive probabilistic information for macroscopic permeability from the lower length scale [197]. One could also find the correlation length from laboratory experiments to reconstruct the permeability field. [198] [26] [199]. The type of reinforcement geometry influences the correlation length as shown in Table.6. The sample should be considerably larger than the correlation length for the results to be meaningful as the correlation length may influence the flow simulation effort required to generate random field samples while conducting stochastic simulations.

(Table.6)

3.2.4. Stationary and isotropic random field

The random permeability fields representing the heterogeneity of a textile preform are assumed to be stationary and isotropic. The stationary assumption means that the first two moments of a random field are constant over a porous medium and the correlation is only a function of the relative distance between two spatial locations. The assumption of stationary random field is valid to model the randomness when addressing textile modelling [203]. Vanaerschot *et al.* [182] modelled the in-plane tow centroid positions for the 2×2 twill woven composite within a virtual specimen as stationary random fields. Zhang *et al.* [198] assumed a stationary random field with a mean permeability value of 1×10^{-9} and a correlation length of half the mould size.

3.2.5. Probability distribution functions of reinforcement permeability

Many studies reported in the literature present empirical random permeability models based on experimental evidence and engineering judgment. Table.7 lists the probability distributions proposed for stochastic simulations. The selection of statistical distribution model for random fields representing permeability data of heterogeneous fibrous media appears to be arbitrary in most stochastic flow simulations, since relevant experimental data are typically not available to support an appropriate selection on the distributional type of permeability data. Hence, log-normal or normal random fields are usually adopted for this purpose [181][200], while other distribution functions such as Weibull distribution are used more rarely [198].

(Table.7)

Research has been done in the past to fit suitable statistical models to permeability data. In general, a set of identical permeability experiments are conducted and the appropriate distribution function is fitted with Kolmogorov-Smirnov (K-S), Chi-Square or Shapiro-Wilk [187] [130] [207][208] relations. Table.8 suggests that widely used Normal probability distribution model has been proposed for permeability, while lognormal distribution has been proposed only by Zhang *et al.* [202]. Similar conclusion was reported by the simulations studies (Table.9), suggesting that normal distribution is the most appropriate probability distribution.

In all cases in Table.8 and Table.9, the authors agreed that the large variations in permeability is due to local inhomogeneity in textile architecture.

(Table.8)

(Table.9)

The type of probability distribution functions used in stochastic flow simulations does not have significant influence on the first two statistical moments (mean and variance) of permeability, but strongly influence simulation results with the skewness of permeability distribution [198]. Wong and Long [213] numerically studied the influence of in-plane variability of the tow path on the statistics of permeability of a non-crimp fabric and a plain weave fabric. The cross-over points of tows were assumed to move randomly by a normal distribution function. It was found that the normal distribution is not necessarily the best distribution for representing the permeability at the mesoscale (unit cell size). They attributed a large skewness in permeability data due to local inhomogeneity and showed this variation would tend to a normal distribution in a large domain. Hence, the statistics of permeability depends not only on the mean and the variance of permeability data, but also on the relative values of the integral scale and domain size.

The lack of experimental permeability data affects also the reliability of the assumptions made for the first two statistical moments of a meso-scale random field permeability. In fact, the standard deviation is often involved in parametric studies, which aim at assessing stochastic response for permeability values. Permeability measurements that are log-normally distributed exhibited stationary coefficient of variation (CV) (the ratio of the standard deviation to the mean) while the standard deviation varies depending on the mean value of permeability measurements. Common values used for CV of random fields modelling permeability are in the order of 0.1%-0.3% [181][214]. Matveev *et al.* [208] predicted CV of the permeability of preform with ideal geometry to be 3.5%. However, statistical evaluation of measured permeability values as documented by Hoes *et al.* [130], the permeability benchmark Exercises I [19] and II [20] for different fabrics shows that CV of permeability are in the order of 20%, including internal geometric variations.

The reported CVs is not limited to a specific value and covers wide range of permeability. CV reported by Li *et al.* [207] is higher than other studies; this could be attributed to the contribution of race-tracking. In most cases, permeability in production direction (warp) is less variable than the cross direction (weft). Permeability measurements in large sample sizes with well-defined conditions allow representing an upper bound on the variability. For higher sample sizes, one can use Hoes *et al.*(2002)[130] and Benchmark II (2014) [20]. Figure.9 shows the variation of CV versus number of samples. From Figure.9, it is observed that a minimum number of 80 samples can more accurately reflect the statistics of permeability (violet circle in Figure.9). This can be considered reasonable number as compared to the expected variations of permeability between 20-30% (Hoes *et al.*(2002)[130]). The predicted CV by the network model (Table.4 and lower bound of violet circle in Figure.9) is reasonable compared to the experimental results.

(Figure.9)

Summary and Outlook

- There are two types of variations that contribute to the uncertainty of measured permeability: (1) the variations over a large sample (mould scale; reproducibility of permeability measurements), (2) variations between different measurements of small specimens taken from a large sample.
- The origin of this variability is partly due to internal geometry of textile reinforcements. This can be called “ergodicity” and normally is taken for granted.
- A prediction of the magnitude of variation about the permeability would help to guide process control and build a robust stochastic flow simulation.
- Due to the lack of statistical information on permeability, stochastic flow simulations are usually performed under assumptions regarding spatial correlation length and coefficient of variation of permeability, which are not adequately justified and will affect the final outcome.
- The validity of the stochastic flow simulations is often questionable. To mitigate this problem, information about the statistics of global permeability can be inferred by characterisation of internal geometric variability.

4. Stochastic Approach to Estimate Permeability Random field

4.1. Inverse Darcy Solution

The majority of the experimental methods for the estimation of permeability are based on two assumptions: (1) textile reinforcements are homogenous; (2) a fluid flow is one dimensional, including 2-dimensional central injection.

Some practical techniques have been suggested to relax the homogeneous permeability assumption and estimate heterogeneous permeability during LCM process. Doménech *et al.* [215] used a digital camera to define the pixels as nodes and associated them as finite elements during the filling process. They proposed a coupled numerical/experimental approach to compute the arrival time of flow at each node as well as filling factor of each mesh. Finally, permeability was estimated from the flow front position and injection pressure. However, the pressure at each node had to be approximated. Nielsen and Pitchumani [216] used a similar approach with image acquisition and a neural network to estimate permeability. Sas [217] quantified the permeability variation within a textile preform by monitoring the flow front profiles with time during resin impregnation. They applied Kardar-Parisi-Zhang, which is a non-linear stochastic partial differential equation, to evaluate the variance of flow front profiles and the percentage of local defects. Wei *et al.* [218] used an experimental set-up similar to Figure.10. A pressure sensor array was mounted in the mould cavity, where the preform is placed, to compute flow velocity at the flow front. Furthermore, images taken by a high speed CCD camera were used to compute the seepage velocity of flow front. Then, the local permeability was computed by the proposed approach in [218] under the assumption of known μ and ϕ , while the permeability in VARTM assembly will vary with compaction as flow front progresses.

(Figure.10)

Summary and Outlook

These approaches provide a practical way of estimating permeability in LCM processes. However, the estimated permeability values have no spatial correlation with fabric heterogeneity and hence fails to provide an accurate global estimate of the spatial permeability field because:

- From the mathematical inverse problems viewpoint, the differentiation of pressure data requires homogenisation.
- In addition to lack of an inverse problem solution, these experiments are being performed on a global scale and do not tell us anything about the local permeability values.
- Transient variations of the flow front speed, which are connected to the variations in local permeability, are not measured with sufficient precision to be able to relate it to the global value.

4.2. The Statistical Inference

Various statistical inference methods have been proposed to reproduce the spatial distribution of permeability. Underlying the assumption of stationary stochastic approach, the modelling may be either continuous, or discrete.

4.2.1. Continuous modelling

In the continuous case, common practice is to assume that permeability field follows a specific probability distribution function. Such an assumption provides the first two moments of permeability without correlation. By using these moments, the Monte Carlo simulation (MCS) produces distributions of possible outcome values. Markicevic *et al.* [194] modelled the dry spot formation in VARTM by studying process parameter variations in which the permeability of distribution medium, the standard deviation of the permeability between tows and the thickness were varied. They randomly assigned 240-480 permeability values between tows with an assumed log-normal distribution. They conducted 4320 simulations over 100 process parameter variations. Correia *et al.* [204] studied the effects of the normal distributions of permeability and fibre volume fraction on the variations of flow using 15,000 Monte Carlo simulations(MCS). The Monte Carlo method was also used by Endruweit and Long [181] to predict the permeability of a non-crimp fabric with in-plane waviness of the tows. It was shown that the permeability and fill time can vary by up to 20% from their mean values. One of the principal limitations of MCS is that quite a large number of random sampling of permeability need to be executed, to ensure convergence and accuracy. Also that may not be the physical reality as well.

To accelerate the statistical convergence of sampling method over MCS, the Latin Hypercube Sampling (LHS) method, which aims to ensure that probability distribution of sampling in the model is even, was used. Padmanabhan and Pitchumani [186] pioneered a stochastic model to study the effects of process and material variable uncertainties on non-isothermal mould filling simulation during RTM. However, MCS and LHS are computationally expensive. The application of MCS to random fields is also a complicated task due to the large number of random sampling onto which a continuous random permeability field is discretised in both spatial and probabilistic spaces. Zhong *et al.* [72] presented a different method. The Monte Carlo simulation based on the Ising model [72] was employed to study the stochastic mould filling simulation of a central injection set-up. In this method macro flow behaviour of resin in fibrous media was derived from the difference of total energy from dominant gaseous state to the

dominantly fluid one, instead of using Darcy's law. With this method, the flow front position at a specific time is randomly generated. For each time interval, a randomly selected region of the flow front progresses. Again this is not physical and may not reflect reality.

4.2.2. Discrete modelling

In the discrete representation, geometric properties of textile preform are statistically introduced, i.e, their spatial distribution. As in continuous representation, discrete permeability field is mainly assumed to be stationary. The polynomial chaos expansion (PCE) [181], Probabilistic Collocation method (PCM) [195] [198], and a data assimilation method [200] [196], which is an effective technique to estimate several state variables with limited information, have been used to represent stochastic mould filling process. The PCM is an intermediate technique between Monte Carlo and stochastic finite element. This method is similar to the spectral stochastic expansion using both Karhunen-Loève expansion (KLE) method and PCE.

The coefficients of PCE are determined by the probabilistic collocation method. In the collocation method, the collocation points are derived from the next higher order orthogonal polynomial for each uncertain parameter and are selected to reduce the error between the polynomial chaos expansions and model outputs, satisfying the collocation points chosen from higher probability zones. Finally, a set of linear equations are formulated for each output parameter. This sampling method does not require the reformulation of the deterministic model.

Recent studies [200] [196] applied systematic data assimilation methods, which are an effective technique to estimate several state variables with limited information, to deduce permeability during resin transfer moulding process. However, the measurement system is complex because it requires installation of several electrodes, which hinders its practical use. In addition, because the method needs to process large volumes of data on account of continuous measurements, the processing cost increases dramatically for large-scale moulds. All these methods apply KLE [198] [199] to discretised Gaussian random field permeability of random fibrous media.

Summary and Outlook

- It is relevant to define the smallest volume, a “unit cell”, at which we can capture macroscopic properties. The unit cell is assumed to repeat throughout the fibrous medium. The unit cell principally represents the minimum size of averaging volume.
- We believe that the virtual geometry resolves permeability at the unit cell scale. On the other hand, permeability determined from conventional experiments represents, at best, an average of the unit cell properties. The determination of permeability at the unit cell level is desirable because
 - (i) Estimating actual value of permeability rather than an average value estimated by conventional experiments will help introduce effect of micro variations on flow front progression and micro-void formation.
 - (ii) The unit cell properties, including porosity and permeability, may open a new window to support problems associated with characterisation of fibrous media. For example, by analysing the properties of sets of unit cells from a given fibrous medium, we could develop stochastic

correlation function that could be used to generate realizations of permeability field. These realizations could be used as input for the inverse problems, providing a suitable stochastic simulation of the flow behaviour.

(iii) Understanding the mesoscopic spatial variability of permeability is an essential input for reliable explanations of anisotropic permeability that may spatially change in magnitude and direction.

5. Conclusions

Permeability is the key variable that influences the resin fluid flow through a dry textile reinforcement during the impregnation step in liquid composite moulding processes. The variation in permeability induced by inherent geometric variations of textile media, which consists of multiscale character, is reviewed. The variations of tow geometry and tow spacing caused during the draping step as well as nesting during compaction step can introduce significant scatter in permeability during the impregnation process, resulting in flow-induced voids. While porous media theory and volume-averaged permeability relations give a basis to quantify these phenomena, traditional methods of permeability estimation used for textile porous media fail to adequately characterize the full relation of fabric heterogeneity to volume-average permeability. Most significantly, the link between microstructural parameters and permeability is treated as a deterministic function at all scales, ignoring the inherent geometry variation of textile reinforcements. Quantification of permeability variation and its correlation length are presented as conditions, which a realistic stochastic permeability field must take into consideration. This allows one to develop and implement a stochastic tool in the framework of flow simulation. Depending on the fabric architecture, particularly the tow packing density in each ply, nesting effect may also change the resin flow pattern and contribute to permeability variations. The influence of nesting is accounted by random variation in layer placement, to construct the statistics of the multilayer permeability response. Moreover, the apparent permeability will vary with race tracking, as that variation assumes that the racetrack is considered a part of the continuum rather than separate flow feature.

The use of a global mould design optimisation algorithm in conjunction with a local uncertainty propagation of preform variation algorithm provides for more robust solution of flow within a textile preform. In this sense, the local analysis of preform variability provides an accurate resolution of porosity distributions, which are essential for the determination of the superficial velocities used to determine permeability distribution. It is indeed clear that the stochastic estimation of flow front advancement during resin injection is worthy of the attention from an inverse problems perspective capable of quantifying inherent uncertainty in permeability due to the forming and compaction of the preform. The stochastic formulation, however, needs to be properly analysed throughout all length scales and while scale up was mentioned here, the scale down to determine what happens on lower length scales would also be necessary.

The evaluation of pore structure (Pore connectivity, aspect ratio, tortuosity) will undoubtedly be a huge advantage compared with the stochastic flow simulations. Pore connectivity is likely one of the most important factors affecting the permeability of the porous medium.

Important parameters characterising the porous medium are the porosity, the sizes and shapes of the pores, and the connectivity between the pores. Permeability will change if the pore space geometry or

connectivity is altered. Alterations may be caused by various physical processes, such as draping and/or nesting. The prediction of the evolution of the macroscopic properties with changing pore space is of substantial value. Such predictions can be achieved by coupled models that represent the mechanical behaviour and mass transport through the porous medium.

The advances in materials imaging, in particular X-ray Computed Tomography (XCT), and the increase of computational power allows for mass transport analysis using the reconstructed pore space. This type of image-based modelling has been combined with several analysis techniques, such as Lattice-Boltzmann methods (Belove 2004,[87]), finite element methods for solving Navier-Stokes flow equations, to study transport through real pore morphologies and to analyse effects of pore space changes (Bodaghi *et al.* [26], Swery [193]). However, the analysis is restricted to the imaged volume, i.e. the imaged volume could contain only a limited set of all possible size and connectivity characteristics of the material. As a result it is yet not certain when image-based analyses could provide macro scale properties. Figure.11 shows a systematic and multidisciplinary contribution for establishing such a link between internal geometry variations and macroscopic stochastic permeability. Starting from tow path data which can be measured easily, it is possible to obtain information on the meso-scale permeability valid for a certain textile reinforcement type. Based on this information, it is important to gather data on the mesoscale level coefficient of variation together with the correlation length of permeability as well as the probability distribution function. Subsequently, the random field permeability is generated in a correlated fashion by K-L expansion method. To model the stochastic nature of fill time, Darcy's description of the mould filling process is employed with the realisation of random permeability field. The Monte-Carlo simulations for generating different realisations of random permeability field is used to obtain stochastic information on the fill time.

The review of literature has clearly shown that although deterministic modelling of flow simulation is quite advanced, the stochastic flow modelling is in its infancy and would gain a sure footing in developing robust manufacturing process window for Liquid Composite Moulding if the local variations unavoidable during the production of textile preforms can be related to the local permeability in an efficient and realistic way. This will shed more light on which parameters in textile production influence the filling and help develop tighter controls on them to improve repeatability in the production process or focus on process control to eliminate micro voids due to filling by developing flow pathways that will be insensitive to such variations or introducing sensors and actuators in the production system to counteract such variations which can be incorporated in the next generation of stochastic flow simulations as a function of textile preform parameters that are likely to introduce such variations.

(Figure.11)

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Figure 1

Figure.1: Different types of fabrics

Figure 2

Figure.2: Dual-scale porosity of 2 by 2 twill carbon fabric: (A) Channels between tows (B) Space between fibres

Figure 3

Figure.3: Sources of variability in LCM. The numbers in parentheses refers to the sections in which the corresponding topic is discussed.

Figure 4

Figure.4: Yearly distribution of the papers published in the field of composite manufacturing for the period of 1991-2017. N is the number of papers per year. The data are obtained from www.scopus.com.

Keywords for flow models are “flow”, “models” and “composite”. Keywords for permeability variability are “permeability,” “variability,” and “composites”.

Figure 5

Figure.5: Plot of K_P/K_S versus K_P/K_I in log-log coordinates

Figure 6

Figure.6: Ratio of porosity between the tows to the tow porosity ϕ_s / ϕ_t plotted against overall permeability to fiber tow permeability ratio K_p / K_t

Figure 7

Figure.7: change in K_T/d_f^2 with ϕ_t , for a regular fibre packing arrangement.

Figure 8

Figure.8: Elliptic flow pattern of a sheared fabric: α is shearing angle, θ is orientation angle, K_1 and K_2 are in-plane principal permeabilities [20]

Figure 9

Figure.9: Magnitude of Coefficient of Variation (CV) as a function of number of samples

Figure 10

Figure.10: Progression of the flow during a vacuum infusion process experiment.

Figure.11: Integrated roadmap for macro-scale flow simulation under uncertainty induced by fabric variation, I and i represent the current and total number of iteration respectively. [188][189][190].

Table.1: Experimental studies of the relationship of pressure profile at the inlet with time for 1D- flow

References	Type of fabric	Measurement technique	Relationship of Δp and t	Their Explanation
Wu <i>et al.</i> (1994) [69]	Random fibre glass mat	Radial flow	Linear	This nonlinear behaviour was attributed to the compressibility of preform.
	8-harness woven carbon		Non-linear	
Parnas <i>et al.</i> (1995)[70]	3D woven glass fabric	Unidirectional flow	Non-linear	Nonlinear behaviour in the pressure due to unsaturated tows
Parseval et al. (1997) [15]	Random fibre mat	Unidirectional flow and radial flow	Linear	For dual scale, the inlet pressure curves did not show linear behaviour and was explained with the introduction of the sink term, s
	Woven fabric		Non-linear	
Amico and Lekakou (2001) [71]	Plain weave glass fibre	Unidirectional flow	Non-linear	Injection pressure tended to an asymptotic value due to the contribution of dual-scale flow
Endruweit <i>et al.</i> (2002) [66]	Biaxial glass-fibre	Radial flow	Non-linear	Compression of the textile reinforcement leading to changes in porosity
Zhong <i>et al.</i> (2004) [72]	Glass fibre woven	Radial flow	Non-linear	Higher pressure needed to be applied compared to random mat
Kim et al. (2017)[73]	Non-crimped unidirectional glass fibre	Unidirectional laminar flow	Non-linear	Nonlinear pressure profile was verified by the numerical solution of Stokes-Brinkman

Table.2: Numerical studies of the relationship of pressure profile at the inlet with time

References	Porous medium	Measurement technique	Relationship of Δp and t	Comments
Pillai and Advani (1998) [62]	Dual-scale	Simulation of Radial flow	Non-linear	Single scale Darcy's law not applicable for a dual-scale porous medium because it not only over predicts the inlet pressure but also fails to capture dual scale flow in inter and intra tow channels.
Bréard et al. (2003)[58]	Dual-scale	Simulation of unidirectional flow	Non-linear	The nonlinear behaviour of the pressure profile for transient flow is due to dual-scale flow
Tan and Pillai (2012)[73]	Dual-scale	Simulation of unidirectional flow	Non-linear	The inlet-pressure profile for single scale porous medium can be approximated by Darcy'law and continuity equation. But this equation fails to predict the pressure history for dual-scale flow.
Gascón et al. (2016)[74]	Single scale	Numerical simulation of unidirectional flow	Linear	Single scale Darcy's law cannot predict the unsaturated flow through dual scale porous media in RTM
	Dual-scale		Non-linear	

Table.3: Numerical estimates of the influence of the dual scale flow on preform permeability.

References	K_P / K_s	K_P / K_t		ϕ_s	ϕ_t	$V_f(\%)$	Geometry	Equations (Computational method)
Sadiq <i>et al.</i> (1995) [81]	1.04	5120		0.5	0.25	38.4	Regular arrays of circular, solid and permeable cylinders	Inverse solution of Darcy's equation
Phelan and Wise (1996) [80]	1	1625	371 2	0.3	0.25	53	Rectangular arrays of solid and porous cylinders	Semi-analytical lubrication
Ranganathan <i>et al.</i> (1996) [82]	1	10000		0.3	0.3	49	An array of porous cylinders with elliptical cross sections	Stokes equation for inter-tow flow and Brinkman equation for intra-tow flow (Finite element package FIDAP)
Papathanasiou (1997) [83]	4	1260		0.25	0.6	30	A uniform square packing of fibre tows	Stokes equations for both inter and intra-tow flow (Boundary Element Method)
Nedanov and Advani (2002) [89]	1	0.7-7000		0.13	0.29	62	Woven fabric with a hexagonal arrangements of fibres	Stokes equation for inter-tow flow and Darcy's equation for

							intra-tow flow (CFD package FIDAP)
Belov <i>et al.</i> (2004) [87]	1.25	1500-7000	0.4	0.42	35	A woven fabric generated by WiseTex software [91]	Lattice Boltzmann method
Hwang and Advani (2010) [92]	5.5	470	0.53	0.26	35	Single and two- tow domain in a hexagonal arrangement of fibres	Stokes equation for inter-tow flow and Brinkman equation for intra-tow flow
Nabovati <i>et al.</i> (2010) [90]	3.3	1000	0.45	0.64	20	An ideal woven fabric with solid and permeable tows	Lattice Boltzmann method for both inter and intra- tow flow
	10	10	.35	0.64	24	Woven fabric in a hexagonal and square arrangements of fibres	
Tahir <i>et al.</i> (2014) [93]	1.03	1461	0.5	0.25	48	Unit cell contains tows and fibres with hexagonal packing	Navier stokes equations for both inter and intra-tow flow (ANSYS Fluent)
	1.06	3221	0.6	0.37	26	Quasi-UD NCF fabric	

Syerko <i>et al</i> (2018)[94]	4.67	82	.25	0.36	48	A woven fabric generated by WiseTex software [91]	The system of equations of momentum (Brinkman equation) and mass conservation
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Table.4: Experimental values of the Kozeny constant k_c , as measured by various research groups

References	Fibrous media types	k_c	
		Transverse flow	Longitudinal flow
Lam and Kardos (1991) [97]	UD* Hercules AS-4 graphite	11	0.35-0.68
Gebart (1992) [96]	UD Ahlstrom R12-256	8	1.66-1.78
Gibson <i>et al.</i> (1996) [98]	UD Roving glass fibre(PPG Hybon 764)	8	1.06
Williams <i>et al.</i> (1974) [99]	Silane glass, random glass, carbon and nylon	0.1-0.8	
Muzzy <i>et al.</i> (1999) [100]	Random glass mat	7.6	
Li and Gu (2005) [101]	Polypropylene fibers and nylon fibers for the fibrous beds and polypropylene particles for the granular beds	12.81	
Lindsay (2012) [102]	Paper	3-7	

* UD = unidirectional

Table.5: Models for permeability as a function of tow fiber volume fraction ($1-\phi_t$) with regular fibre packing

References	Geometry	Intra-tow models
Kozeny-Carman(1937) [95]	Granular beds consisting of ellipsoids
Happel (1959) [103]	Square array of cylinders
Sparrow and Loeffler (1959) [104]	Triangular or square array of cylinders
Sangani and Acrivos (1982) [106]	Square array of cylinders
Drummond and Tahir (1984) [109]	Square array of cylinders
	Hexagonal array of cylinders
Gutowski <i>et al.</i> (1987) [45]	Parallel array of graphite fibres
Gebart (1992)[96] *	Square array of cylinders: C=57
	Hexagonal array of cylinders: C=53	

Gebart (1992) [96] *	Square array of cylinders: $C_1=0.1, V_f^{max}=0.78$
	Hexagonal array of cylinders: $C_1=0.057, V_f^{max}=0.91$	
Sharaoui and Kaviany (1992) [107]	Two-dimensional periodic array of cylinders
Bruschke and Advani (1993)[108]	Array of circular cylinders with square packing arrangement
Lee and Yang (1997) [110]	Parallel array of circular cylinders

* K_T =permeability perpendicular to the fibres

Table.6: Permeability correlation length for various fabric types (network model)

References	Network model	reinforcement geometry scale		Size of discretised random field (mm)	Correlation length (mm)			Sample dimension (y mm × x mm)	Comments
		Yarn spacing (mm)	Strand size (mm)		K_x	K_y	K_z		
Murata <i>et al.</i> (2017)[200]	Glass fabric	-----		150	90	90	15	180 × 180	Assumed value
Matsuzaki and Shiota (2017) [196]	Not specified	-----		50	210	105	14	150 × 300	Assumed value
Desplentere et al. (2006) [201]	Plain woven glass	3	---	3787	5.1	5.1	-----	200 × 200	Defined by the analysis of the geometrical variability
Zhang <i>et al.</i> (2011) [202]	Chopped strand glass	-----	4	83 × 83	10.1	11.3	-----	475 × 375	Defined by the analysis of the geometrical variability
Bodaghi <i>et al.</i> (2017)[26]	2×2 twill woven carbon	3	-----	10 × 10	21	21	-----	100 × 100	Defined by the analysis of the geometrical variability
Yun <i>et al.</i> (2018) [185]	E-glass woven	Not specified		24 × 12	-----	-----	5	120 × 60	Defined by the analysis of the geometrical

								variability
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Table.7: Probabilistic models for stochastic flow simulations

References		Objective	Probability model	Coefficient of variation (CV) (%)
Padmanabhan and Pitchumani (1999)[186]		A Monte-Carlo simulation Minimizing fill time as well as output parameter variabilities	Log-normal	1
Correia <i>et al.</i> (2004) [204]		Monte-Carlo based flow simulation	Normal	22
Desplentere <i>et al.</i> (2006)[201]		Stochastic mould filling simulation for RTM	Log-normal	20
Markicevic <i>et al.</i> [194]		Addressing dry spot by stochastic modelling of preform heterogeneity in VARTM process	Log-normal	
Li <i>et al.</i> (2006)[205]	1D flow	A Monte-Carlo simulation based RTM flow	Weibull	21
	2D flow		Normal	20
Zhang <i>et al.</i> [198]		Meso-scale stochastic simulation for mould filling process	Log-normal	1
Matsuzaki <i>et al.</i> (2017) [206]		A flow monitoring as well as VaRTM resin-impregnation simulation	Normal	10-30
Yun <i>et al.</i> (2018)[185]		Addressing dry spots due to through thickness heterogeneity	Gamma	100

Table.8: Probabilistic models for permeability based on experimental studies. ϕ is the porosity fraction,

N_s is number of samples and CV is coefficient of variation.

References	Material description (Areal density (g/m ²))	ϕ (%) (layers)	N_s	Technique	Probability model	CV(%)	
						K_x	K_y
Steenkamer <i>et al.</i> (1995) [209]	Continuous strand E-glass mat (450)	71.8 (5)	-----	Radial flow experiment	Normal	15.3	18.8
	Biaxial E-glass knit (686)	56.1				8.9	12.3
	Biaxial E-glass knit plus mat (912)	45.3				15	20
Parnas <i>et al.</i> (1997) [210]	3D woven E-glass fabric (882)	41.3 (10)	10	Radial flow experiment	Normal	13	
Bikerton <i>et al.</i> (1999) [211]	Continuous-strand random mater	93.1 (1)	3	Unidirectional method	Normal	5.8	
		92.4 (1)	3			8.6	
		70.7 (1)	3			11.4	
	Scotnorchbrite	91.7 (1)	3			5.8	
		83.5 (1)	3			3.7	
		73.2 (1)	3			5.7	
Pan <i>et al.</i> (2000) [187]	0/90 balanced knitted E-glass fabric (626)	55(6)	32	Unidirectional method	Normal	6.9	
	Plain woven (624)	55	32			13.1	
Hoes <i>et al.</i> (2002) [130]	Plain weave E-glass (420)	58.3 (5)	86	Radial flow experiment	Normal	21	22.2
	Twill weave E-glass (380)	47.2 (7)	87			14.4	21.6

Li <i>et al.</i> (2005) [207]	Woven fabric(810)	50	46	Unidirectional method	Weibull	30	
Endruweit <i>et al.</i> (2006)[146]	Non-crimp glass fibre (950)	55 (3)	20	Radial flow experiment	Normal	22.5	26.1
	Continuous glass random mat (450)	74(3)	20			29.3	27.7
	5-harness satin weave carbon fabric (380)	54 (5)	18			17.9	12
	5-harness satin weave carbon fabric (290)	58 (7)	15			10	9.1
	Plain weave glass fibre fabric (912)	53 (3)	19			29.2	25.7
Liu and Parnas (2007)[25]	Basalt fabric (750)	64.2 (6)	64	radial flow experiment	Normal Weibull	25.5	27.8
Zhang <i>et al.</i> (2012) [202]	Chopped strand mat (457)	62	37	radial flow experiment	Log-normal	21	
Benchmark II (2014) [20]	2×2 twill carbon fabric (285)	55(10)	72	unidirectional flow	Normal	17.7	28
Matveev <i>et al.</i> (2017)[208]	Dry 24K carbon fibre tows (194)	46 (16)	31	unidirectional flow	Lognormal	7.5	11

Table.9: Probabilistic models of permeability based on Simulation studies

References	Material description (Areal density (g/m ²))	ϕ (%) (layers)	N _s	Technique	Probability model	CV(%)	
						K _x	K _y
Endruweit <i>et al.</i> (2006)[212]	Non-crimp glass fibre (936)	67 (4)	100	Stochastic simulations of radial injection	Normal	25	
Wong and long (2006) [213]	Non-crimp fabric	60	100	Stochastic simulations	Normal	15	
Loendersloot and Akkerman (2006) [192]	Biaxial Non-crimp fabric (534)	53	25	Predicted by meso –scale network model	Normal	15	
Bodaghi <i>et al.</i> (2017) [26]	2×2 twill carbon fabric (285)	22-26 (1)	100	Predicted by meso –scale network model	Normal	12	15