Numerical Determination of Permeability Tensor Components for 3D-braided Composites Using RVC Approach

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Abstract

Today, one of the most promising trends in the design and manufacturing of composite structures is the use of 3D-reinforced thermoplastic composites. The present paper is concerned with the problem of resin transfer molding (RTM) process modeling, which is an important stage of 3D thermoplastic composites design.

It is known that during the impregnation of woven preform local starved spots may occur, the textile pattern may distort and as a result the final structure will differ in mechanical properties form the initial design. The proper selection of RTM process parameters, such as injection holes placement, pressure profile and flow rate is a challenge for designers and process engineers. Nowadays, specialized software is developed for the solution of that problem, but the RTM process modeling in these environments is associated with considerable difficulties, caused by the need to set the permeability tensor, which components should be determined experimentally for each fiber material and for each weaving type. However, the permeability parameters can be determined in virtual experiments using the representative volume cell (RVC) approach by simulating a coupled-field problem of a viscous incompressible fluid flow through a porous medium.

The paper demonstrates such an approach for permeability tensor components determination for the chosen 3D textile pattern using LS-DYNA with ALE computational method. Resin flow interaction with the fibers is modeled using FSI approach, while the flow through the fiber material is described by Darcy's law. As a result, resin pressure drop curves along three RVC directions were determined, on the basis of which the permeability tensor components were obtained.

Keywords: *Composites, RTM, modeling, ALE, FSI, porous flow, anisotropic permeability.*

1 Introduction

The future of composite materials industry, among other things, is associated with the design of structures made of 3D-reinforced textile preforms, impregnated with a viscous resin with subsequent solidification. One of the main reasons, which makes to develop new composite materials are low impact resistance and susceptibility to interply cracking, inherent to traditional layered composite designs. Furthermore, the automated preform production with specialized textile machinery will significantly reduce the proportion of manual labor, thereby increasing the performance of the production process and quality of the final product. Using such technology it is possible to create full-strength designs based on the use of 3D textile preforms. Thus, each structure can be designed taking into account the operating loads and the weaving type can be chosen to ensure the full strength of the whole structure. This, in turn, leads to the fact that for each specific part the material can be designed and optimized with the structure. By choosing and optimizing the scheme of weaving, the designer can provide a full strength solution for rather complex, both in terms of the design and operating loads, structures. There is a new concept for an engineer – material design.

There are several problems that must be solved by an engineer during the design of such structures. Among them, the problem of woven preform infusion is one of the most major and difficult problems. As it is known, during the resin infusion of woven preform local porosity zones may occur, fabric structure can distort and the final product will differ significantly in its main characteristics from the initial design. That’s why during the design of such structures, the process engineer must perform the selection of the optimal location for the resin admission holes, pressure profiles, flow rates and other process parameters, which will provide the required quality of the product. Currently, for the solution of such problems the specialized software was developed (such as, for example, ESI PAM-

RTM and RTM-WORX). Using this software, the engineer can design an optimal resin infusion process, which will provide low porosity and fiber disorientation while ensuring adequate process time and resin consumption. But for an adequate simulation of the resin transfer molding process one should know the permeability tensor values for the particular weaving type and fibers he uses. The values of permeability tensor are usually determined by conducting sets of experiments on fiber and preform infusion. However, the components of the permeability tensor can be determined in a virtual experiment using the representative volume cell approach through modeling of a viscous incompressible fluid flowing through a porous medium.

2 Darcy's law and permeability tensor

Permeability is part of the proportionality constant in Darcy's law which relates discharge (flow rate) and fluid physical properties (e.g. viscosity), to a pressure gradient applied to the porous media:

$$V = \frac{k}{\mu}\frac{\Delta P}{L} \tag{1}$$

Therefore:

$$k = V\frac{\mu L}{\Delta P} \tag{2}$$

where:

V is the superficial fluid flow velocity through the medium (i.e., the average velocity calculated as if the fluid were the only phase present in the porous medium),

k is the permeability of a medium,

μ is the dynamic viscosity of the fluid,

ΔP is the applied pressure difference,

L is the thickness of the bed of the porous medium.

To model permeability in anisotropic media, a permeability tensor is needed. Pressure can be applied in three directions, and for each direction, permeability can be measured (via Darcy's law in 3D) in three directions, thus leading to a 3 by 3 tensor. The tensor is realised using a 3 by 3 matrix being both symmetric and positive definite. The tensor is positive definite as the component of the flow parallel to the pressure drop is always in the same direction as the pressure drop. The permeability tensor is always diagonalizable (being both symmetric and positive definite). The eigenvectors will yield the principal directions of flow, meaning the directions where flow is parallel to the pressure drop, and the eigenvalues representing the principal permeabilities.

There is an option in LS-DYNA FSI coupling algorithm to use the Ergun equation to model fluid-porous structure interaction [1]. The Ergun equation is based on the superposition of two asymptotic solutions, one for low velocity flow (first term on right) and one for high velocity flow (second term on right), so instead of Darcy's law the following equation is used:

$$\frac{\Delta P}{L} = \frac{\mu}{K_1}V + \frac{\rho}{K_2}V^2 \tag{3}$$

$$K_1 = \frac{\varepsilon^3 D^2}{150(1-\varepsilon)^2}, \qquad K_2 = \frac{\varepsilon^3 D}{1.75(1-\varepsilon)},$$

where:

K_1 – constant in viscous term – this is not permeability;

K_2 – constant in inertia term;

D – equivalent spherical diameter. Ergun developed this equation to model flow in chemical extraction columns. These vertical cylindrical tanks are packed with irregular shaped objects. *D* is a length scale representing the equivalent diameter of the packing material relative to an enclosing sphere;

ΔP – pressure drop;

L – length of flow channel;

V – fluid velocity;

μ – fluid viscosity;

ε – porosity, (void volume)/(total volume);

ρ – fluid density.

If we only consider the first (viscous) term in the Ergun equation (3), then K_1=*k* and we can use the Ergun equation to model RTM porous media flow [1].

3 RTM modeling approach

A proposed method for the determination of permeability tensor components is based on the representative volume cell (unit cell) approach. It was assumed that textile preform under consideration has a periodical weaving structure, so the representative unit cell can be allocated, which replication will give the whole structure geometry. As the geometry of the cell (weaving structure) is not symmetric (if it is symmetrical, than it is possible to choose a smaller cell), the permeability of the cell is anisotropic, so three principal permabilties were to be determined. The principal axes in that case are normal to the periodical planes of the unit cell. So to determine three permeability values k_1, k_2 and k_3 the flow of a viscous fluid through a porous media was modeled in three flow directions, normal to the unit cell boundaries. An LS-DYNA ALE approach with fluid structure interaction modeling (FSI) was used for that purpose. The whole RVC structure, which had a Lagrangian (solid) mesh type, was surrounded by the Eulerian mesh to hold the viscous flow.
The fluid density and viscosity were entered using the *MAT_NULL keyword. A simple equation of state was used to relate the pressure to the fluid compressibility:

$$P = \rho_0 C^2 \left(\frac{\rho}{\rho_0} - 1 \right) \tag{4}$$

The objective was to calculate the pressure drop over the length of the RVC in three directions due to a fluid-porous media interaction.
While modeling RTM with unit cell approach, the flow needs to be constrained over the RVC Eulerian mesh boundaries. Otherwise, the flow will exit the domain of the RVC. In a properly constrained model, the flow will remain inside the domain. The *ALE_ESSENTIAL_BOUNDARY keyword was used for that purpose [2]. This keyword applies the flow condition (e.g., stick, or slip) along the ALE Euler mesh surface automatically.

3.1 RVC geometry

An arbitrary unit cell of 3D textile preform was chosen to illustrate the described approach. The geometry of the unit cell was build using TexGen [3] open source software. This software allows generating arbitrary geometrical (CAD) models for different woven composite structures
The chosen fabric pattern is shown in Fig. 1. It has 25x25 periodic volume cells.

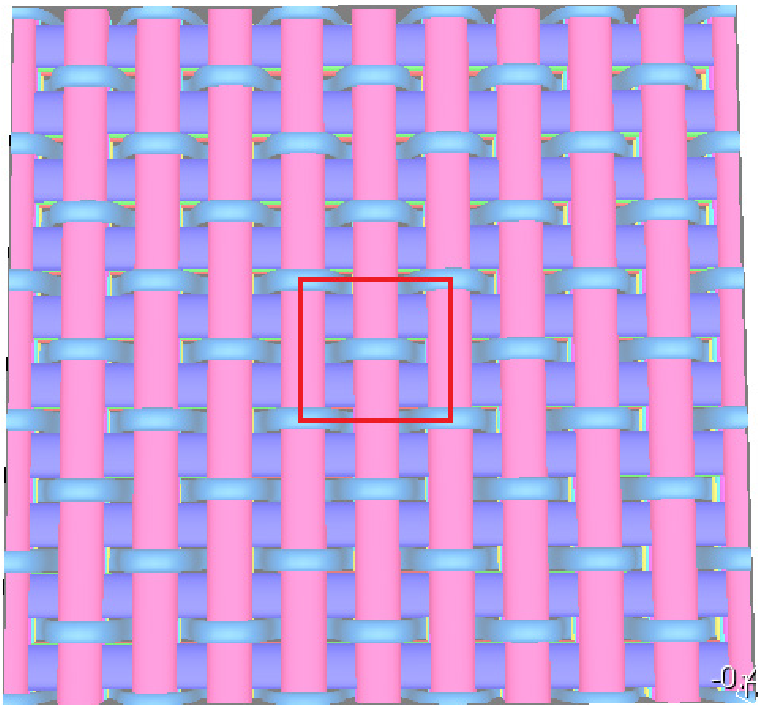

Fig. 1: Considered 3D woven textile preform with emphasized RVC.

RVC geometrical model is shown in Fig. 2.

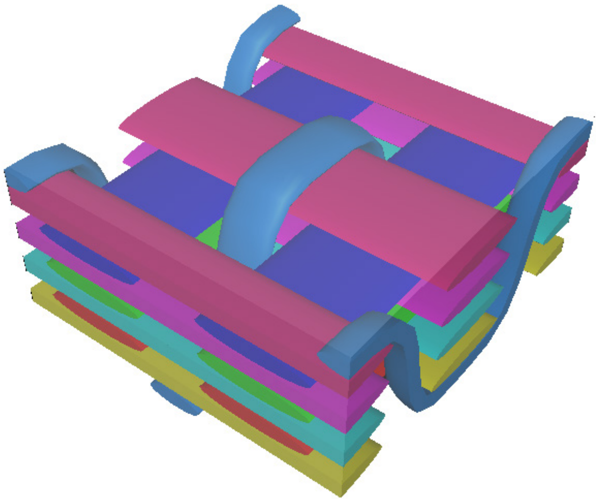

Fig. 2: The RVC geometry in TexGen.

The weaving structure consists of 7 plies of orthogonally oriented yarns, stitched through the thickness. Geometrical parameters of RVC are listed in Table 1. The RVC size is 3.3x3.15x1.465 mm.

Table 1: Geometrical parameters of the weaving.

Warp yarn width w_x, m,	1
Distance between warp yarns s_y, mm	1,575
Weft yarn width w_y, mm	1
Distance between weft yarn s_x, mm	1,65
Stitching yarn width, mm	0,5
Yarn thickness t, mm	0,15

It is proposed in this work that fibers sections are elliptic.

3.2 Numerical modeling of RTM process for the considered RVC

For RTM modeling the approach described by Shapiro [1, 2] is used. This technique was applied for the RTM process modeling if resin flow through woven textile preform with volumetric weaving structure as described above. For the considered RVC, which was chosen to illustrate the concept, pressure drop was determined for resin flow in three orthogonal directions. The results of an analysis were three principal permeability coefficients in anisotropic Darcy's law.
Solid finite element model of RVC is shown in Fig. 3.

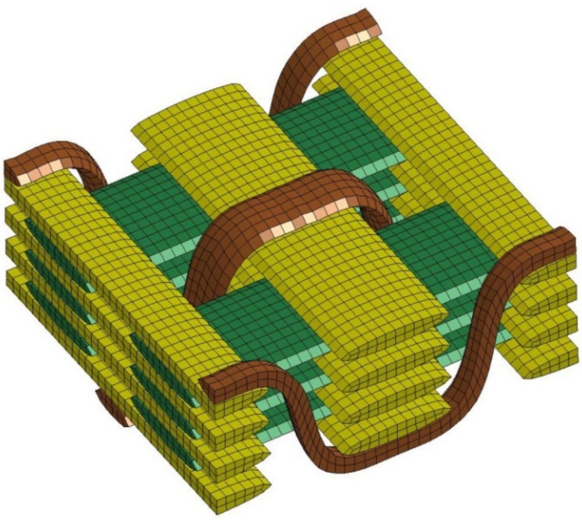

Fig. 3: Finite element model of the RVC.

RTM process modeling was performed using Eulerian-Lagrangian coupling (fluid-structure interaction, FSI). An Eulerian mesh overlapping the Lagrangian RVC mesh was build inside the cuboid, bounding the RVC yarns so that the Eulerian element size was equal to the Lagrangian one. An ambient element layer with prescribed inlet velocity was added to the Eulerian mesh boundary, which receive the flow.. The following material properties and initial conditions were given:

Resin viscosity μ=0.2 Pa·s;

Flow velocity V=0.5 mm/s;

Yarn permeability $k_{yarn} = 10^{-10}$ m^2;

The complete FE model for fluid flow through porous media modeling in Z (stitch) direction is shown in Fig. 4.

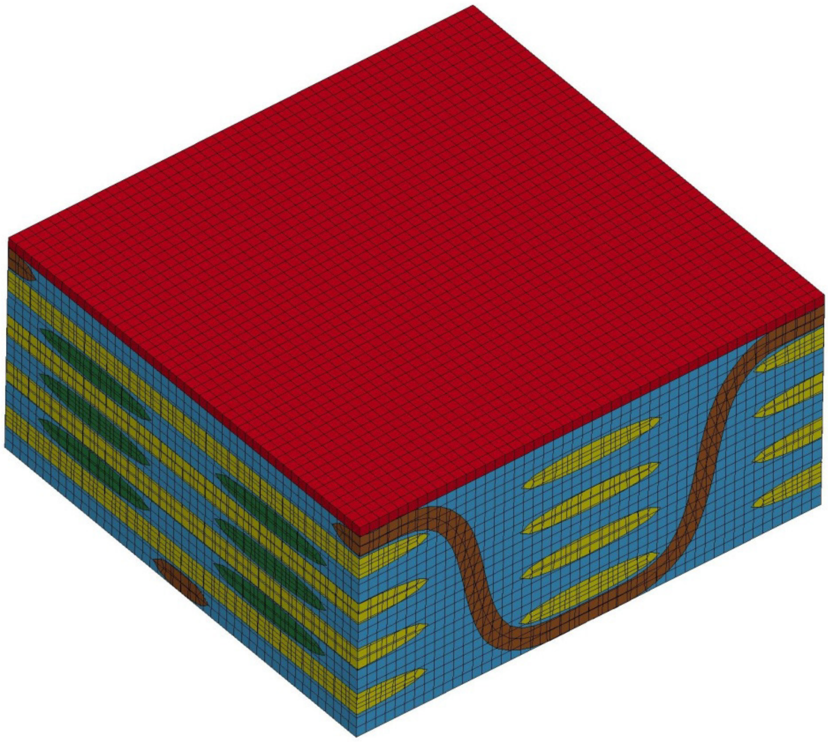

Fig. 4: FE model for RTM modeling in stitch direction.

As a result of the calculations, the pressure drop was determined during the molding process in specific direction. The appropriate chart is shown in Fig. 5.

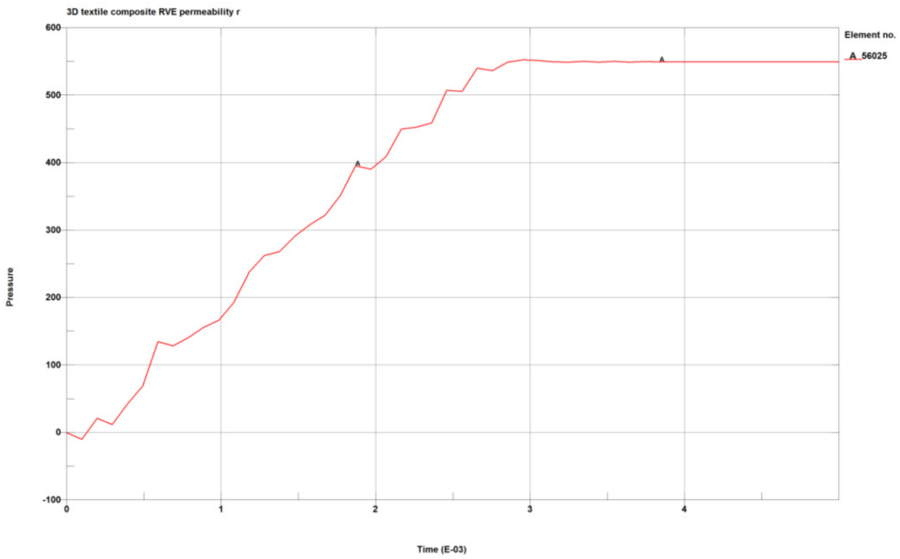

Fig. 5: Pressure-time chart for resin flow in Z-direction. Time scale is 1/1000. Pressure is in Pa.

3.3 Permeability determination

Calculated pressure drop for the specified direction was *ΔP = 550 Pa*. Hence, the permeability k_z of considered RVC in the stitch direction is:

$$k_z = \frac{\mu}{\Delta P} VL = \frac{0.2}{550} \cdot 5 \cdot 10^{-4} \cdot 1.465 \cdot 10^{-3} = 2.67 \cdot 10^{-10} \text{ m}^2.$$

Thus, the fabric permeability in this direction is 2.67 times higher than the yarn permeability. The molding process is shown in Fig. 6.

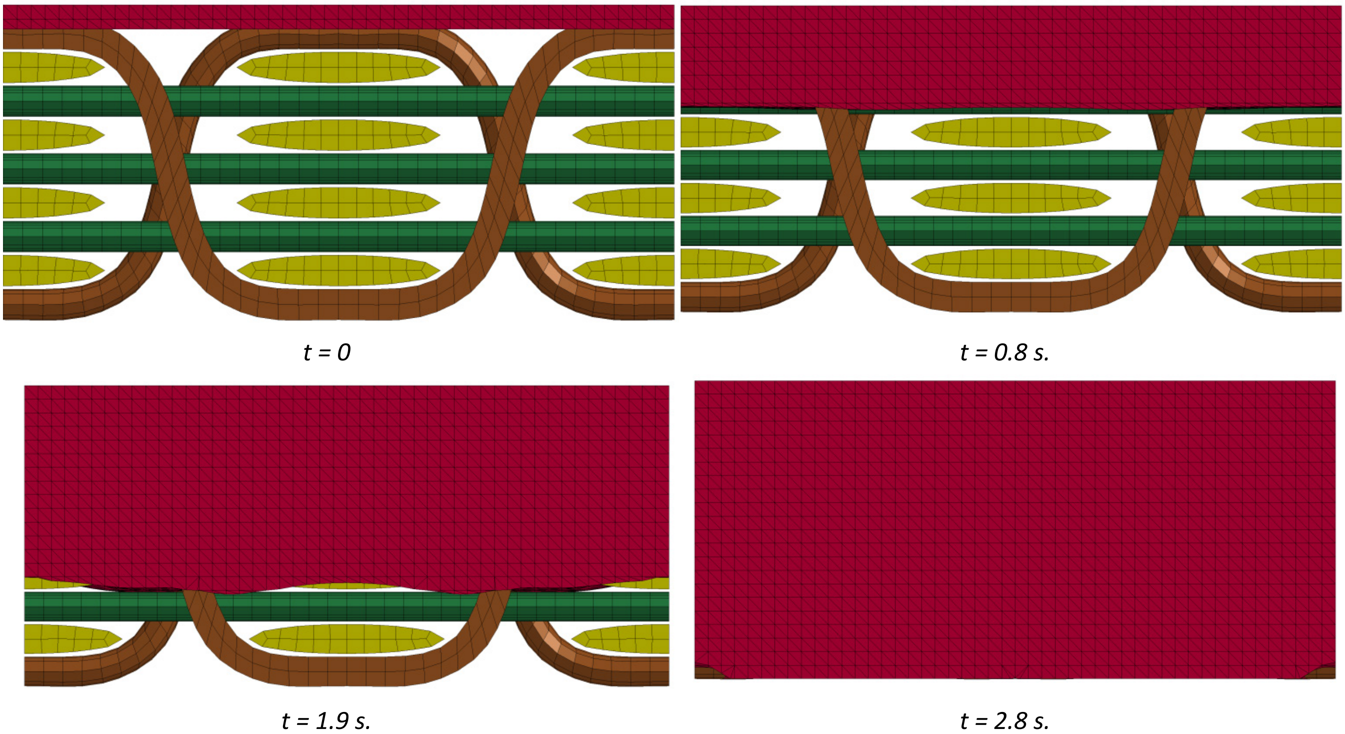

Fig. 6: Resin flow through the RVC.

The same calculations were performed for other two directions of the RVC (along global X and Y axes). Corresponding pressure drop charts are shown in Fig. 7. Calculated pressure drops for both directions were near the same and were equal to *ΔP = 1150 Pa*, which gives permeability $k_x = k_y = 1.27 \cdot 10^{-10}$ m^2. Thus, the in-plane fabric permeability is 2 times less than in normal direction.

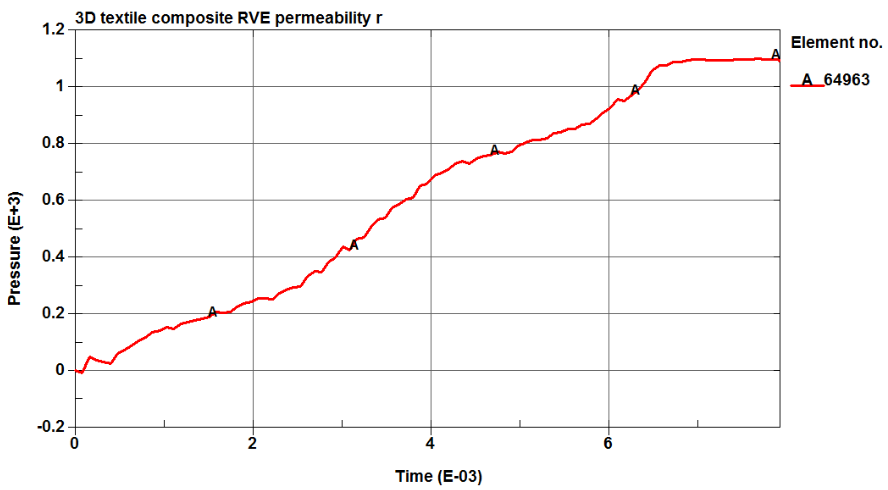

Fig. 7: Pressure drop chart in X-direction, Pa.

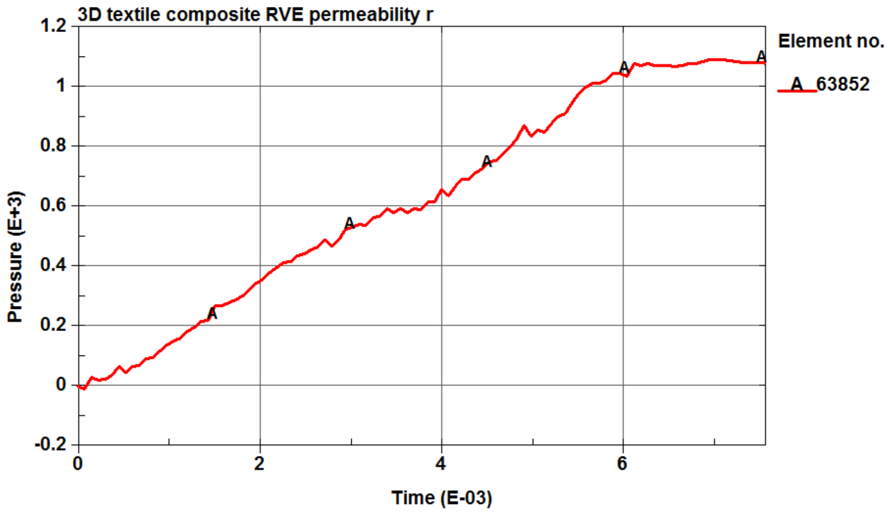

Fig. 7: Pressure drop chart in Y-direction, Pa.

4 Summary

The RTM process modeling was conducted using LS-DYNA ALE approach with FSI coupling of viscous resin flow to fabric yarn porous media. For the numerical determination of permeability tensor components, the RTM simulation was performed on arbitrary textile preform unit cell (representative volume cell) in three orthogonal direction of the RVC. As a result of simulation, the pressure drop was determined in three directions and principal permeabilties were calculated. It was shown that for the chosen textile pattern the permeability in stitch direction is 2.7 times higher than for the plain yarn material. Permeability in ply directions was determined to be 2 times less than in stitch direction. Thus, by the example of arbitrary textile composite representative volume cell an approach for permeability components determination for textile preforms with periodic structure was illustrated. This approach can be used to replace full-scale experiments on resin injection for the determination of permeability. However, the yarn permeability still has to be determined experimentally, but only once for each preform made of the same yarns. Obtained permeabilities could be than used to model the RTM or vacuum infusion process for an arbitrary composite structure with the selected weaving type.

5 References

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[3]. Sherburn, M.: “Geometric and Mechanical Modelling of Textiles”, Thesis for the degree of Doctor of Philosophy, The University of Nottingham, 2007.