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# A numerical study of the influence from architecture on the permeability of 3D-woven fibre reinforcement

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ABSTRACT

Various modelling aspects of the permeability of three-dimensional (3D) woven textile preforms are studied using computational fluid dynamics (CFD). The models are built using a recently developed technique able to generate close to authentic representations of 3D textile arrangements. One objective of the study is to investigate how parameters such as the tow architecture and the level of detail in the CFD models influence the results. A second objective is to investigate how the inter and intra-tow porosity affect the permeability. They are varied in a way that somewhat resembles how they would change during compaction, although compaction as such is not modelled. It is concluded that the intra-tow porosity has little effect on the overall permeability of a 3D-woven preform. Detailed modelling of local variation of the intra-tow porosity is thus redundant, which is also demonstrated. The inter-tow porosity, on the other hand, has a prominent influence on the overall permeability. The overall permeability is inherently anisotropic but when the inter-tow porosity is increased the permeability does not increase uniformly but becomes more isotropic. Good agreement is obtained between the numerical simulations and experiments performed in a parallel study.

## 1. Introduction

Fibre reinforced composite materials receive increasing attention in many fields of application since the current emphasis on energy efficiency makes more applications weight-critical. Sheet metal is often replaced with composite materials containing two-dimensional (2D) fibre reinforcement. However, stresses in joining elements, stiffeners and stringers are often three-dimensional (3D), which could make the relatively poor out-of-plane strength and associated risks for failure due to delamination a major concern, if multi-layer composite materials are used. To overcome this problem various forms of 3D textile preforms have been developed, such as 3D braids, non-interlaced 3D fabrics [1,2], different forms of 2D-woven 3D-fabrics such as layer-to-layer and through-thickness angle interlock weaves, and 3D-weaves [3].

It should be noted that the nomenclature for 3D textiles is very ambiguous in the literature, which is unfortunate since it impedes clear distinctions between different architectures and the specific features and properties they govern. Here a principle promoted in [2] is adopted stating that a textile technique should not be called weaving unless it incorporates shedding.

Efficient impregnation is key to good properties of fibre reinforced composite materials. The quality of the final product is therefore dependent on the matrix flow and the flow parameters during processing.

Liquid composite moulding (LCM) is extensively used in marine, automotive and civil aircraft industry for manufacturing of thermoset composite parts. Various types of LCM include resin transfer moulding (RTM), vacuum assisted resin transfer moulding (VARTM) and structural reaction injection moulding (SRIM); all of them relying on sufficiently high permeability of the fibre reinforcements at hand.

Considerable effort has been spent in the past to estimate the permeability of fibrous structures. Initial models of the permeability of fibrous porous media were based on the capillary model, e.g. the Kozney Carman model [4] with modifications proposed by Gutowski et al. [5,6]. Numerical models of flow across aligned arrays of infinitely long impermeable cylinders were later performed by Sangani and Acrivos [7], Hjellming and Walker [8], Gebart [9], and Bruschke and Advani [10]. Among these models, Gebart's model seems to be most widely accepted. It is also verified and used in numerous other studies, e.g. [11–18].

Gebart [9] proposed analytical relations for the permeability of unidirectional fibres in hexagonal and quadratic arrangements, without use of empirical constants. Later, Lundström [11] studied flow during resin transfer moulding (RTM) both experimentally

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and analytically. Moreover, Lundström validated Gebart's model and stated excellent agreement between calculated and numerically computed permeabilities. Lundström also presented an expression for the transverse permeability of packings of impermeable tows with lenticular cross sections.

The models presented in Refs. [5,6,9,10] were single phase models. However, in reality composite materials are characterised by dual scale – intra-tow and inter-tow – porosity. The concept of dual scale models for fibrous porous materials was initially presented by Phelan [19].

Later, Sadiq et al. [20] performed experimental studies of transverse viscous flow through square arrangements of solid and porous tows. It was concluded that the overall permeability ($\kappa_o$) of a fabric with porous tows was 25% higher than the permeability of the corresponding fabric with solid tows. It was however stated by Ranganathan et al. [21] and Nedanov and Advani [13] that the effect of the intra-tow permeability ($\kappa_t$) is insignificant if it is two orders of magnitude lower than the inter-tow permeability ($\kappa_s$). It was also stated by Gooijer et al. [22,23] that $\kappa_t$ has a much smaller impact on $\kappa_o$ than $\kappa_s$. The discrepancy between these studies is addressed in [18].

A dual scale problem can either be solved by incorporating filaments in the tow geometry, or by computing $\kappa_t$ analytically and using it as homogenised input permeability for the tows. However, the former option may be very expensive computationally. Therefore the latter option would generally be preferred, provided that the homogenisation provides sufficient representation of $\kappa_t$ [18].

Ngo and Tamma [12,14] predicted $\kappa_o$ of a non-interlaced fabric (referred to as a 3D orthogonal woven fabric) assuming transversely isotropic permeable tows. Gebart's relations were used as input for $\kappa_t$ of the tows. Song et al. [24] computed the permeability tensor of a 3D braided fabric and Endruweit and Long [25] studied the permeability of 3D angle interlock weaves.

Vernet and Trochu [26] studied the permeability of 3D angle interlocked fabrics with varying weave parameters, both experimentally and analytically. They concluded that presence of macro pores is the main source of pressure drop in the RTM process. Song et al. [24], predicted the permeability tensor for a 3D circular braided preform assuming impermeable tows and Newtonian flow. The permeability estimated from the numerical simulations was found to be higher than the experimental. Moreover they verified independence of the pressure difference and viscosity on the permeability. More recently Nabovati et al. [17] studied flow through an idealised 3D multi filament structure employing lattice Boltzmann's method.

Through-thickness permeabilities of 3D angle interlock weaves and non-interlaced fabrics were analytically and experimentally characterised by Xiao et al. [27]. Zeng et al. [28] used computer tomograph (CT) scans and image processing as input for finite element (FE) models. They characterised the in-plane as well as the through-thickness permeability of the fabric using computational fluid dynamics (CFD) code.

The numerical models presented in the past for various 3D-textiles [15,17,24] incorporate highly idealised tow geometries, in most cases assuming fibre tows with perfect circular or elliptical cross sections. As the fibre architecture has been shown to affect $\kappa_o$ that kind of idealisation is likely limiting the accuracy of the models. To the knowledge of the authors, predictions of permeability considering locally varying cross section areas of tows, and thus locally varying inter and intra-tow porosity, has not been studied in the past.

In this work the CFD software ANSYS Fluent is used to model flow through 3D-woven textile preforms. An objective is to investigate how parameters related to the fibrous architecture and the level of detail in the CFD models influence predictions of the permeability. It is also investigated how $\kappa_o$ varies with the inter-tow porosity ($\phi_s$) and the intra-tow porosity ($\phi_t$). Another objective is to compare the results from the numerical simulations with results from a parallel experimental study [29].

## 2. Theory and description of the numerical model

A 3D-woven textile is a heterogeneous material containing features at several length scales, ranging from the diameter of individual filaments, via the diameter and undulation of yarns, to the finite dimensions of the woven preform. Impregnation of such a textile is thus a multi-scale problem. The weave pattern however imposes that the yarns are arranged in regular patterns allowing for a periodic representative volume element (RVE) to be distinguished. Within a RVE the impregnation can then be reduced to a dual length scale problem.

A sparse 3D-geometry with thin tows is generated using a methodology previously presented by Stig and Hallström [30,31]. The internal geometry is first generated in a separate step where the tows are outlined as slender thin-walled tubes. The mechanical properties of the tube walls are set to mimic the dry yarn behaviour, i.e. being stiff in the fibre direction and very compliant in the transverse direction, and in shear.

The tubes are then inflated to their final size, i.e. the target inter-tow porosity, under general contact conditions [30], aiming for a similar spread and distribution of the yarns as one would find after an infusion process in a mould. The resulting tow cross section shapes may vary substantially along their paths due to the spatial competition with neighbouring tows but the tow lengths remain virtually unaltered. It should be noted that such lengthwise variation of the cross section is necessary to obtain the tow packing levels typically found in many real complex 3D textile architectures. The numerical models for the final FE analysis are then created following the scheme presented in [31].

The yarn undulation and variation of cross sectional shape are illustrated in Figs. 1–3. Fig. 1 shows a RVE at $\phi_s = 0.2$, where the infiltrated fibre tows (Fig. 1a) have been separated from the matrix (Fig. 1b) for better visualisation. Fig. 2 shows images of cross sectional views from a CT scan of the real material (Fig. 2a) and from corresponding numerical model (Fig. 2b). Finally Fig. 3 shows an image of a single yarn from the real material, illustrating the lengthwise variation of cross sectional area and shape.

Meshing of the pure matrix regions in composite models can be a challenge [32], especially for low $\phi_s$ values. As part of the adopted approach one can however stipulate a certain contact clearance during inflation of the tows in the initial FE simulation and hence generate sufficient gaps between the tows to enable a good mesh in the subsequent flow simulations.

Some input parameters necessary for the model generation are kept constant for all models, i.e. the tow fibre content, the tow crimp and the RVE size. These parameters are presented in Table 1. The tow crimp, the RVE size and the cross section areas of the tows are extracted from measurements on microscopy images of composite samples.

The tow crimp is here defined as $l_t/\lambda$ where $l_t$ is the total (curvilinear) length of the tow and $\lambda$ is the wavelength of the tow path. (The RVE size is thus defined by the wavelengths of the warp and the horizontal and vertical wefts.)

Individual filaments are not included in the geometrical description of the tows since it is not feasible with the available computer power. Instead the tows are assumed to be porous in a homogenised sense, which was shown to provide corresponding results for 2D textiles in a previous study [18].

The warp tows in the 3D-weave under consideration are fully interlaced with both horizontal and vertical wefts, in accordance